



Farm structure and environmental context drive farmers' decisions on the spatial distribution of ecological focus areas in Germany

V. Alarcón-Segura · S. Roilo · A. Paulus ·
M. Beckmann · N. Klein · A. F. Cord

Received: 27 October 2022 / Accepted: 26 June 2023 / Published online: 6 July 2023
© The Author(s) 2023

Abstract

Context Ecological Focus Areas (EFAs) were designed as part of the greening strategy of the common agricultural policy to conserve biodiversity in European farmland, prevent soil erosion and improve soil quality. Farmers receive economic support if they dedicate at least 5% of their arable farmland to any type of EFA, which can be selected from a list of options drawn up at the European Union level. However, EFAs have been criticized for failing to achieve their environmental goals and being ineffective in conserving farmland biodiversity, mainly because

they are not spatially targeted and because they promote economic rather than ecological considerations in farm management decisions.

Objectives We used a spatially explicit approach to assess the influence of farm and field context as well as field terrain and soil conditions on the likelihood of whether or not a particular EFA type was implemented in a field.

Methods We used a multinomial model approach using field-level land use and management data from 879 farms that complied with the EFA policy in 2019 in the Mulde River Basin in Saxony, Germany. Geospatial environmental information was used to assess which predictor variables (related to farm context, field context or field terrain and soil conditions) increased the probability of a field being assigned to a particular EFA. We tested the hypothesis that productive EFAs are more often implemented on fields that are more suitable for agricultural production and that EFA options that are considered more valuable for biodiversity (e.g. non-productive EFAs) are allocated on fields that are less suitable for agricultural production.

Results We found that farms embedded in landscapes with a low proportion of small woody features or nature conservation areas mainly fulfilled the EFA policy with productive EFAs (e.g. nitrogen fixing crops). Conversely, farms with a higher proportion of small woody features or nature conservation areas were more likely to adopt non-productive EFAs. As predicted, large and compact fields with higher

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10980-023-01709-8>.

V. Alarcón-Segura (✉) · S. Roilo · A. F. Cord
Chair of Computational Landscape Ecology, Technische Universität Dresden, Helmholtzstr. 10, 10169 Dresden, Germany
e-mail: viviana.alarconsegura@tu-dresden.de

A. Paulus · M. Beckmann
UFZ - Helmholtz Centre for Environmental Research,
Department of Computational Landscape Ecology,
Permoserstr. 15, 04318 Leipzig, Germany

N. Klein
Chair of Uncertainty Quantification and Statistical Learning, Research Center Trustworthy Data Science & Security (UA Ruhr) and Department of Statistics (Technische Universität Dortmund), Joseph-von-Fraunhofer-Straße 25, 44227 Dortmund, Germany

soil fertility and lower erosion risk were assigned to productive EFAs. Non-productive EFAs were placed on small fields in naturally disadvantaged areas. EFA options considered particularly beneficial for biodiversity, such as fallow land, were allocated far away from other semi-natural or nature protection areas.

Conclusions Our results highlight that the lack of spatial targeting of EFAs may result in EFA options being assigned to areas where their relative contribution to conservation goals is lower (e.g. farms with higher shares of protected areas) and absent in areas where they are most needed (e.g. high intensity farms). To ensure that greening policies actually promote biodiversity in European agriculture, incentives are needed to encourage greater uptake of ecologically effective measures on intensively used farms. These should be coupled with additional measures to conserve threatened species with specific habitat requirements.

Keywords Farm context · Farmland biodiversity · Field context · Greening policy · Multinomial regression · Soil conditions · Terrain conditions · Spatial allocation

Introduction

To achieve greater environmental sustainability, the Common Agricultural Policy (CAP) of the European Union (EU) introduced a direct payment scheme (greening) in 2013, aimed at protecting and enhancing biodiversity, water, and soils in European farmland (European Union 2013; European Commission 2022). Mandatory greening practices include: (i) the maintenance of permanent grassland, (ii) the obligation of agricultural diversification of farmland (cultivation of at least two crops if the arable farmland exceeds 10 hectares), and (iii) the allocation of at least 5% of the arable area to ecological focus areas (EFAs) if the arable area of conventional farms exceeds 15 hectares (German Federal Environmental Agency 2014; European Commission 2017, 2022). Farmers must comply with these requirements to qualify for the greening payments, except farms already implementing sustainable farming practices such as organic farming (European Commission 2022). The ecological value of EFAs varies across EFA types (Cole et al. 2012; Cormont et al. 2016). While non-productive options

such as buffer strips, fallow land, and landscape features are considered most beneficial for conserving biodiversity (Pe'er et al. 2017; Sutter et al. 2018; Tardjuelo et al. 2020a, 2020b), less conservation-effective (namely productive) options, such as planting nitrogen-fixing or catch crops, represent more than 70% of the registered EFAs (Zinngrebe et al. 2017; Nilsson et al. 2019; Pe'er et al. 2020). Results from interviews with stakeholders, farmers, and agricultural representatives have shown that farmers consider the EFA regulation complicated (Oppermann 2015; Bonke et al. 2021). Overall, economic and administrative motivations appear to be more important than ecological considerations in defining farm management practices concerning EFA implementation (Zinngrebe et al. 2017; Nitsch et al. 2018; Brown et al. 2021; Bonke et al. 2021). Nevertheless, farmers' motivations for managing their land include the environmental context in which their farm is embedded (Brown et al. 2021; Santos et al. 2021). Farm management decisions may also be heavily constrained by the farm context (e.g. farm size), the field context (e.g. field size), or the field terrain and soil conditions (e.g. soil fertility) (Nitsch et al. 2018). Also, the success of particular land uses in enhancing biodiversity or ecosystem services may highly depend on their proximity to and connectivity with other semi-natural areas (Tschardt et al. 2005, 2012). Hence, the consideration of a broader set of factors influencing farm management practices, including the ecological context of the farm, is urgently needed to broaden our understanding of how to manage agricultural landscapes in more sustainable ways (Tzilivakis et al. 2016; Singh and Leppanen 2020; Brown et al. 2021).

Farms across the EU differ in their environmental context according to their geographic location. Additionally, various policy tools exist to support the CAP greening policy and reach the EU environmental targets across member states. For instance, farmers can receive further economic support for areas considered challenging to cultivate (European Commission 2022). In our study region, locations near water bodies (SMEKUL 2021a) and within water protection (SMEKUL 2021b) or Natura 2000 (European Environment Agency 2022) areas have special restrictions regarding management practices or nutrient/pest control inputs. To account for regional differences, member states can select a subset of EFA options considered more suitable for their specific context.

Furthermore, there is a weighting factor for each type of EFA to reflect their ecological benefits and implementation costs. Weighting factors can range from 0.3 (e.g. for catch crops) to two (e.g. for hedges) and are used to calculate the exact area per farm relevant for the policy subsidy payments. In Germany, farmers can select among 20 different land use options eligible as EFA (Zinngrebe et al. 2017; Lakes et al. 2020, see Table S1).

In the present study, we used field-level information on land use and management from the Integrated Administration and Control System (IACS) (SMEKUL 2019), as well as geospatial information on small woody features and nature protection areas, to assess which structural, terrain and soil conditions influence the probability of a field being assigned to a specific EFA. Since EFA policies focus on the farm level, our predictors included variables reflecting the farm context in terms of the diversity of additional habitats within the farm boundaries, the relative usability of a specific field for production, and the terrain and soil conditions of the field compared to the other fields of the same farm. Overall, we expected that fields whose structural (size, compactness, proximity to other landscape elements) or terrain and soil conditions (slope, soil fertility) are below the farm's average are more likely to be assigned to an EFA. Additionally, we expected that large farms with a smaller proportion of protected areas or small woody features, whose fields are predominantly suitable for production, would most likely meet the policy requirements with productive EFA options. Since landscape elements are not easily movable and can be used to receive EFA policy payments, we anticipated that farms with landscape features within their boundaries are likely to register them under the policy. Conversely, farms without landscape features within their boundaries are more likely to allocate productive EFA options than other EFA types.

Materials and methods

Study region

The study area is the Mulde River Basin, located in the western part of the federal state of Saxony, Germany (Fig. 1). It covers an area of 5814 km²; the terrain varies from flat to hilly, and the elevation ranges

between 24 and 1214 m.a.s.l. (Sachsen Staatsbetrieb Geobasisinformation und Vermessung 2016). The climate is predominantly continental, with total annual precipitation between 570 and 1260 mm and mean annual temperatures between 7.4 and 14.1 °C (DWD 2020). 38% of the study area is covered by arable land, with winter wheat, oilseed rape, winter barley, and maize as predominant crops, followed by permanent grassland (mowing pastures and meadows).

Data preparation

Our data included field-level information on land use and management of 879 farms (41,936 fields) that complied with EFA policy in 2019 (SMEKUL 2019). The median number of fields per farm was 25. The median farm size was 100 hectares, and the median field size was 6 hectares. Farmers could select among 20 land use types to be registered as EFA (Table S1). In our study, a farm consisted of a group of fields registered in the IACS database (SMEKUL 2019) under the same anonymized farm identification number. A field consisted of a parcel with uniform land use (a certain type of crop or EFA). We grouped our predictor variables into three categories; predictors related to the farm context, the field context, or the terrain and soil conditions (Table 1).

Farm context predictors

This category included: the farm area (FARM AREA) calculated as the area of all fields registered under the same anonymized farm identification number, the percentage of the farm covered by Natura 2000 areas (NATURA), the percentage of the farm covered by landscape features registered as EFA (LAND FEAT), the percentage of the farm area covered by fields near small woody features (i.e. in a buffer of 50 m, SWF), the percentage of the farm area designated as naturally constrained (ANC), and the percentage of the farm area designated as areas of importance for drinking water and medicinal spring protection areas (WATERPROT) (Table 1).

Field context predictors

We used z transformation to standardize the values of each field concerning the farm context. For instance, a positive value of the field area means that the

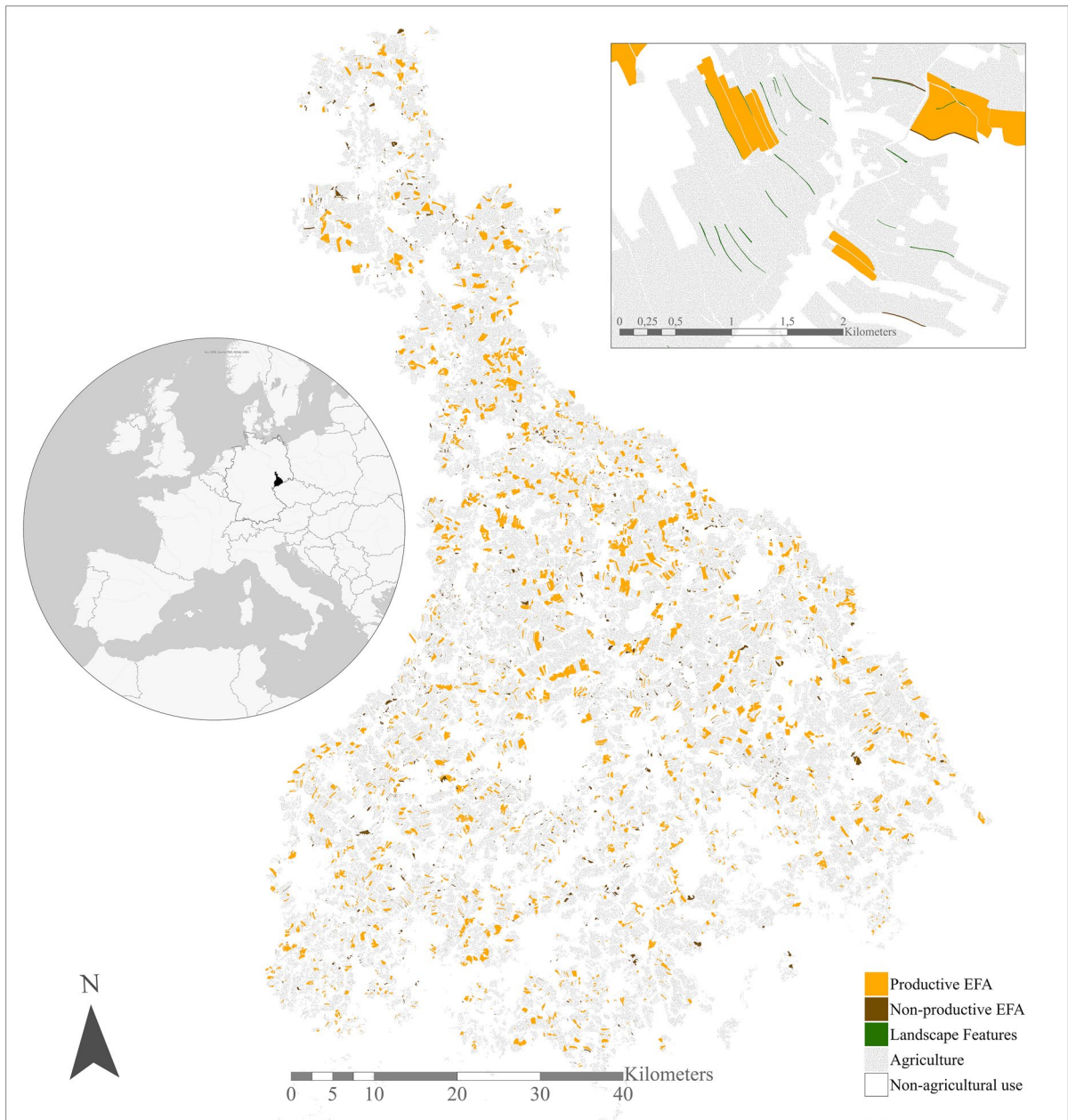


Fig. 1 Depiction of the geographical location of the study area and the distribution of productive, non-productive, and landscape features as EFAs used in our analysis. The square in the top right represents an inset of the data

respective field is larger than the average field of the farm to which it belongs. The field context predictors category included: the standard z-score of the area of the field (FIELDAREA), the standard z-score of the compactness index of the field (COMPACTNESS), the standard z-score of the distance of the field to the

farm centroid (DISTANCE), a binary predictor of the presence of a small woody feature in the proximity of 50-meter buffer (SWF), information on whether the field belonged to an area designated as naturally constrained (ANC), and the presence of a water body in the proximity of 20-meter buffer (WATERBODY)

Table 1 Overview of the explanatory variables used in the regression models grouped by category

Category	Variable name	Variable description	Source
Farm context	FARM AREA	Total area (in hectares) of fields belonging to the same holding	SMEKUL (2019)
	NATURA (%)	Percentage of farm area covered by areas designated in European Union's Natura 2000 network of protected areas	European Environment Agency (2022)
	LANDFEAT (%)	Percentage of farm area covered by landscape features registered as EFA	SMEKUL (2019)
	SWF (%)	Percentage of farm area covered by fields nearby (5 m) to a small woody feature	European Environment Agency (2018)
	ANC (%)	Percentage of farm area covered by areas of natural constraints, i.e. considered more difficult to farm	SMEKUL (2019), European Commission (2022)
	WATERPROT (%)	Percentage of farm area in zones of Saxony's drinking water and medicinal spring protection areas	SMEKUL 2021b
Field context	FIELDAREA	Standardized (z-score) value of the field area in relation with the mean-field area of their respective farm	SMEKUL 2019
	COMPACTNESS	Standardized (z-score) value of the Richardson compactness index calculated as $2 * \sqrt{\pi * \text{field area}} / \text{field perimeter}$ A compact polygon has simple boundaries with vertices relatively equidistant from the centroid. A circle is the shape of maximum compactness.	SMEKUL 2019
	DISTANCE	Standardized (z-score) value of the distance of the centroid of the field to the respective farm centroid.	SMEKUL (2019)
	SWF	Dummy variable describing the presence (1) or absence (0) of a small woody feature on a 50-meter buffer surrounding a field.	European Environment Agency (2018)
	ANC	Binary variable describing whether the field is in an area classified as naturally constrained area (ANC) (1) or not (0).	SMEKUL (2019), European Commission (2022)
	WATER BODY	Binary variable describing the presence (1) or absence (0) of a water body (from the water network of flowing and standing water of Saxony) on a 50-meter buffer surrounding a field.	SMEKUL (2021a)

Table 1 (continued)

Category	Variable name	Variable description	Source
Soil and Terrain conditions	SOIL FERTILITY	Standardized (z-score) value of the field soil fertility concerning the mean field soil fertility of the respective farm.	SMEKUL (2021c)
	SLOPE	Standardized (z-score) value of the field slope concerning the mean field slope of the respective farm.	SMEKUL (2021c)
	SOILMOISTURE	Standardized (z-score) value of the field soil moisture concerning the mean field soil moisture of the respective farm.	SMEKUL (2021c)
	WIND EROSION	Standardized (z-score) value of the field wind erosion concerning the mean field wind erosion of the respective farm.	SMEKUL (2021c)
	EROSION (KLSR)	Standardized (z-score) value of the field water erosion risk concerning the mean field erosion risk of the respective farm.	SMEKUL (2021c)

(Table 1). We selected the 20-meter buffer distance of water bodies used by Paulus et al. (2022), who studied the spatial allocation of agri-environmental schemes in our study region. The five meters buffer represents an intermediate distance that considers the effects of field edges on pollinators (Reynolds et al. 2022) or natural enemies (Büchi 2002).

Soil and terrain conditions

This category included values of soil fertility (SOIL FERTILITY), soil moisture (SOIL MOISTURE), wind (WINDEROSION), and water erosion (EROSION(KLSR)) extracted from the digital soil map at a scale of 1:50,000 from the Saxon State Ministry for Energy, Climate Protection, Environment, and Agriculture (SMEKUL 2021c) (Table 1). The soil fertility index considered the capillarity, risk of waterlogging, cation exchange capacity, stone content, and plant-available water in the root space of the soil (Table S2). The soil moisture index was calculated based on parameters such as the soil pore system, climate, and terrain (Table S3). The wind erosion indicator described the erosion hazard depending on the soil type and long-term average wind speed (Table S4). The water erosion risk considered the soil type, slope length, slope inclination, and regenerative erosivity of the soil (Table S5). All predictors were tested for collinearity using pairwise correlation analysis. Since no correlations of

Pearson's $lrl > 0.7$ occurred (Dormann et al. 2013), no variables were excluded (Fig. S1–3).

Statistical analysis

We used multinomial regression models to evaluate the influence of variables related to the farm and field context and the field terrain and soil conditions on EFA allocation in farmland. Multinomial regression is a logistic regression employed to predict the probability that a case is in a particular category when the dependent outcome includes more than two categories. Multinomial models break the outcome variable into a series of comparisons between pairs of categories, on which the probability (odds) of an observation being a member of a specific group rather than the reference group is calculated. In multinomial models, a logistic transformation of the odds (Log (OR)) is the dependent variable. The odds value can range from 0 to infinity and express the likelihood that an observation is a member of the reference group rather than a member of the group used for comparison. It holds that $odds = p / (1 - p)$. The odds ratio (OR) estimates the change in the odds of membership in the target group for a one-unit increase in the predictor and it is calculated by using the regression coefficient of the predictor as the exponent:

$$\log(odds) = \text{logit}(p) = \log(p/(1 - p)) = \beta_0 + \beta_1 x_1 + \dots$$

Where p = the probability that a case is in a particular category, β_0 is the intercept, and β_1, \dots are the regression coefficients of x_1 .

In order to identify specific responses according to the EFA group (e.g. productive, non-productive, landscape features) or EFA type (e.g. catch crops, nitrogen-fixing crops, etc.), we ran four multinomial models. All models included the same predictor variables (described in Table 1) and had fields dedicated to agricultural production (defined as NOEFA) as a reference value. We used Model 1 to identify differences in drivers of EFA allocation according to their productive value. Besides the reference value (NOEFA),

Model 1 included three additional response categories: (i) productive EFA, (ii) non-productive EFA, and (iii) landscape features registered as EFA. We used Model 2, Model 3, and Model 4 to identify important drivers for specific EFAs (See Figs. S4, S5, S6). Model 2 incorporated only productive EFAs ($c=6$) as the response categories. Model 3 included response non-productive EFAs ($c=6$), while Model 4 had EFA landscape features ($c=8$) as response categories. Given that we only considered farms with at least one field dedicated to one of our focal EFAs (defined by the model), all models differed in the number of farms and fields used as input (Table 2).

Table 2 Description of the model ID, input data (number of fields and number of farms), and response categories of the four models used in our analysis. Response categories referred to the discrete outcomes used in each model. Class frequency

refers to the number of fields used as data input for the discrete outcomes on each model. NOEFA refers to fields used for agricultural production

Model ID	Number of fields	Number of farms	Response categories	Class frequency
Model 1 (EFA group)	41,936	879	Non-Productive EFA	2808
			Productive EFA	2440
			Landscape Features	2328
			NOEFA (as reference category)	34,360
Model 2 (Productive EFAs)	34,737	618	Catch crop	1812
			Nitrogen fixing	531
			Undersown	59
			Afforestation	27
			Short rotation plantation	9
			Cup plant mix	2
			NOEFA (as reference category)	32,297
			Model 3 (Non-productive EFAs)	29,782
Model 4 (Landscape features registered as EFA)	16,577	268	Buffer strips (AL)	1065
			Bee pastures (annual)	267
			Strips at the forest edge	199
			Bee pastures (perennial)	43
			Buffer strips (GL)	31
			NOEFA (as reference category)	26,974
			Hedges	933
			Row of trees	809
			Field trees	439
			Field borders	101
Wetlands	21			
Rock and stone bars, natural petrified surface	18			
Single trees	4			
Natural stone or dry stone wall	3			
NOEFA (as reference category)	14,249			

All data analysis and data processing was conducted in R version 4.0.5 (R Core Team 2021) using the packages *nnet* (Fox and Weisberg 2019), *car* (Fox and Weisberg 2019), *caret* (Kuhn 2008), *dplyr* (Wickham et al. 2019), *raster* (Hijmans and van Etten 2012), *sf* (Pebesma 2018), and *terra* (Hijmans 2023). Details of the code can be found in the GitHub repository related to this manuscript (<https://github.com/viv-alarcon/EFAallocationinfarmland.git>).

Results

7% of all fields were allocated with a productive EFA, 6% with a non-productive EFA, and 5% to landscape features registered as EFA. Among productive EFAs, catch crops, and nitrogen-fixing were the most commonly adopted options. Fallow land and buffer strips were the most frequently allocated non-productive EFAs, and hedges and rows of trees were often registered as landscape features. Farms covered with a low percentage of Natura 2000 (NATURA), landscape features registered as EFA (LAND FEAT), small woody features (SWF), or water protection areas (WATER PROT) mostly allocated productive EFAs (Fig. 2). Conversely, farms with higher values on the same variables were more prone to allocate non-productive EFAs or landscape features.

Small and linear fields (FIELD AREA, COMPACTNESS) had higher probabilities of being allocated with non-productive EFAs or landscape features (Fig. 2). Non-productive EFAs and landscape features were allocated further away from small woody features (SWF) or water bodies (WATER BODY), but they were frequently present in fields designated as naturally constrained for agricultural production (ANC). Conversely, large and rounded fields were most prone to be assigned with productive EFAs. Contrary to our expectations, EFA fields were not allocated in fields with low soil fertility (SOIL FERTILITY). Nevertheless, both productive and non-productive EFAs were allocated in fields with lower risks of water erosion (EROSION (KLSR)).

Among productive options, catch crops and nitrogen-fixing crops responded differently to the same variables (Table 3, Fig. S4). While nitrogen crops were frequently allocated on small farms (FARM AREA) with a lower percentage of landscape features (LAND FEAT), small woody features (SWF) and

water protection areas (WATER PROT), catch crops were allocated in farms with higher values of Natura 2000 (NATURA), landscape features (LAND FEAT (%)), and water protection areas (WATER PROT) (Table 3, Fig. S4). Catch crops were frequently assigned to large and rounded fields (FIELD AREA, COMPACTNESS) in naturally constrained (ANC) areas. Fallow land was more likely to be allocated in farms with lower values of NATURA, LAND FEAT, and WATER PROT), and in small and linearly shaped fields (Table 3, Fig. S5). Conversely, buffer strips were most often established on farms with higher values of NATURA, LAND FEAT, SWF or WATER PROT. Hedges and rows of trees were most abundant in farms with low percentages of SWF and ANC, but within these farms, to fields located in ANC areas (Table 3, Fig. S6). Most variables related to terrain and soil conditions had non-significant effects for the majority of EFA types, with the exception of slope and erosion KLSR.

Discussion

In this study, we used a spatially-explicit approach to analyze how the farm context, the field context, and the terrain and soil conditions influenced the allocation of EFAs in farmland. We demonstrated that the farm and the field contexts, rather than the terrain and soil conditions, are decisive for the assignment of a particular EFA type to a particular field. In our study region, EFA types known to benefit biodiversity, such as fallow land, buffer strips, and landscape features (Martin et al. 2019; Pe'er et al. 2022), were used on farms already embedded in contexts with a higher cover of nature conservation and non-crop habitats (Fig. 2). In contrast, productive EFAs such as catch crops or nitrogen-fixing crops were often found on farms where cropland dominated (Fig. 2). These results have important implications for conserving farmland biodiversity. Considering that the effectiveness of conservation measures in agricultural areas is highest in landscapes with intermediate levels of land use heterogeneity (“intermediate landscape-complexity hypothesis”, Tschardt et al. 2012), the potential of EFAs to contribute to biodiversity conservation in farmland can be strongly moderated by their spatial distribution (Sutter et al. 2018; Concepción and Díaz 2019; Concepción et al. 2020).

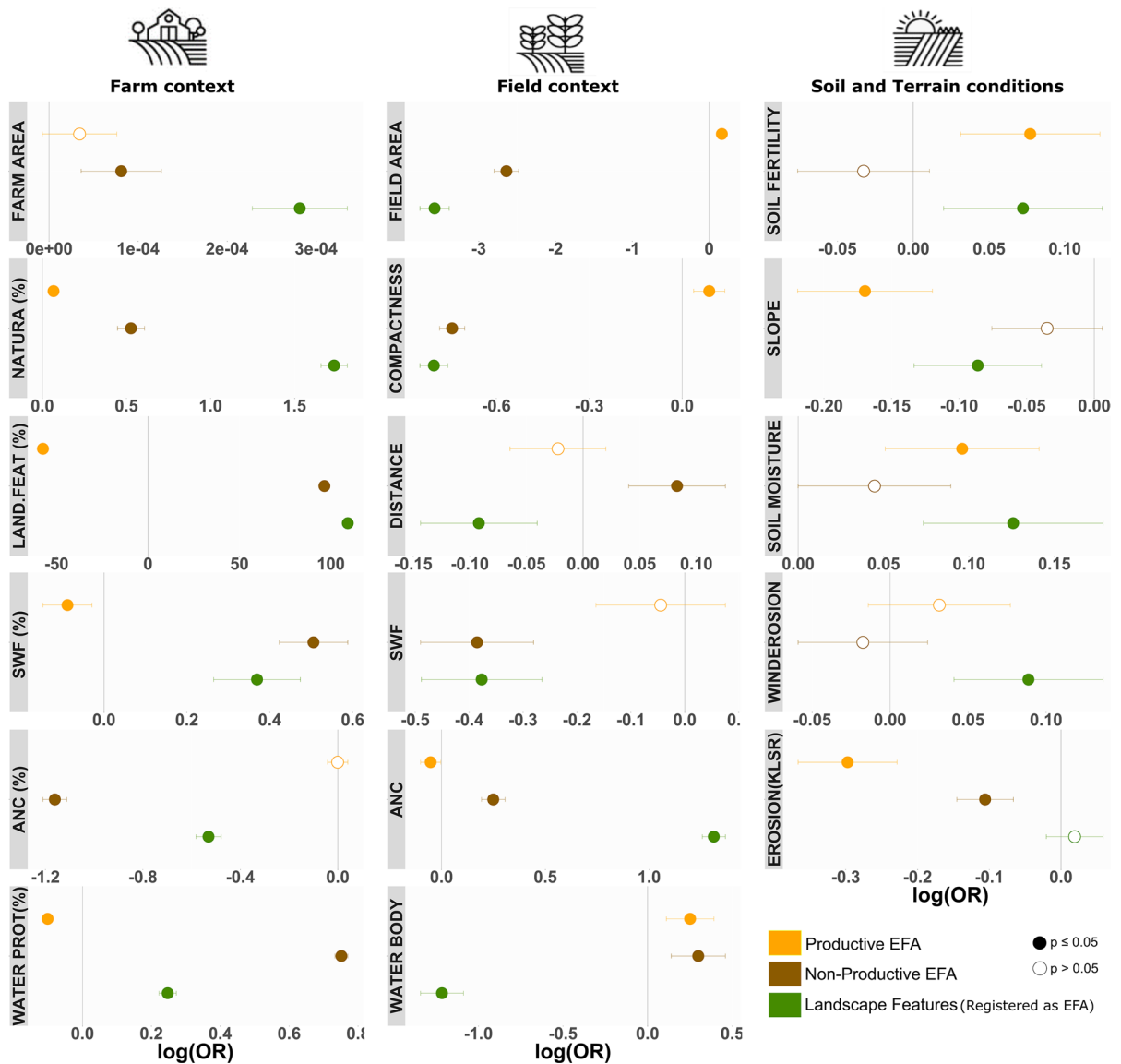


Fig. 2 Model coefficients (logarithm of odd ratio) of the multinomial regression used to evaluate the drivers of EFA allocation according to the EFA group (model 1). Explanatory variables are grouped into three categories (farm context, field context, soil and terrain conditions). Colored circles indicate p-values lower than or equal to 0.05. Farm context indicators (except farm area) reflected the percentage of farm area covered by: Natura 2000 designated area (NATURA (%)), landscape features registered as EFA (LAND FEAT (%)), small

woody features (SWF (%)), naturally constrained areas (ANC (%)) or water protection areas (WATER PROT (%)). SWF indicates the presence (1) or absence (0) of a small woody feature in a buffer of 50 m around the field. ANC indicates whether the field is in a naturally constrained area. WATER BODY indicates the presence (1) or absence (0) of a water body in a buffer of 50 m around the field. EROSION (KLSR) refers to the water erosion risk

EFA on farms embedded in complex landscapes may contribute little to restoring existing biodiversity on this land. On the other hand, EFAs on farms embedded in simplified landscapes may also

contribute little to restoring the biodiversity that has already been lost in these areas. The allocation of EFAs in an intensively used area, however, has the potential to increase landscape complexity, for

Table 3 Effect direction of the two most frequently adopted EFA of each category. The plus symbol (+) indicates significant positive effects, the minus symbol (–) indicates negativesignificant effects and ns indicates non-significant effects at the significance level of ≤ 0.05

		Nitrogen Fixing	Catch crop	Fallow land	Buffer strips	Hedges	Rows of trees
Farm context	FARM AREA	–	ns	–	ns	+	ns
	NATURA (%)	+	+	–	+	+	ns
Field context	LAND FEAT (%)	–	+	–	+	+	+
	SWF (%)	–	ns	ns	+	–	–
	ANC (%)	ns	+	–	–	–	–
	WATER PROT (%)	–	+	–	+	–	+
	FIELD AREA	–	+	–	–	–	–
	COMPACTNESS	ns	+	–	–	–	–
	DISTANCE	+	–	+	ns	–	ns
	SWF	ns	ns	–	–	–	ns
	ANC	+	ns	ns	+	+	+
	WATER BODY	ns	+	ns	+	–	–
Soil and terrain conditions	SOIL FERTILITY	ns	+	ns	ns	ns	ns
	SLOPE	–	–	+	–	ns	–
	SOIL MOISTURE	ns	+	ns	ns	+	ns
	WIND EROSION	ns	ns	ns	–	+	ns
	EROSION (KLSR)	–	–	–	ns	ns	+

instance by increasing crop diversity or the number of non-crop elements within farm boundaries (Concepción et al. 2012). Nevertheless, EFAs should not be used as the only tool to conserve biodiversity in farmlands, as their benefits for threatened or specialist species depend highly on their ecological quality (Herzog et al. 2017; Pfiffner et al. 2018). Further, many EFAs only benefit farmland generalist species (Kleijn et al. 2006; Aviron et al. 2007, 2009) and need to be complemented with additional nature protection efforts or improved and tailored agri-environmental schemes in order to protect and enhance a wider range of biodiversity (Aviron et al. 2009).

Farm area in our study region was a determining factor only for a subset of the EFA options (Table 3). Fallow land and nitrogen-fixing crops were most often adopted by small farms, while hedges were most frequently used by larger farms (Table 3). Large farms with a higher cover of landscape features in their boundaries used these elements to fulfill the policy requirements. Interestingly, farms that did not fulfill their EFA quota with landscape elements tended to allocate productive instead of non-productive EFA (Fig. 2). These results support previous findings on the prevalence

of economic rather than ecological considerations on farmers' decisions on greening policy allocation (Zinngrebe et al. 2017). Productive EFAs (e.g. catch crops and nitrogen-fixing crops) are mainly targeted to reduce soil erosion and facilitate nutrient uptake (Cerdà et al. 2022; Quintarelli et al. 2022) and may help to facilitate crop production in the same field on the following year (Brown et al. 2021; Wittstock et al. 2022). On the other hand, the placement of non-productive EFAs and landscape features is not spatially flexible and may appear disadvantageous from the farmer's point of view, given that working with large machinery may be more difficult if individual trees or hedges are present at the field boundaries. While productive EFA options were commonly assigned to large, rounded fields with lower soil erosion hazard, non-productive EFAs were allocated in small, linear fields in areas considered disadvantaged for crop production (Fig. 2). A similar pattern was found by Paulus et al. (2022) for Agri-environmental schemes allocation in our study region. Paulus et al. (2022) demonstrated that Agri-environmental schemes are more often allocated in areas with low potential for agricultural intensification, supporting the notion that the lack of careful

spatial targeting of agricultural policies may diminish their ecological contribution.

Conclusions

Farmers' economic considerations play an essential role in deciding which type of EFA to choose (e.g. productive versus non-productive) and where to place it (e.g. large and rounded fields versus small, linear, and less fertile fields). Our results demonstrate that the farm and the field context have a significant impact on the spatial distribution of greening measures within the farm boundaries. These findings are especially important for possible future spatial targeting of conservation and nature protection measures (including eco-schemes) on farmland. This relates to several measures that are spatially flexible, such as fallow land and buffer strips—options that are widely recognized in expert-based assessments as highly valuable for biodiversity and ecosystem services (Pe'er et al. 2017; Traba and Morales 2019).

Acknowledgements We would like to thank the Saxon State Ministry for Energy, Climate Protection, Environment, and Agriculture (SMEKUL) for providing the LPIS/IACS data (InVeKoS Sachsen). We also thank the Center for Information Services and High-Performance Computing (ZIH) of the Technische Universität Dresden for the generous allocation of computing resources. The collaboration of the co-authors was initiated by the membership of A.F.C and N.K. in *Die Junge Akademie* at the Berlin-Brandenburg Academy of Sciences and Humanities and the German National Academy of Sciences Leopoldina. The Open access funding was enabled and organized by Projekt DEAL.

Author contributions VAS, SR, AP, MB, and AFC contributed to the conceptualization and design of the study. Material preparation, data collection, and analysis were performed by VAS, SR, and AP, NK advised and assisted with the statistical analysis. VAS wrote the first draft of the manuscript. All authors commented on previous manuscript versions, contributed critically to the drafts, and gave final approval for publication.

Funding Open Access funding enabled and organized by Projekt DEAL. This work was supported by the European Union's Horizon 2020 research and innovation program under Grant Agreement No. 817501 (BESTMAP).

Data availability The dataset used for this study will be publicly available in a data repository (OSF) after publication.

Declarations

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Aviron S, Jeanneret P, Schüpbach B, Herzog F (2007) Effects of agri-environmental measures, site and landscape conditions on butterfly diversity of swiss grassland. *Agric Ecosyst Environ* 122:295–304
- Aviron S, Nitsch H, Jeanneret P et al (2009) Ecological cross compliance promotes farmland biodiversity in Switzerland. *Front Ecol Environ* 7:247–252
- Bonke V, Michels M, Musshoff O (2021) Will Farmers accept lower gross margins for the sustainable cultivation method of mixed cropping? First insights from Germany. *Sustainability* 13:1631
- Brown C, Kovács E, Herzon I et al (2021) Simplistic understandings of farmer motivations could undermine the environmental potential of the common agricultural policy. *Land Use Policy* 101:105136
- Büchi R (2002) Mortality of pollen beetle (*Meligethes* spp.) larvae due to predators and parasitoids in rape fields and the effect of conservation strips. *Agric Ecosyst Environ* 90:255–263
- Cerdà A, Franch-Pardo I, Novara A et al (2022) Examining the effectiveness of catch crops as a nature-based solution to mitigate surface soil and water losses as an environmental Regional concern. *Earth Syst Environ* 6:29–44
- Cole LJ, Brocklehurst S, Mccracken DI et al (2012) Riparian field margins: their potential to enhance biodiversity in intensively managed grasslands. *Insect Conserv Divers* 5:86–94
- Concepción ED, Díaz M (2019) Varying potential of conservation tools of the common agricultural policy for farmland bird preservation. *Sci Total Environ*. <https://doi.org/10.1016/j.scitotenv.2019.133618>
- Concepción ED, Díaz M, Kleijn D et al (2012) Interactive effects of landscape context constrain the effectiveness of local agri-environmental management: landscape

- constrains the effectiveness of local management. *J Appl Ecol*. <https://doi.org/10.1111/j.1365-2664.2012.02131.x>
- Concepción ED, Aneva I, Jay M et al (2020) Optimizing biodiversity gain of European agriculture through regional targeting and adaptive management of conservation tools. *Biol Conserv*. <https://doi.org/10.1016/j.biocon.2019.108384>
- Cormont A, Siepel H, Clement J et al (2016) Landscape complexity and farmland biodiversity: evaluating the CAP target on natural elements. *J Nat Conserv* 30:19–26
- Dormann CF, Elith J, Bacher S et al (2013) Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. *Ecography* 36:27–46
- DWD (2020) Klimastatusbericht Deutschland Jahr 2019. https://www.dwd.de/DE/leistungen/klimastatusbericht/publikationen/ksb_2019.pdf?__blob=publicationFile&v=5
- European Commission (2017) Report from the commission to the European parliament and the council on the implementation of the ecological focus area obligation under the green direct payment scheme (Issue March). <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52017DC0152>
- European Commission (2022) Sustainable land use (greening). https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/income-support/greening_en
- European Environment Agency (2018) Copernicus Land Monitoring Service (small woody features). <https://land.copernicus.eu/pan-european/high-resolution-layers/small-woody-features#:~:text=The%20HRL%20Small%20Woody%20Features,features%20across%20the%20EEA39%20countries>
- European Environment Agency (2022) The Natura 2000 protected areas network. <https://www.eea.europa.eu/themes/biodiversity/natura-2000#:~:text=Natura%202000%20>
- European Union (2013) Regulation (EU) no 1307/2013 of the European Parliament and of the Council of 17 December 2013 establishing rules for direct payments to farmers under support schemes within the framework of the common agricultural policy and repealing Council Regulation. *Off J Eur Union* 1307:608–670
- Fox J, Weisberg S (2019) An R companion to applied regression, Third edition
- German Federal Environmental Agency (2014) Ecological focus areas—crucial for biodiversity in the agricultural landscape position of the German federal agency for nature conservation. https://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/ecological_focus_areas_-_crucial_for_biodiversity_in_the_agricultural_landscape_klu.pdf
- Herzog F, Lüscher G, Arndorfer M et al (2017) European farm scale habitat descriptors for the evaluation of biodiversity. *Ecol Indic* 77:205–217
- Hijmans RJ (2023) `_terra: Spatial Data Analysis_`
- Hijmans RJ, van Etten J (2012) raster: Geographic analysis and modeling with raster data
- Kleijn D, Baquero RA, Clough Y et al (2006) Mixed biodiversity benefits of agri-environment schemes in five European countries: Biodiversity effects of European agri-environment schemes. *Ecol Lett* 9:243–254
- Kuhn M (2008) Building predictive models in R using the caret package. *J Stat Softw* 28:1–26
- Lakes T, Garcia-Marquez J, Müller D et al (2020) How green is greening? A fine-scale analysis of spatio-temporal dynamics in Germany. <https://doi.org/10.18452/21031>
- Martin EA, Dainese M, Clough Y et al (2019) The interplay of landscape composition and configuration: new pathways to manage functional biodiversity and agroecosystem services across Europe. *Ecol Lett* 22:1083–1094
- Nilsson L, Clough Y, Smith HG et al (2019) A suboptimal array of options erodes the value of CAP ecological focus areas. *Land Use Policy* 85:407–418
- Nitsch H, Röder N, Oppermann R et al (2018) Ökologische Vorrangflächen: gut gedacht—schlecht gemacht? *Nat Landsch* 93:258–265
- Oppermann R (2015) Ökologische Vorrangflächen. *Nat Landsch* 90:263–270
- Paulus A, Hagemann N, Baaken MC et al (2022) Landscape context and farm characteristics are key to farmers' adoption of agri-environmental schemes. *Land Use Policy* 121:106320
- Pe'er G, Zinngrebe Y, Hauck J et al (2017) Adding some green to the greening: improving the EU's ecological focus areas for biodiversity and farmers' evaluation of EU's ecological focus areas. *Conserv Lett* 10:517–530
- Pe'er G, Bonn A, Bruelheide H et al (2020) Action needed for the EU common agricultural policy to address sustainability challenges. *People Nat* 2:305–316
- Peer G, Finn JA, Díaz M et al (2022) How can the European common agricultural policy help halt biodiversity loss? Recommendations by over 300 experts. *Conserv Lett*. <https://doi.org/10.1111/conl.12901>
- Pebesma E (2018) Simple features for R: standardized support for spatial vector data. *R J* 10:439
- Pfiffner L, Ostermaier M, Stoeckli S, Müller A (2018) Wild bees respond complementarily to 'high-quality' perennial and annual habitats of organic farms in a complex landscape. *J Insect Conserv* 22:551–562
- Quintarelli V, Radicetti E, Allevalo E et al (2022) Cover crops for sustainable cropping systems: a review. *Agriculture* 12:2076
- R Core Team (2021) R: a language and environment for statistical computing. R Core Team
- Reynolds VA, Cunningham SA, Rader R, Mayfield MM (2022) Adjacent crop type impacts potential pollinator communities and their pollination services in remnants of natural vegetation. *Divers Distrib* 28:1269–1281
- Sachsen Staatsbetrieb Geobasisinformation und Vermessung (2016) Digitale Geländemodell (DGM20) für den Freistaat Sachsen. <https://www.geodaten.sachsen.de/downloadbereich-dgm25-4162.html>
- Santos JL, Moreira F, Ribeiro PF et al (2021) A farming systems approach to linking agricultural policies with biodiversity and ecosystem services. *Front Ecol Environ* 19:168–175
- Singh A, Leppanen C (2020) Known target and nontarget effects of the novel neonicotinoid cycloxaprid to arthropods: a systematic review. *Integr Environ Assess Manag* 16:831–840

- SMEKUL (2019) Regionale Entwicklung der Viehhaltung in Sachsen. <https://www.landwirtschaft.sachsen.de/regionale-entwicklung-der-viehhaltung-in-sachsen-40177.html>
- SMEKUL (2021a) Gewässernetz in Sachsen. <http://www.wasser.sachsen.de/gewaesse.rnetz-12793.html>
- SMEKUL (2021b) Wasserschutzgebiete. <http://www.wasser.sachsen.de/wasserschutzg.ebiete-12591.html>
- SMEKUL (2021c) Bodenkarte 1: 50.000. <http://www.boden.sachsen.de/digitale-boden.karte-1-50-000-19474.html>
- Sutter L, Albrecht M, Jeanneret P (2018) Landscape greening and local creation of wildflower strips and hedgerows promote multiple ecosystem services. *J Appl Ecol* 55:612–620
- Tarjuelo R, Benítez-López A, Casas F et al (2020) Living in seasonally dynamic farmland: the role of natural and semi-natural habitats in the movements and habitat selection of a declining bird. *Biol Conserv*. <https://doi.org/10.1016/j.biocon.2020.108794>
- Tarjuelo R, Margalida A, Mougeot F (2020) Changing the fallow paradigm: a win–win strategy for the post-2020 common agricultural policy to halt farmland bird declines. *J Appl Ecol* 57:642–649
- Traba J, Morales MB (2019) The decline of farmland birds in Spain is strongly associated to the loss of fallowland. *Sci Rep* 9:9473
- Tscharntke T, Klein AM, Kruess A et al (2005) Landscape perspectives on agricultural intensification and biodiversity—ecosystem service management. *Ecol Lett* 8:857–874
- Tscharntke T, Tylianakis JM, Rand TA et al (2012) Landscape moderation of biodiversity patterns and processes - eight hypotheses. *Biol Rev* 87:661–685
- Tzivilakis J, Warner DJ, Green A et al (2016) An indicator framework to help maximise potential benefits for ecosystem services and biodiversity from ecological focus areas. *Ecol Indic* 69:859–872
- Wickham H, François R, Henry L, Müller K (2019) dplyr: a grammar of data manipulation
- Wittstock F, Paulus A, Beckmann M et al (2022) Understanding farmers' decision-making on agri-environmental schemes: a case study from Saxony, Germany. *Land Use Policy* 122:106371
- Zinngrebe Y, Pe'er G, Schueler S et al (2017) The EU's ecological focus areas—how experts explain farmers' choices in Germany. *Land Use Policy* 65:93–108

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.