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RESEARCH ARTICLE

Associations between farmland birds and fallow area at large scales: Consistently positive over three periods of the EU Common Agricultural Policy but moderated by landscape complexity

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Abstract

1. Fallow agricultural land provides habitat for threatened and declining farmland biodiversity. Policy change under the EU's Common Agricultural Policy (CAP) has been driving the area of fallows over the past decades. It is still unclear, whether positive relationships between farmland biodiversity and fallow area are general in time and space, and what landscape factors moderate them at large scales.
2. We analysed associations between fallow area and species richness and abundance of 24 farmland birds in 3 years covering three CAP funding periods, by linking agricultural statistics at the district level to plot-level bird data from a national-scale monitoring scheme. We tested whether these relationships are moderated by species' habitat preferences and landscape configurational complexity, measured as the edge density of woody features.
3. Species richness was positively associated with fallow area in all three funding periods. We found a hump-shaped response along a gradient of increasing landscape configurational complexity. The associations between fallow area and species richness peaked at intermediate values of edge density.
4. The associations between species abundance and fallow area varied among species, but there was strong support for positive and consistent associations in 15 (63%) of the studied species. There was little support for a moderating effect of landscape configurational complexity on the associations of fallow area and bird abundance.
5. *Policy implications*. To support farmland biodiversity, we suggest promoting fallow land across all agricultural landscapes and anchoring respective ambitious targets in the CAP strategic plans. An increase of fallow land beyond minimum requirements through voluntary measures, such as eco-schemes and agri-environment schemes, should particularly target landscapes with intermediate configurational complexity.

KEYWORDS
agricultural intensification, biodiversity conservation, farmland biodiversity, Germany, landscape configuration, monitoring, multilevel modelling, set-aside

1 | INTRODUCTION

Agricultural intensification is a major global driver of biodiversity loss (IPBES, 2019). Intensification comprises several processes leading to the simplification and homogenization of landscapes through a decline in landscape heterogeneity (e.g. loss of semi-natural habitats, increasing field size) but also the use of agrochemicals, increasing farm mechanization and specialization (Emmerson et al., 2016; Kleijn et al., 2009; Tscharntke et al., 2005). Due to intensification and homogenization, biodiversity in agricultural landscapes has been declining across Europe and North America since at least the 1960s (Robinson & Sutherland, 2002; Stanton et al., 2018). Declines in abundance of farmland animals and plants (Meyer et al., 2013), range retractions (Eichenberg et al., 2021), community reorganization and even country-wide species extinctions (Ollerton et al., 2014) can follow agricultural intensification.

Intensification leads to the loss of non-productive features in agricultural landscapes, such as field margins, hedgerows and fallow land. These features drive biodiversity patterns and persistence (Benton et al., 2003; Šálek et al., 2018; Van Buskirk & Willi, 2004). In particular, fallow land provides undisturbed habitat for plants, and food and shelter for animals across trophic levels (Tscharntke et al., 2011; Van Buskirk & Willi, 2004). A high proportion of fallow land in agricultural landscapes promotes farmland biodiversity (Ekroos et al., 2019; Herkert, 2009; Herzon et al., 2011).

In Europe, fallows have been part of farming systems since early cultivation (Allen, 2000). In the last decades, fallows have become a prominent conservation measure in the European Union (EU) for promoting farmland biodiversity in agricultural landscapes, and fallow area is largely driven by supra(national) policies. In the EU, the Common Agricultural Policy (CAP) is the main policy instrument used to distribute public payments to the agricultural sector. Its design and implementation have a large impact on farm management, and therefore on farmland biodiversity (Pe'er et al., 2014). Mandatory set-aside schemes were introduced in the 1992 CAP. All larger cash-crop farms had to set aside around 10% of their arable land between 1992 and 2007. In 2007, mandatory set-aside was abolished and fallow area declined strongly across all EU member states (Tarjuelo et al., 2020, Figure 1). From 2015 to 2022, most farmers were obliged to manage 5% of their arable land as Ecological Focus Areas (EFA) to receive subsidies. The implementation of fallow land was one option for EFAs (Zinngrebe et al., 2017). Fallow area increased in some countries of the EU after the 2013 CAP reform (+68% in Germany from 2014 to 2016, Zinngrebe et al., 2017, Figure 1). However, the area of fallow land did not reach similar levels as during the period of mandatory set-aside (Tarjuelo et al., 2020, Figure 1).

Landscape complexity plays an important role in shaping biodiversity in agro-ecosystems (Gonthier et al., 2014), but the effect of landscape structure on the effectiveness of fallows for promoting farmland biodiversity remains unclear (but see Wretenberg et al., 2010). Complex agricultural landscapes contain various

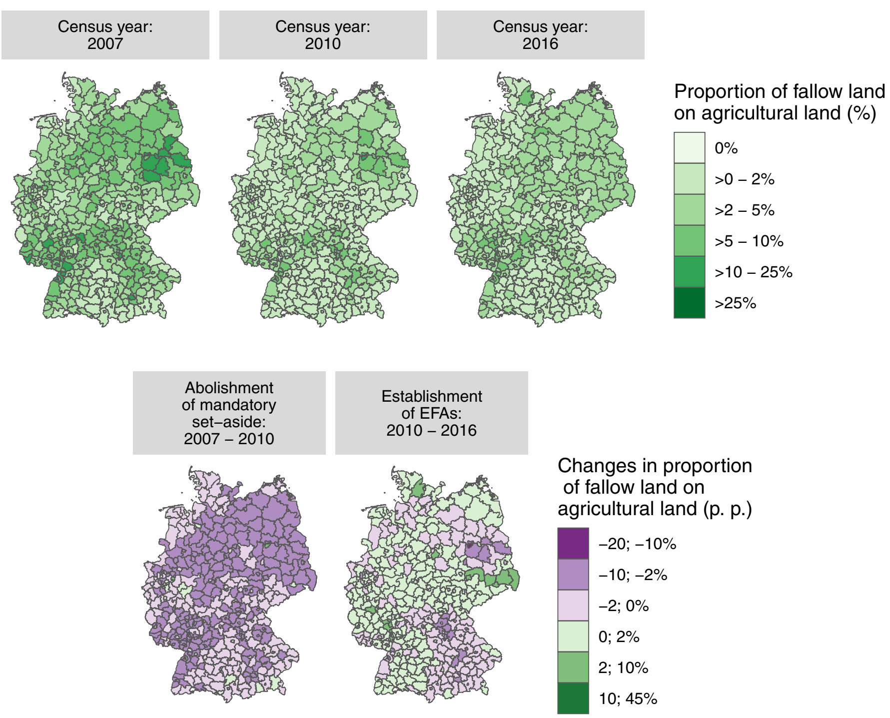

FIGURE 1 Proportion fallow land of all agricultural land across all German districts at three points in time (upper panel) and changes in the proportion of fallow land in percentage points (p. p.) between 2007 and 2010 (after the abolition of compulsory set aside in 2007), and between 2010 and 2016 (after the introduction of Ecological Focus Areas, EFAs) (lower panel).

land-cover types and semi-natural habitats, with a high amount of small woody features (e.g. hedgerows, small woods, scattered trees) (Concepción et al., 2008). Increasing the area of fallows in such high-complexity landscapes might have little effect on biodiversity because local species richness might be close to the regional species pool (Tscharntke et al., 2011). In contrast, extremely simplified, 'cleared', agricultural landscapes are dominated by cultivated land with little semi-natural habitat or woody features. Here, source populations of most farmland species might be too isolated and depleted to respond to increases in the resources provided by more fallows (Tscharntke et al., 2012). The 'intermediate landscape complexity hypothesis' predicts that local conservation measures will be most effective in promoting species richness in agricultural landscapes of intermediate complexity and less effective in both completely cleared and highly complex landscapes (Tscharntke et al., 2005, 2012). Empirical evidence suggests that species richness does increase in simple landscapes of intermediate complexity containing a low to medium amount of semi-natural habitats, once fallows are provided (Wretenberg et al., 2007, 2010).

The area of fallows also affects the abundance of farmland bird species (Traba & Morales, 2019). Fallows, compared with productive fields, provide food and undisturbed habitat leading to higher bird population densities (Henderson et al., 2000) and higher reproductive success (Whittingham et al., 2006). It is likely that associations between species abundance and fallow area are moderated by species-specific ecological preferences to forage and nest either on the ground or in edge structures (Berg & Pärt, 1994). Some species avoid vertical structures and field margins and breed in field centres (e.g. Eurasian Skylark, Western Yellow Wagtail, Northern Lapwing; hereafter: field-breeders), others use herbaceous margins for breeding and integrate bushes or trees into their breeding territories (e.g. Grey Partridge and Corn Bunting; hereafter: edge-breeders). Other farmland birds prefer woodland edges (e.g. Tree Pipit, Woodlark), hedgerows and scrubs (e.g. Red-backed Shrike) or trees (e.g. Eurasian Starling) for breeding, but visit fallows for foraging (hereafter foraging visitors). The associations between farmland bird abundance and fallow area could also be moderated by landscape complexity. Several studies have shown that the abundance of open-farmland bird species in fallows is highest in long-term fallows in simple landscapes (Ekroos et al., 2019; Toivonen et al., 2015).

We investigated the spatial associations between fallow area and farmland biodiversity at three different points in time (2007, 2010, 2016) that cover three CAP funding periods, harnessing a national-scale bird monitoring dataset. We used farmland birds as model organisms, as they are established biodiversity indicators (Gregory et al., 2005), have a long history of monitoring (Brlík et al., 2021) and respond strongly to fallows (Chamberlain et al., 2000; Ekroos et al., 2019; Herkert, 2009; Traba & Morales, 2019). We also tested whether the strengths of the spatial relationships between species richness and abundance of farmland birds and fallow land area were moderated by species habitat preferences and landscape configurational complexity. We hypothesized the following:

1. Farmland bird species richness and abundance are positively associated with fallow area independent of the CAP funding period because fallows serve as high-quality habitats allowing for high breeding success and survival of farmland bird populations.
2. Associations of farmland bird abundance with fallow area are moderated by species' breeding habitat preferences.
3. The relationships of farmland bird species richness with fallow area are strongest in landscapes of intermediate configurational complexity and weaker in landscapes with low ('cleared') or high ('complex') configurational complexity because those landscapes are avoided by several farmland bird species.

2 | MATERIALS AND METHODS

2.1 | Bird data

We used data on 24 farmland bird species (Table S1) from the German Common Breeding Bird Survey (CBBS). In this monitoring programme, more than 2600 sample plots of 1 km^2 were selected in a randomly stratified way. Up to 1800 of these are surveyed annually (Kamp et al., 2021). Within each plot, experienced volunteer observers walk a predefined route of ca. 3 km in length and record all individuals of all common bird species (without distance limits) four times a year between 10 March and 20 June. Territory mapping is used to combine the observations into territories along the route. We used the annual number of territories per sample plot and species as a measure of abundance and used this information to calculate plot-level species richness. No ethical approval is required to conduct the CBBS. All CBBS routes are situated on public roads, footpaths or other public access points in the landscape with general right of access. No permit is needed in Germany to count or identify birds from public roads or food paths.

We classified the selected farmland bird species into field-breeders, edge-breeders and foraging visitors based on their nesting and foraging preferences (Text S1).

To match the bird data with agricultural census data, we used only data from the years 2007, 2010 and 2016 for which census data were available. Furthermore, only CBBS plots with at least 10% agricultural area (cropland and grassland) were included in the analysis. This resulted in 613, 742 and 948 plots available for analysis for the years 2007, 2010 and 2016. Each CBBS plot was assigned to a German district (NUTS3 level) based on its midpoint.

2.2 | Agricultural census data

To estimate the area of fallow and total agricultural land, we used agricultural census data collected by regional statistical authorities at the farm level and later aggregated at the district level (n=401 districts; Figure 1). For some districts, no values are available due to confidentiality restrictions. Therefore, we used a dataset with imputed values

(Gocht & Röder, 2014; Johann Heinrich von Thünen-Institut, 2021). Given that the districts differ in size, we used the proportion fallow over the total agricultural area. The data used here are from the census years 2007, 2010 and 2016. These represent three funding periods of the CAP: the compulsory 'set-aside period' between 2003 and 2007, the abolition of compulsory set-aside between 2008 and 2013 and the introduction of Ecological Focus Areas as greening measure resulting in an increase of fallows between 2014 and 2022 (Figure 1).

Fallows are managed in various ways that lead to differences in vegetation structure and composition (Underwood & Tucker, 2016). In the agricultural census data, fallow land is defined as agricultural land on which there is no production (i.e. no crops grown and harvested). In Germany, fallows cannot be treated with pesticides or fertilized and need to be mulched or mown once a year (Text S2). Fallows comprise fields with spontaneous succession and fields sown, for example, with grasses or wildflowers (Nitsch et al., 2017). They are maintained for a single or multiple growing seasons (rotational/annual vs. perennial fallows).

2.3 | Landscape complexity

We quantified landscape complexity within a buffer of 1 km around the midpoints of the CBBS plots (Figure S1) because farmland birds respond strongly to landscape complexity at this spatial scale (Winqvist et al., 2011). Landscape complexity was measured by calculating the total length of edges between woody features and agricultural land (i.e. cropland and grassland combined) for each buffer. Spatial information on linear (e.g. hedgerows) and patchy (e.g. isolated patches of trees or shrubs) small woody features were gathered from Copernicus Land Monitoring Service (2015). Information on agricultural land (cropland and grassland) and forest cover were obtained from ATKIS Base DLM (Bundesamt für Kartographie und Geodäsie, version 2018). We merged the geometries of woody features from remote sensing with the ATKIS forest geometries and calculated the edge length between these woody geometries and agricultural fields. We subsequently computed the edge density in metres per hectare of agricultural land (i.e. including grassland). Thus, landscapes with high edge density values indicated high configurational complexity (Figure S1). Edge density was used instead of a compositional descriptor because woody features such as hedgerows or forest patches are effectively protected under German law since at least 2005 (e.g. §9 BundesWaldGesetz). We, therefore, assumed constant edge density between 2007 and 2016. Descriptive statistics of the computed variable are given in Table S2. Edges between non-woody elements, such as ditches or paths, and fields were not considered.

2.4 | Data analysis

We modelled plot-level bird species richness and abundance as a function of the proportion of fallow land at the district level, and of edge density within the plot buffer (CBBS). We also included total agricultural land cover per buffer to account for variations in habitat availability for farmland birds. These variables were z-standardized. Given the hierarchical structure of the data, CBBS plots nested in districts, we applied a multilevel modelling approach using a Bayesian framework. This framework enables flexible model building adapted to the hypotheses and the data and also allows considering interregional variability as well as the repeated measure structure of our data (Gelman & Hill, 2006). We conducted residual checks to ensure that inferences drawn from the fitted models can be interpreted with sufficient confidence. Since a square root transformation of the variable 'proportion fallow' improved the linearity of the relationships with the response variables we transformed the covariate.

Only three time points with fallow land data were available from the agricultural census data. Given this limited temporal replicability, we refrained from a temporal analysis directly linking farmland bird populations to fallow area. We focused on the estimation of the spatial associations between fallow area and farmland birds. To avoid potential confusion between the spatial and the temporal gradient of fallow land area on farmland birds (Oedekoven et al., 2017) we fitted separate models for each of the 3 years.

The models fitted to the species richness data were of the form:

$$y_{ij} \sim \mathrm{TN}(\mu_{ij}, \sigma),$$

where y is the species richness being modelled based on a truncated normal distribution (TN) with a lower bound set at 0 and with expected value μ and standard deviation σ. Other statistical distributions were explored such as the negative binomial distribution or Gaussian distribution with a log link, but the model results showed poorer fit for these distributions compared with the truncated normal distribution with an identity link. The indices are i: the individual observations and j: the district. The expected values were modelled as follows:

$$\mu_{ij} = \beta_{0j} + \beta_{1j} \times \text{edge density}_i + \beta_{2j} \times \text{edge density}_i^2 + \beta_3 \times \text{agricultural land cover}_i.$$

The coefficients β_0, β_1 and β_2 were modelled as follows:

$$\beta_{0j} \sim \mathrm{N}\left(\delta_0 + \delta_1 \times \text{fallow}_j, \sigma_{\text{district}_{\text{intercept}}}\right),$$

$$\beta_{1j} \sim \mathrm{N}(\gamma_0 + \gamma_1 \times \text{fallow}_j, \sigma_{\text{district\_beta1}}),$$

$$\beta_{2j} \sim \mathrm{N}(\upsilon_0 + \upsilon_1 \times \text{fallow}_j, \sigma_{\text{district\_beta2}}).$$

The σ's are independent deviation parameters. The coefficients β_0, β_1 and β_2 varied between the districts in relation to group-level predictors, which is the proportion of fallow land in the district.

The models fitted to the species-level abundance data were of the form:

$$y_{ij} \sim \mathrm{ZINB}(\mu_{ij}, \sigma, \theta_i),$$

where y corresponds to the abundance data being modelled based on a zero-inflated negative binomial distribution with the expected value: μ, the deviation σ and the zero-inflation term θ. The expected values were modelled as follows:

$$\log(\mu_{ij}) = \beta_{0j} + \beta_{1j} \times \text{edge density}_i + \beta_2 \times \text{agricultural land cover}_i.$$

The hierarchical structure of these models was similar to the species richness model. The coefficient θ was modelled as follows:

$$\text{logit}(\theta_i) = \alpha_0 + \alpha_1 \times \text{edge density}_i + \alpha_2 \times \text{agricultural land cover}_i.$$

Fallow area was not included in the zero-inflated part of the models, as this would require setting a hierarchical structure for this term similar to the expected value that would lead to models being overly complex for our purpose and hypothesis.

The models were fitted in R (Version 3.6.1) using the BRMS package v2.16 (Bürkner, 2017) with weakly informative priors (Table S3). Default sampling settings were used except for the parameter adapt_delta and max_treedepth which were set to 0.9 and 25, respectively. Posterior distributions were estimated by running four independent chains for 2000 iterations, half of which were used as burn-in for the sampler and discarded. We used convergence checks to ensure that the *R*hat values for all parameters were below 1.1 and efficiency checks ensuring that the effective sample size of the parameters was larger than 400 (Vehtari, 2021). We also used posterior predictive checks comparing the density of the observed data against the density of simulated data using the function 'pp_check'. Finally, we tested for spatial autocorrelation of scaled residuals using the DHARMA package v0.4 (Hartig, 2019) and the 'posterior_predict' function taking into account the full model structure and the uncertainties of all parameters (i.e. including all hierarchical terms). Two aspects of the spatial autocorrelation were checked: (i) the global Moran's *I* value derived from the function 'testSpatialAutocorrelation' for all models and (ii) a spline fit to the correlogram of the residuals derived from the function 'spline.correlog' of the package NCF v1.2 (Bjornstad, 2020) for the species richness model. *R*-square values of the models were computed using the function 'bayes_R2', both considering all parameters in the models (conditional *R*-square) and restricting the *R*-square to the observation-level parameters (marginal *R*-square).

To test our first and third hypotheses, we extracted the posterior draws of the δ, γ and ν parameters from the models fitted to bird species richness. The conditional effect of fallows ($\delta + \gamma \times$ edge density $+ \nu \times$ edge density^2) was then computed along a gradient of edge density comprising 95% of the observed values and ranging from 5 (2.5% quantile) to 113 m/ha (97.5% quantile). To test for the hump-shaped relation of the effect of fallows with landscape complexity, the function 'hypothesis' was used with the test: $\nu < 0$.

To test our second hypothesis, we used two meta-analysis models with, separately, the estimated coefficients δ and γ from the species-level abundance models as response variables, and survey year and the group membership as covariates. The uncertainty around the estimated coefficient was included in this model which was fitted using the formula function 'se'. To explore the associations between fallow area and group-level abundance, we additionally derived geometric means per group from predicted species-level abundance. The predictions were derived using the function 'posterior_epred' across a gradient of fallow area values spanning 90% of the observed data and for three edge density values corresponding to the mean, the 10th and the 90th quantiles. These predicted values were then used to derive the geometric means (*G*) using the following equation (Buckland et al., 2011):

$$G_b = \exp\left(\frac{1}{S}\sum_{i=1}^{S} \log \frac{n_{ab}}{n_{a\%b}}\right),$$

where a indexes the different species within a group with S species, b indexes the different values of fallow area used to derive the prediction, $\tilde{b}$ is the average fallow area value and n is the predicted abundance for the given species and fallow area value.

3 | RESULTS

All model parameters were efficiently sampled (effective sample size >400) and converged (*R*hat < 1.1). In addition, posterior predictive checks revealed that the distribution of simulated data based on the model parameters' posterior distributions matched the distributions of the observed data (Figures S2–S5). Spatial autocorrelation of the model residuals was generally low for the species richness models (Figure S6). Correlograms showed no evidence of a spatial signal in the residuals of these models (Figure S7). Residuals of the species-level abundance models also showed low spatial autocorrelation (Moran's *I* −7e^{-3} to 3e^{-2}). Conditional R^2 was on average 38%, and marginal R^2 was on average 27% for the species richness models. The abundance models explained between 9% (European Goldfinch in 2010) and 61% (Eurasian Skylark in 2010) of the variance in the data. When considering only the observation-level parameters without the hierarchical terms the models explained between 0.6% (Fieldfare in 2016) and 49% (Corn Bunting in 2016) of the variance in the data.

The proportion of fallow land was generally positively associated with farmland bird species richness and bird abundance (Figures 2 and 3), suggesting we can accept our first hypothesis. The relationships of species richness with fallows were dependent on landscape configurational complexity and showed a hump-shaped curve (Figure 2, posterior probability 1, 0.97 and 0.99 for the years 2007, 2010 and 2016, respectively), suggesting we can accept our third hypothesis. In low-complexity landscapes with edge densities below 14 m/ha, the relationships of fallow area with species richness were equivocal in at least one of the focal years (i.e. the 95% credible interval crossed 0). The relationships of fallow area with species richness were strongest in landscapes with edge density around 65 m/ha (95% credible intervals 47–89 m/ha, 19–152 m/ha and 48–107 m/ha for the years 2007, 2010 and

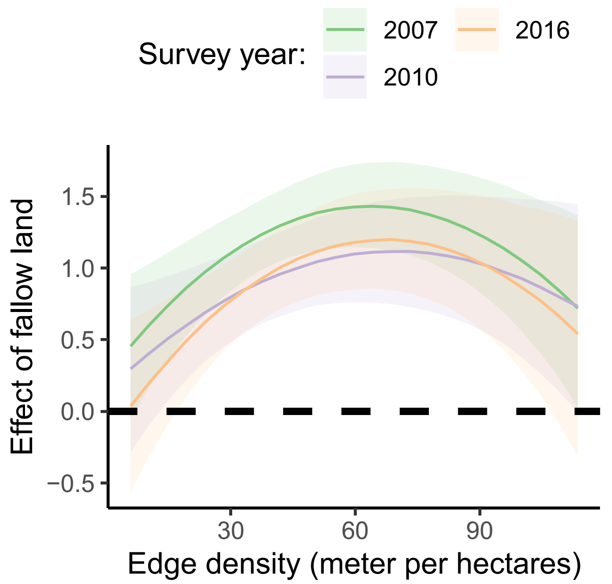

FIGURE 2 Effect of the proportion of fallow land on farmland bird species richness conditional on landscape configurational complexity (edge density of woody features in m/ha). The thick lines represent the posterior mean of the estimated effect and the contour lines the 95% credible interval around the estimated means.

2016). This represents a high edge density in Germany, as 78% of the buffers had lower edge densities. For landscapes with edge densities higher than 60 to 70 m/ha the strength of the effect of fallow area declined, but the uncertainty around the estimated relation of fallow area increased markedly, potentially due to the low number of data points at this end of the gradient. The associations were consistent across all years (Figure 2).

Fifteen out of the twenty-four studied species (63%) were strongly and positively associated with fallow area in two or more years (Figure 3), and only two negatively (Northern Lapwing and Fieldfare). At the group level, edge-breeders and foraging visitors were positively associated with the area of fallows, while there was equivocal evidence for field-breeders (credible intervals overlapping zero, Figure 3). Predictive plots of the geometric mean of species abundances suggest an increase of abundance with increasing fallow area for edge-breeders and foraging visitors, but high uncertainty and variation of the mean slope direction across years (Figure 4). The strength of the associations between fallow area and the abundance of edge-breeders was larger than for field-breeders (posterior probability = 0.99) and foraging visitors (posterior probability = 0.97). There was little evidence for a difference in the response of foraging visitors and field-breeders (posterior probability = 0.15). The interaction term between fallow area and edge density had no clear directional association at the species level in general (Figure S8). At the group level, there was some evidence for a positive interaction for field-breeding species. This implies that the associations between fallow area and the abundance of field-breeders increased with increasing edge density (Figure S9).

4 | DISCUSSION

We found good support for our first hypothesis stating that farmland bird populations are associated with fallow land area across three CAP funding periods. Our results are consistent with previous large-scale studies (e.g. Busch et al., 2020; Chamberlain et al., 2000; Herkert, 2009; Traba & Morales, 2019), although they go beyond the correlation of single national yearly estimates of fallow area and national bird population trends, by directly linking fallow land area with plot-level bird data from a national-scale monitoring scheme, albeit only with district-level land-use data (but see Herzon et al., 2011). We suggest that, given the large number of monitoring plots and consistent patterns over 3 years, the relationship is indeed causal. The massive loss of fallows in the period 2007 to 2016 was therefore a likely driver of farmland bird declines. The associations of bird species richness and abundance with fallow area were moderated by habitat preferences and landscape complexity (cf. Wretenberg et al., 2007).

The strength of the associations of bird abundance with fallow area was species-specific, positive for 15 species in at least 2 years. Except for Red-backed Shrike, all species with consistent positive associations with fallow area were field- and edge-breeders that benefit from fallows as foraging habitat and safe nesting habitat. They prefer a mosaic of ground vegetation with sufficient cover to hide their nests and adjacent bare ground or short swards to forage. Corn Bunting, Yellowhammer, Skylark and Red-backed Shrike prefer fallows during the breeding season (Burgess et al., 2015; Henderson et al., 2012; Meichtry-Stier et al., 2018). Woodlark, Ortolan Bunting and Corn bunting were most strongly associated with fallows. These are commoner and more widely distributed in Eastern Germany (Gedeon et al., 2014), where poorer soils prevail and climate is more continental compared with Western Germany. Vegetation succession is, therefore, slower in these regions (Manthey, 1999), leading to a higher availability of patchy and short vegetation. In contrast to the other species, Northern Lapwing and Fieldfare showed consistent negative associations with fallow area. These two species prefer short, open swards or bare ground on crop fields and avoid fallows that vegetate fast. This might explain their negative associations with fallow area.

Although we did not find strong indications for a moderating effect of landscape configurational complexity on species abundance (Figure S8), the position of fallows in the landscape and their size might also govern whether a species benefits from fallow land. Field-breeders that avoid vertical structures and edges such as Eurasian Skylark (Chamberlain & Gregory, 1999) or Northern Lapwing (Chamberlain et al., 2009; Schmidt et al., 2017) might only benefit from fallows when they are established far away from such landscape features and have a certain minimum area (Schmidt et al., 2017). Instead, edge-breeders and foraging visitors might use fallows close to their breeding site on field edges (Henderson et al., 2000). There was some evidence for stronger relationships of fallows with field-breeders in the most complex landscapes. One possible explanation for this is that the CBBS plots showing the

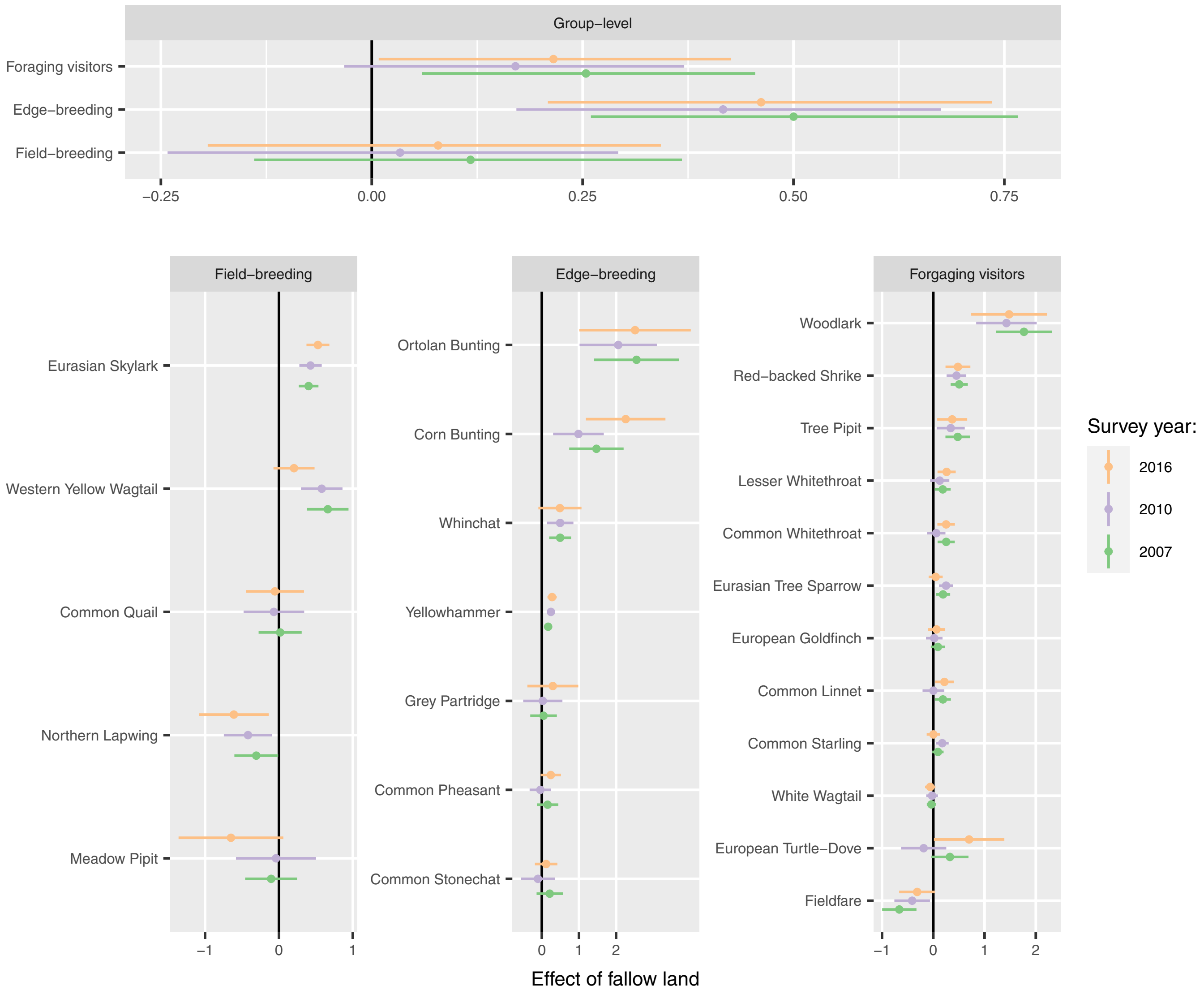

FIGURE 3 Estimated coefficients (posterior means ± 95% CrI) from models relating proportion fallow land to bird abundance. The bottom panels show the effect on the abundance of single species in the three functional groups. The top panels show the estimated group-level effects arising from a meta-analysis model. Note the different *x*-axis scale in the three bottom panels.

highest edge density values in their surroundings were still rather open landscapes (Figure S1) where populations of field-breeders could be maintained, albeit at low densities. In these complex landscapes the abundance of field-breeders is low and particularly at risk from breeding failure due to high predation pressure at forest edges (Ludwig et al., 2012). In agricultural landscapes, predators often concentrate near woody features, and densities in non-productive features such as sown flower strips are low, especially away from their edges (Laux et al., 2022). Therefore, fallow land might offer safe nesting sites for ground-foraging and ground-nesting birds such as Eurasian Skylark, while at the same time providing sufficient food resources (Berg & Pärt, 1994).

Providing or retaining fallows will potentially affect a broad range of farmland bird species, including those that declined most in Germany (e.g. Grey Partridge; Kamp et al., 2021). Identifying effective conservation measures that might reverse the declines of these species is therefore important. Previous studies from other parts of Europe have shown that fallow area and availability might slow down or even reverse negative population trends, for example, in Switzerland (Meichtry-Stier et al., 2018) and Portugal (Delgado & Moreira, 2010).

Our results partially support the 'intermediate landscape complexity hypothesis' (Tscharntke et al., 2012) postulating that conservation measures will be most effective for restoring high levels of species richness in landscapes with intermediate complexity. We found that spatial associations between fallows and farmland bird species richness were lower in landscapes with low edge density compared with landscapes with intermediate edge density. This could be due to the fact that in 'cleared' landscapes the species pool is limited by the lack of woody features required by numerous species and providing fallow land alone is not sufficient to increase farmland bird diversity (Tscharntke et al., 2012). At the other extreme of

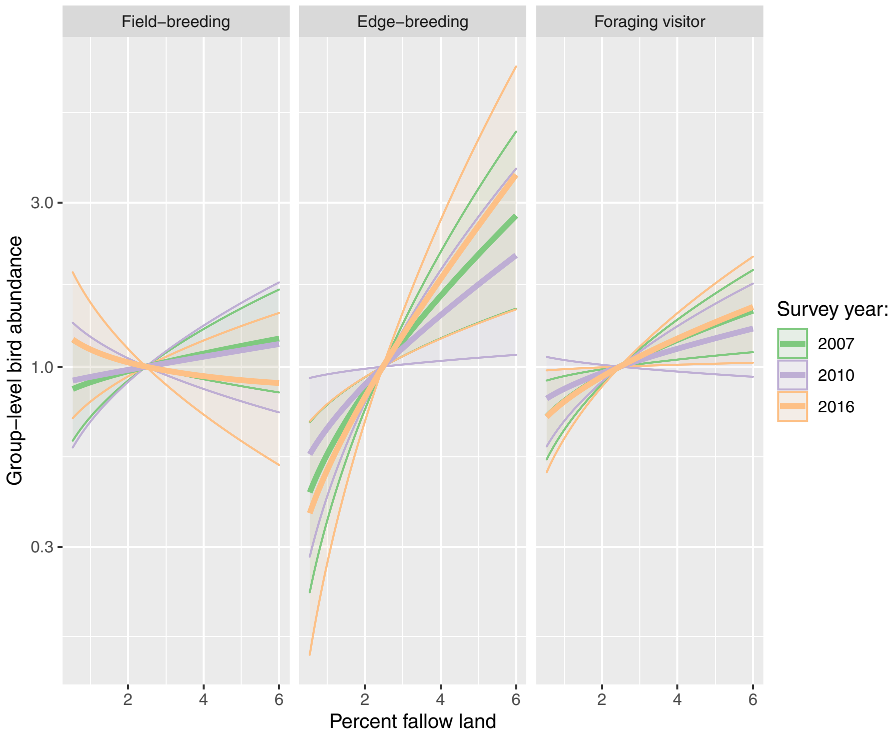

FIGURE 4 Group-level geometric mean calculated following Buckland et al. (2011) from species-level predictions across a gradient of fallow area and for the average edge density value. The bold solid lines represent the mean and the shaded area and thin lines represent the 95% credible intervals.

Census year	2007	2010	2016
Minimum–Maximum (%)	0.00–73.10/0.00–14.30	0.03–35.10/0.01–14.30	0.19–100/0.01–44.30
Median (%)	5.72/3.83	2.33/1.55	3.08/2.01
Number of districts >4%	295/193	113/55	132/58
Number of districts >10%	77/17	17/2	11/2

TABLE 1 Descriptive statistics of the proportion of fallow land at district level (per total arable land left of the '/', and per total agricultural land on the right) reported in the agricultural census data for the years 2007 (compulsory set-aside), 2010 (abolition of compulsory set-aside) and 2016 (introduction of Ecological Focus Areas). There are 401 districts in Germany.

the gradient, the effect of fallows weakened at an edge density exceeding 60–70 m/ha. However, for these most complex landscapes, the uncertainty around the magnitude of the effect of fallow land increased strongly. This might be due to limitations of the modelling framework and/or the low number of CBBS plots that exhibited a high edge density. However, it seems likely that the effect of fallows declined in these most complex landscapes because farmland bird species richness was already maximized. Increasing the proportion of fallow land would in that case not result in an increase in species richness (Tscharntke et al., 2011).

Biodiversity benefits from fallows not only depend on the overall area left non-productive but also on management (Sanz-Pérez et al., 2021; Van Buskirk & Willi, 2004). There is evidence that extensive fallow management tailored to individual species is more effective in increasing local farmland bird abundance than conservation measures that adopt more generic management prescriptions (Sanz-Pérez et al., 2021). Habitat suitability for farmland birds varies with fallow age. Biodiversity benefits generally increase with fallow age (Staggenborg & Anthes, 2022), but declines for fallows left uncultivated for more than 10 years have been reported (Lameris et al., 2016).

For the current CAP period, the German 2023–2027 strategic plan (BMEL, 2022) requires farmers to leave 4% of their arable land as non-productive features (including fallows). In 269 out of 401 (67%) of our districts, the proportion of fallow land was below 4% in 2016 (Table 1). Increases in non-productive features, such as fallows, to meet this new minimum requirement could lead to increases in farmland bird richness and abundance. However, we suggest that 4% would not be sufficient to restore, across all districts, the farmland bird richness and abundance that were observed before the strong decrease in fallow land around 2007. The districts that would need to increase fallow area to 4% are not necessarily the ones that showed the most severe losses of fallows from 2007 to 2016 (Figure 1). Additional CAP instruments based on farmers' voluntary participation, such as eco-schemes and agri-environment schemes, will probably increase the area of fallows primarily in less productive regions (Röder & Offermann, 2021). These additional fallows will be needed to fulfil the target of 10%

of the agricultural area covered by high-diversity landscape features set in the EU Biodiversity Strategy to support and restore agricultural biodiversity in Europe (European Commission, 2020). These instruments should integrate simple fallow management practices prescriptions that meet the requirements of the targeted species group (Tarjuelo et al., 2020).

Our study has several limitations. First, the fallow land data extracted from agricultural census data did not contain information on fallow management that drives vegetation structure and composition, which in turn can affect breeding bird species. Future analysis capitalizing on other data sources such as the Integrated Administration and Control System (IACS) could address this limitation (Nitsch et al., 2017). Furthermore, fallow land data were solely available at the district level, not at the level of the CBBS plots. This adds uncertainty and noise to our model estimates, especially in large districts where fallow land is not homogeneously distributed across the agricultural area. In essence, our statistical analysis relates farming systems on a landscape scale in which the proportion of fallow land, and not fallow area per se, were linked to bird population. Future studies using georeferenced information on fallow land such as available in IACS could overcome this limitation (Jerrentrup et al., 2017). Future evaluations on the impact of fallow land, or more broadly of local conservation measures, on farmland biodiversity, could also be improved by combining data of before-after designs on impact sites with control data from large-scale national monitoring schemes (Josefsson et al., 2020; Redhead et al., 2022).

We recommend including the following in future strategies for fallow land development:

1. Re-establish and maintain a minimum amount of fallow land across all agricultural landscapes, for instance through the enhanced conditionality of the 2023–2027 CAP;
2. Increase the proportion of fallow land beyond minimum required amount especially: (i) in regions that experienced the strongest loss in fallow land and (ii) in landscapes with an intermediate level of configurational complexity, that is, edge density around 65 m/ha.

In addition to fallow expansion, other non-productive biodiversity-friendly features should be supported by policies to bridge the gap between the 2023–2027 CAP and the EU Biodiversity Strategy targets, such as restoring species-rich grasslands (Alison et al., 2017) or preserving isolated trees and high-quality hedgerows in agricultural landscapes (Pustkowiak et al., 2021).

AUTHOR CONTRIBUTIONS

Sebastian Klimek, Norbert Röder, Johannes Kamp and Lionel Hertzog conceived the idea; Lionel Hertzog, Johannes Kamp, Claudia Frank, Sebastian Klimek, Norbert Röder and Hannah Böhner defined the questions and the methodological approach; Lionel Hertzog, Johannes Kamp and Claudia Frank collected the data; Lionel Hertzog carried out analyses and led the writing. All authors contributed substantially to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest or personal relationships that could have influenced this work.

DATA AVAILABILITY STATEMENT

Code and data to reproduce the analysis and main figures are available via Zenodo at https://doi.org/10.5281/zenodo.5561412 (Hertzog et al., 2023).

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SUPPORTING INFORMATION

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

Table S1: Classification of the farmland bird species into categories together with species-level prevalence and sample size.

Text S1: Justification for the grouping of bird species according to their breeding habitat preferences.

Text S2: Management prescription for fallows in Germany.

Figure S1: Aerial photographs of selected CBBS plots along the landscape structural complexity gradient.

Table S2: Descriptive statistics of the computed landscape configurational complexity (edge density) variable.

Table S3: Prior distribution of the model coefficients.

Figure S2: Posterior predictive checks for species richness models.

Figure S3–S5: Posterior predictive checks for abundance models.

Figure S6: Residual spatial autocorrelation.

Figure S7: Correlogram of model residuals for species richness models.

Figure S8: Estimated interaction effect fallow land: Edge density for species-level abundance models.

Figure S9: Group-level geometric means computed for different edge density values.

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