Losses and gains of fallows drive farmland bird populations over three funding periods of the EU Common Agricultural Policy

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Abstract

Fallow 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 and influenced trends in farmland biodiversity. We analyzed the impact of changes in fallow area across Germany on species richness and abundance of farmland birds over three CAP funding periods. We examined whether responses to fallow land area were modulated by species habitat preferences and landscape complexity. We combined spatial data on fallow land area from three agricultural censuses in Germany (2007, 2010 and 2016) with country-wide, annual monitoring data on farmland birds. Farmland bird species richness and the abundance of edge- and field-breeders responded positively to increases in

fallows. The effect of fallows on bird richness was strongest at intermediate levels of landscape complexity. There was support for an increasing effect strength of fallow land area on field-breeders' abundance with increasing landscape complexity. We conclude that the loss of fallows in the period 2007 to 2016 resulted in strong declines of farmland birds. We predict that a future increase of the proportion of fallow land to 4%, as envisaged in the post-2020 CAP for Germany, will result in an average increase of 7% in farmland bird species richness and of 11% in average farmland bird abundance compared to 2016, but will depend on species-specific habitat preferences. Increasing the proportion of fallow land will be a key lever to stabilize and revert negative farmland bird population trends. An increase of fallow area in all but the least complex landscapes will boost farmland bird richness and abundance of field breeders. Increasing the proportion of fallow land to 4% is projected to, on average, bring farmland bird richness and abundance back to the levels observed in 2007 acknowledging that farmland bird populations were already severely depleted in 2007. A more ambitious expansion of fallow land towards 10%, such as in the context of the EU Biodiversity Strategy for 2030, should be targeted towards areas that experienced the strongest loss of fallows and towards landscapes with intermediate structural complexity.

Keywords: agricultural intensification, biodiversity conservation, Germany, Common Agricultural Policy, ecological focus areas, 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 an increasing use of agrochemicals, farm mechanization and specialization (Tscharntke et al. 2005, Kleijn et al 2009, Emmerson et al. 2016). As a consequence, biodiversity in agricultural landscapes has been declining across Europe and North America since at least the 1960s (Stanton et al., 2018). In addition, 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) following agricultural intensification have been documented.

An important component of intensification is the loss of non-productive features in agricultural landscapes. The availability of non-productive features such as field margins, hedgerows and fallow land plays an important role in driving biodiversity patterns (Van Buskirk & Willi 2004, Sálek et al. 2018). Fallow land in agricultural landscapes provides undisturbed habitat for plants, and food and shelter for animals across trophic levels (Van Buskirk & Willi, 2004: Tscharntke et al., 2011). In Europe, fallows have been part of farming systems since early cultivation (Allen 2000). Today, fallow land area is largely driven by supranational and national policies.

In the European Union (EU), agricultural land-use patterns are heavily influenced by the Common Agricultural Policy (CAP). The CAP is the main policy instrument used to distribute public payments in the agricultural sector. Its design and implementation have a large impact on farm management and overall land use, and therefore on farmland biodiversity (Pe'er et al., 2014). Mandatory set-aside schemes were introduced in the CAP in 1992 and made up a large proportion of all fallows across the EU. All larger cash-crop farmers had to set aside (i.e., leave fallow) around 10% of their arable land between 1992 and 2007. In 2007, mandatory set-aside was abolished and, as a result, the total fallow area declined strongly across

68 all EU member states (Tarjuelo et al. 2020, Figure 1). Fallow land area increased across the EU after the
69 2013 CAP reform, which obliged most farmers to manage 5% of their arable land as Ecological Focus Areas
70 to receive subsidies. However, the area of fallow land did not reach similar levels as during the period of
71 mandatory set-aside (Tarjuelo et al., 2020, Figure 1).

72 There is little doubt that farmland biodiversity generally benefits from a high proportion of fallow land in
73 the agricultural landscapes (Van Buskirk & Willi, 2004). However, it is currently unclear, whether this effect
74 is mediated by landscape context. In structurally complex landscapes characterized by a high density of
75 "non-crop" elements such as hedgerows, small woods and semi-natural grasslands, local species richness
76 might be close to the regional species pool. Therefore, increasing the area of fallows might have little effect
77 on species richness and diversity (Tscharntke et al., 2011). At the other extreme, in homogenous, cleared
78 landscapes with no or little of such elements, potential source populations might be isolated and too
79 depleted to respond to increases in the area of fallows and resources provided (Tscharntke et al., 2012).
80 The 'intermediate landscape complexity hypothesis' predicts that local conservation measures will be
81 most effective in promoting species richness and diversity in moderately complex landscapes and less
82 effective in both cleared and highly complex landscapes (Tscharntke et al. 2005, 2012). Indeed, empirical
83 evidence suggests that species richness does increase in structurally simple landscapes containing a low
84 to medium amount of semi-natural habitat, once fallows are provided (Wretenberg et al., 2010).

85 The area of fallows in the agricultural landscape also affect the abundance of farmland species. Fallows,
86 compared to managed fields, provide food and undisturbed reproduction habitat leading to higher
87 population densities and higher reproductive success (Whittingham et al. 2006). It is likely that abundance
88 responses to changes in the area of fallows will be mediated by species-specific ecological requirements,
89 such as the preference to forage and reproduce in open farmland or in edge habitats (Berg & Pärt 1994).
90 Additionally, landscape complexity could also mediate the response of farmland species abundance to
91 changes in the area of fallow land. Fallows were reported to harbor higher abundances of plants compared

to field margins especially in simpler landscapes (Ma & Herzon 2014) and the abundance of open farmland bird species in fallows was highest in simpler landscapes (Toivonen et al 2015).

We investigated the impact of changing proportions of fallows in agricultural landscapes on farmland biodiversity spanning three CAP funding periods between 2007 and 2016. We combined high resolution land management and biodiversity data for Germany. We used farmland birds as model organisms, as they are established biodiversity indicators (Gregory et al., 2005), subject of a long history of monitoring (Brlík et al., 2021) and have been suggested to strongly respond to changes in fallow land area (Traba & Morales 2019). In addition, we assessed how landscape structural complexity modulates the response of species richness and abundance to changes in the proportion of fallows. We tested the following hypotheses:

1. An increasing proportion of fallows in the landscape leads to increased farmland bird species richness and abundance due to increased food availability, i.e. seeds and invertebrates.
2. The effect of the proportion of fallows on bird abundance varies with species' habitat preferences, as species breeding in fields and their edges will profit from additional food and nesting resources while species breeding in hedgerows and other woody structures might be constrained by the availability of nesting sites.
3. An increasing landscape complexity dampens the positive effect of an increasing proportion of fallow land on the abundance of species of open landscapes (field breeders).
4. The strongest effect of a change in the proportion of fallows on bird species richness will be observed in landscapes with intermediate structural complexity.

To provide guidance on policy development in the context of the current post-2020 CAP discussions we projected changes in fallow land area under different scenarios. More specifically, we projected the impact of a) the mandatory establishment of fallows on 4% of the arable land as envisaged under the enhanced conditionality of the post-2020 CAP (COM, 2021) and b) establishing fallows on 10% of

the utilized agricultural area according to the EU biodiversity strategy's commitment to dedicate 10% of farmland to 'high-diversity landscape features' by 2030 (COM, 2020).

2. Materials and Methods

2.1. Bird data

We used data on 24 bird species associated with farmland and open habitats from the German Common Breeding Bird Survey (CBBS) coordinated by the Dachverband Deutscher Avifaunisten (Kamp et al., 2021). This monitoring scheme was established in 2004. Volunteers map the territories of all breeding birds along routes of approx. 3 km length four times in the period 19 March–20 June. More than 2600 sample plots of 1 km² are distributed across Germany, based on a stratified random sampling approach, and up to 1800 of these are surveyed annually (Kamp et al., 2021). We used the number of bird territories per plot as a measure of breeding bird abundance and calculated plot-level species richness from the raw data. To match the data to the agricultural census data (see below), only data from the years 2007, 2010 and 2016 were used. Further, only CBBS plots with at least 10% of agricultural land-cover (arable and grassland) were kept. This resulted in 613, 742 and 948 plots available for analysis for the years 2007, 2010 and 2016. 359 of these plots were surveyed in all three years, 363 in two years and 500 in a single year. Each CBBS plot was assigned to a German district (NUTS level 3) based on its midpoint.

We classified the selected farmland bird species into three categories based on their ecological requirements and their preference to use arable fields and fallows for breeding or foraging using species-specific habitat associations reported in the literature (Table S1 and Text S1). Species that are known to breed mainly inside fields, including fallows, were categorized as 'field-breeders' (n=5), species that prefer the edges of fields and fallows were categorized as 'edge-breeders' (n=7). Species that are known to breed

138 outside of fields and fallows (e.g. in hedgerows), but visit those regularly for foraging were classified as
139 'foraging visitors' (n=12). We calculated species richness across all categories and total abundance for each
140 category separately. To account for the fact that some species reach larger population sizes and densities
141 than others, we scaled bird species abundance to values between 0 and 100, 100 corresponding to the
142 maximum abundance reported for the respective species in any year. The species-level scaled abundances
143 were then summed to the nearest integer per category.
144

145 *2.2. Agricultural census data*

146 To estimate the area of fallow land for the three focal years, we used agricultural census data at the district
147 level across Germany (n=401 districts; Fig. 1). Data on agricultural management are collected in Germany
148 by the regional statistical authorities at the level of individual farms. This includes e.g. the total agricultural
149 area and the area left fallow (or 'set aside') per farm. The latest data are from the years 2007, 2010 and
150 2016. Due to confidentiality restrictions the officially published data have gaps. Therefore, we used a
151 dataset with gaps filled (Gocht & Röder 2014), provided by Thünen Atlas (2021). Given that the districts
152 differ in size, we used the proportion of fallow land in further analysis computed as the fallow land area
153 divided by the cultivated agricultural (arable plus grassland) area. The census years cover three funding
154 periods of the CAP: the 'set-aside' period (2007; promotion of fallow land area), the abolition of mandatory
155 'set-aside' (2010; decrease of fallow land area) and the introduction of Ecological Focus Areas as key
156 'greening measure' (2016; increase of fallow land area; Fig. 1).
157

158 The term "fallow" comprises a whole range of options that vary widely in terms of vegetation structure
159 and composition (Underwood & Tucker, 2006). In the agricultural census data, fallow land is defined as
160 agricultural land on which there is no production. Fallow land may either be bare land with crop stubbles
161 ploughed in and natural regeneration of vegetation, or sown with plant mixes ranging from simple grass

mixtures to limit the establishment of weeds to dedicated seed mixtures of wildflowers designed to benefit farmland biodiversity (Nitsch et al., 2016). Fallows can be present for one growing season (rotational or annual fallow) or over several growing seasons (perennial fallow). Fallows can further differ with respect to their size and management, but have in common that they are not fertilized and treated with pesticides. To comply with the CAP's requirement regarding minimum maintenance, the vegetation must be mulched or mown once a year.

2.3. Landscape complexity

We quantified landscape complexity in a radius of 1 km around the midpoints of the CBBS plots, because farmland birds respond strongly to landscape complexity at this spatial scale (e.g. Winquist et al. 2011). Landscape complexity was measured as the total length of edges between woody features and agricultural land for each 1 km landscape sector. Spatial information on linear (e.g. hedgerows), patchy (e.g. isolated patches of trees or shrubs) and additional small woody features were gathered from a 2015 pan-European high-resolution layer (Copernicus Land Monitoring Service 2015). Information on the land-cover classes agricultural land (comprising arable land and grassland) and forest (closed deciduous and coniferous forests) were obtained from vector-based high-resolution (1:25000) land-cover data (ATKIS Base DLM). We merged the geometries of the woody features with the ATKIS forest geometries and calculated the edge length between these woody geometries and agricultural fields. We subsequently computed the edge density in meter per hectare. Thus, landscapes with high edge density values indicated high structural complexity (see also Figure S1).

2.4 Data analysis

We modelled species richness and the total scaled bird abundance for the three categories (field-breeders, edge-breeders and foraging visitors) as a function of the covariates.

We used a multilevel modelling approach with covariates (all z-standardized) calculated both at the landscape and at the district scale. Landscape structural complexity (m edge/ha) and agricultural land area (ha) were calculated for each 1 km landscape sector around the CBBS-plots while % fallow was quantified at the district scale. Table S2 presents the summary statistics of all covariates. Agricultural land area was included as covariate in the models to account for the changes in habitat availability. Exploration of the data suggested that a square root transformation of % fallow improved the linearity of the relationship with the response variables; we therefore transformed the covariate accordingly.

The model fitted to the species richness data was of the form:

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

Where *y* is to the species richness being modelled based on a truncated normal distribution (*TN*) with a lower bound set at 0 and with the expected value μ and the standard deviation σ. The indices are *i*: the individual observations, *j*: the district for a given year and *k*: the district. The expected values were modelled as follows:

$$\mu_{ijk} = \beta_{0jk} + \beta_{1jk} * edge\ \mathrm{density}_i + \beta_{2jk} * edge\ \mathrm{density}_i^2 + \beta_3 * agricultural\ \mathrm{land\ cover_i}$$

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

$$\beta_{0jk} \sim N(\delta_{0k} + \delta_1 * fallow_j, \sigma_{district:year})$$

$$\beta_{1jk} \sim N(\gamma_{0k} + \gamma_1 * fallow_j, \sigma_{district:year})$$

$$\beta_{2jk} \sim N(\upsilon_{0k} + \upsilon_1 * fallow_j, \sigma_{district:year})$$

$$\delta_{0k} \sim N(0, \sigma_{district})$$

$$\gamma_{0k} \sim N(0, \sigma_{district})$$

$$\upsilon_{0k} \sim N(0, \sigma_{district})$$

The *σ's* are independent deviation parameters. The models fitted to the abundance data were of the form:

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

Where *y* corresponds to the scaled abundance data being modelled based on a zero-inflated negative binomial (*ZINB*) distribution with the expected value: μ, the deviation σ and the zero-inflation term θ. The expected values were modelled as follow:

$$\log(\mu_{ijk}) = \beta_{0jk} + \beta_{1jk} * edge\ density_i + \beta_2 * agricultural\ land\ cover_{\mathrm{i}}$$

With a similar hierarchical structure as for the species richness model. The coefficient θ was modelled as follow:

$$logit(\theta_i) = \alpha_0 + \alpha_1 * edge\ density_i + \alpha_2 * agricultural\ land\ cover_i$$

The models were fitted in R (Version 3.6.1) using the brms packages (Brückner 2017) with weakly informative prior distributions (see Table S3). Default sampling setting 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 conducted the following model checks:

- convergence checks ensuring that the Rhat values for all parameters was below 1.1.
- efficiency checks ensuring that the ratio of effective sample size over the number of posterior samples was above 10%.
- posterior predictive checks comparing the density of the observed data against the density of simulated data drawn from the posterior distribution of the model parameters.

- Spatial autocorrelation of the residuals checks using the DHARMa package (Hartig 2019).

A sensitivity analysis was conducted to explore the impact of individual species on the estimated effects of fallows for the different bird categories. Each species was dropped once at a time from the computation of the total scaled abundance and the models were refitted. The posterior distributions of the fallow slope and the interaction between edge density and fallow were then compared between the initial model and the model without the focal species (see Table S4). Furthermore, species-specific models were fitted following the same model structure used to fit the scaled abundance data at the level of the bird categories (see Figure S2).

To test our first, third and fourth hypothesis, we extracted the posterior draws of the estimated effect of fallows and its interaction with landscape structural complexity from the four fitted models. The effect of fallows 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 (97.5% quantile) edges per hectare.

To test our second hypothesis, we compared the strength of the effects of fallows on bird population abundance between the three different bird classes using the posterior draws of model coefficient extracted as defined above and for the following edge density values: 5, 47 (mean of observed values) and 113 m edges per hectares. We compared the posterior draws between the three bird classes.

To inform future agricultural policies, we derived three scenarios of changes in fallow area:

1) The '*Past change*' scenario: fallow area decreases on average from 4 to 2%, corresponding to the average values observed in 2007 and 2016 respectively.
2) The '*post-2020 CAP'* scenario: fallow area is projected to increase from the observed levels in 2016 to 4% in all districts as induced by the post-2020 CAP regulations as set in the national strategic plan for Germany. The post-2020 CAP will link payments to farmers to a stronger set of mandatory requirements ("enhanced conditionality", Tarjuelo et al. 2020).

3) The EU *Biodiversity strategy* scenario: fallow area is projected to increase from the observed levels in 2016 to at least 10% in all districts, in order to achieve the goal of the EU biodiversity strategy for 2030 to bring back at least 10% of agricultural area under 'high-diversity landscape features' such as buffer strips, hedges, non-productive trees and fallow land. Under this policy scenario we assume that 10% of farmland is solely dedicated to fallow land.

We estimated changes in bird richness and abundance for each scenario based on the expected posterior values (the μ) from the fitted models. These predicted changes in bird richness and abundance were derived along the same gradient of edge density as defined above.

To explore regional differences in the impact of past and future changes in fallow land on bird richness and abundance, we derived the expected posterior values (the μ) across all districts based on the proportion of fallow land observed in 2007, 2016 and two post-2020 scenarios (scenario 2 and 3 described above). We calculated the absolute differences in the expected posterior values for any given district between: (i) 2007 and 2016, (ii) 2016 and post-2020 and (iii) 2007 and post-2020. These predictions were derived for average level of landscape structural complexity and agricultural area but do consider variations in species richness and abundance between years and districts not explained by the model covariates.

3. Results

All model parameters were efficiently sampled (effective sample size ratio larger than 10%) and converged (rhat smaller than 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 (Figure S3). Spatial autocorrelation of the model residuals was generally low (Moran's I 0.03 to 0.06,

Figure S4). The models explained between 33% (foraging visitors) and 57% (field-breeders) of the variance in the data.

Supporting our first hypothesis, the proportion of fallow land had generally a positive effect on farmland bird species richness and bird abundance across all three categories (Figure 2).

The response of species richness to fallow was dependent on landscape structural complexity and showed a hump-shaped relationship (posterior probability = 0.98), supporting our fourth hypothesis. In landscapes with edge densities below 12.5 m / ha, the direction of the effect of fallow land on species richness was uncertain (i.e. the 95% credible interval crossed 0). The strongest effect of fallow land on species richness was found in landscapes with 75 m of edges per hectare. This represents a high edge density in Germany, as 85% of the 1 km landscape sectors had lower edge densities. For landscapes with edge densities higher than 75 m per hectare the strength of the effect of fallow land declined but at the same time the uncertainty around the estimated effect of fallow land increased markedly, potentially due to the low number of data points at this end of the gradient (Figure 2).

Field-breeders' abundance increased with the proportion of fallow land, especially in landscapes with higher edge densities compared to landscapes with lower edge densities (posterior probability = 0.95) contrary to hypothesis 3. The abundance of edge-breeders increased with the proportion of fallow land, independent of landscape structural complexity (posterior probability = 0.73). For foraging visitors, the effect of fallow land was also independent from landscape structural complexity, but the uncertainty around the direction of the estimated effect was large at low and high edge densities.

The strength of the effect of fallow land on bird abundance varied between the three categories. Field- and edge-breeders showed stronger responses to the proportion of fallow land compared to foraging visitors (Table S5). In addition, field- and edge-breeders showed similar responses to the proportion of fallow land in landscapes with low edge densities, but the response of edge-breeders to the proportion of fallow land was weaker than that of field-breeders in landscapes with average and high edge densities.

Landscape structural complexity had a hump-shaped relationship with bird species richness, but positively affected the abundance of both edge-breeders and foraging visitors. It negatively affected the abundance of field-breeders (Figure S5).

In our scenarios, the estimated impact of gains and losses of fallow land between 2007, 2016 and post-2020 on bird richness depended on the landscape structural complexity (Figure 3). Estimated changes in the abundance of field-breeders to changes in fallow land remained, however, constant across the landscape structural complexity gradient despite the presence of a positive interaction between fallow land and landscapes structural complexity (Figure 2). This pattern is due to the fact that field-breeders are negatively affected by landscape structural complexity (Figure S5) so that for high landscape structural complexity the effect of fallow land on field breeders is relatively large; but given that field breeders maintain low population sizes in such landscapes the absolute effect of fallow land is small. The abundance of edge-breeders and foraging visitors was estimated to respond to changes in fallow land independently from landscapes structural complexity. Compared to 2016 bird richness and abundance were predicted to increase, on average, by 7 and 11% respectively under the *post-2020 CAP* scenario.

The observed changes in the proportion of fallow land between 2007 and 2016 led, in most districts, to declines in farmland bird richness and abundance (Figure 4 and Figure S6). These declines were especially marked in northern and eastern Germany. Overall, both future scenarios suggest increases in species richness and abundance compared to 2016, especially in northwestern and southern Germany, with higher increases for the '*Biodiversity strategy*' scenario compared to the *'post-2020 CAP'* scenario. Various districts in Germany which had a high proportion of fallow in 2007, such as in eastern Germany, will not recover to the levels of farmland bird richness and abundance observed in 2007 under the *'post 2020 CAP'* scenario. In these districts even an increase of fallow land to at least 10% as envisaged in the '*Biodiversity strategy*' scenario would not be sufficient to reach the 2007 levels regarding bird abundance and diversity (Figure S7).

4. Discussion

Our study corroborates the general prediction from our first hypothesis that farmland bird populations are linked to changes in fallow land area driven by recent CAP reforms. Consistent with previous studies (e.g. Traba & Morales 2019, Busch et al. 2020), we found that the loss of fallows in the period 2007 to 2016 negatively affected farmland birds. Our findings demonstrate that the responses of farmland bird species richness and abundance to fallow land area were modulated by species habitat preferences and landscape complexity, which has remained largely unexplored so far.

Comparing the strength of the effect of fallow land between bird species with varying habitat preferences provided support for our second hypothesis. The abundance of field and edge-breeders showed stronger responses to the proportion of fallow land than foraging visitors. Providing or retaining fallows will therefore particularly affect those bird species breeding in or at the edges of fallows. Some of these species are amongst the farmland birds that have shown the strongest declines in recent decades such as grey partridge or skylark (Kamp et al 2021). Identifying effective conservation measures that have potential to reverse the declines of these species is therefore important.

We did not find evidence for an interaction between the proportion of fallow land and landscape structural complexity on the abundance of edge-breeders and foraging visitors, while there was evidence for a stronger relative effect of fallow land in landscapes with higher edge density on the abundance of field-breeders. We reject therefore our third hypothesis. This counterintuitive result could be explained by the fact that the CBBS plots showing the 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 (Figure S5). 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). Therefore,

343 fallow land could offer suitable nesting sites for ground foraging and nesting birds such as skylark and
344 lapwing that are safe from predators and at the same time providing plentiful insect and seed resources
345 (Berg and Pärt 1994). Interestingly, for a given change in fallow land, absolute change in the abundance of
346 field-breeders remained largely constant across the landscape complexity gradient. In other words,
347 increasing the proportion of fallow land in simple or complex landscapes will lead to the same absolute
348 changes in the abundance of field-breeders.

349 Our results partially support the 'intermediate landscape complexity hypothesis' (Tscharntke et al 2012)
350 postulating that management interventions will be most effective for restoring high levels of species
351 richness in simple landscapes with moderate complexity. Indeed, we found that the effect of an increasing
352 proportion of fallows on farmland bird species richness was lower in landscapes with low edge density
353 compared to landscapes with intermediate edge density. This could be due to the fact that in cleared
354 landscapes (no edges between agricultural land and woody features) the species pool is limited by the lack
355 of woody features required by numerous species and providing fallow land alone is not sufficient to
356 increase farmland bird diversity (Tscharntke et al. 2012). At the other extreme of the landscape complexity
357 gradient, our results show that the effect of fallow land declines in landscapes with an edge density
358 exceeding 75 m per ha. However, for these most complex landscapes the uncertainty around the
359 magnitude of the effect of fallow land increases strongly. This might be due to limitations of the modeling
360 framework or the low number of plots that exhibited a large edge density. It seems, however, likely that
361 the effect of fallows declines in these most complex landscapes because farmland bird species richness is
362 saturated (Tscharntke et al 2011).

363 Projections derived from the models show that implementing a proportion of fallow of 4% on agricultural
364 land could lead to marked increases in farmland bird richness, especially in landscapes of intermediate
365 structural complexity, and in the abundance of field- and edge-breeders compared to the situation in 2016.
366 However, a proportion of 4% fallow land would not be sufficient to restore, across all districts, the former

levels of abundance and species richness in farmland birds that were observed before the strong decrease in fallow land around 2007. Indeed, the districts that would need to increase their proportion of fallows to meet future enhanced conditionality requirements under the post-2020 CAP are not necessarily the ones that showed the most severe losses in fallow land between 2007 and 2016 (Figure 1). Hence, a more ambitious target is needed to restore farmland bird species richness and abundance to levels before 2007 in particular in these districts. Populations of farmland birds in 2007 were already depleted across Germany. Indeed, farmland bird abundance was already around 20% lower in 2007 compared to the early 1990s (Kamp et al. 2021). The post-2020 CAP target of a 4% increase in fallow area would therefore bring us back to an already degraded state. Our results show that dedicating 10% of the farmed land to fallows as an example of a particularly biodiversity-friendly measure as proposed by the EU Biodiversity Strategy for 2030 or national conservation agencies (BfN 2021) will lead to markedly higher levels in farmland bird species richness and abundance.

Biodiversity benefits from fallows not only depend on the overall area left non-productive, but also on the way fallows are managed (Van Buskrik & Willi 2004, Sanz-Pérez et al. 2021). There is evidence that extensive fallow management targeted to the requirements of individual species can be more effective in increasing local farmland bird abundance than conservation measures that adopt more generic management prescriptions (Sanz-Pérez et al. 2021). A successful promotion and uptake of such targeted measures as part of eco-schemes and agri-climate environment schemes within the post-2020 CAP will depend on a better understanding of farmer motivations in addition to economic considerations (Brown et al. 2021). Habitat suitability for farmland birds also depends on fallow age, i.e. the time since the last cultivation in multi-year fallows. Biodiversity benefits generally increase with fallow age (Van Buskirk & Willi 2004) but declines for fallows left uncultivated for more than ten years have been reported (Lameris et al. 2017).

Our recommendations for future strategies on fallow land development are:

1. Reestablish and maintain a minimal amount of fallow land across all agricultural landscapes: the 4% threshold enacted in the enhanced conditionality of the post-2020 CAP would restore bird richness and abundance, on average, to levels observed in 2007;
2. Increase the proportion of fallow land to beyond 4% especially: (i) in regions that experienced the strongest loss in fallow land and (ii) in landscapes with an intermediate level of structural complexity, i.e. edge density between 15 and 75 m per ha.

In addition to fallow expansion and targeted fallow management, other non-productive biodiversity-friendly features should be supported, for instance, as parts of voluntary measures such as eco-schemes or agri-environment climate measures to bridge the gap between the new post-2020 CAP and the EU biodiversity strategy targets. These could include restoring species-rich grasslands (Alison et al. 2017) or preserving isolated features such as habitat trees and high-quality hedgerows in agricultural landscapes (Pustkowiak et al. 2021).

Author contributions

S.K., N.R., J.K. and L.H. conceived the idea; L.H., J.K., C.F., S.K., N.R. and H.B. defined the questions and the methodological approach; L.H., J.K. and C.F. collected the data; L.H. carried out analyses and led the writing; and J.K, C.F., S.K., N.R. and H.B. contributed to the writing.

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Figures

Figure 1: Proportion of fallow land on agricultural land (arable plus grassland) across all German districts at three time steps (upper panel) and changes in the proportion of fallow land in percentage points (p. p.) between 2007 and 2010 (after the abolishment of mandatory set aside in 2007), and between 2010 and 2016 (after the establishment of Ecological Focus Areas) (lower panel).

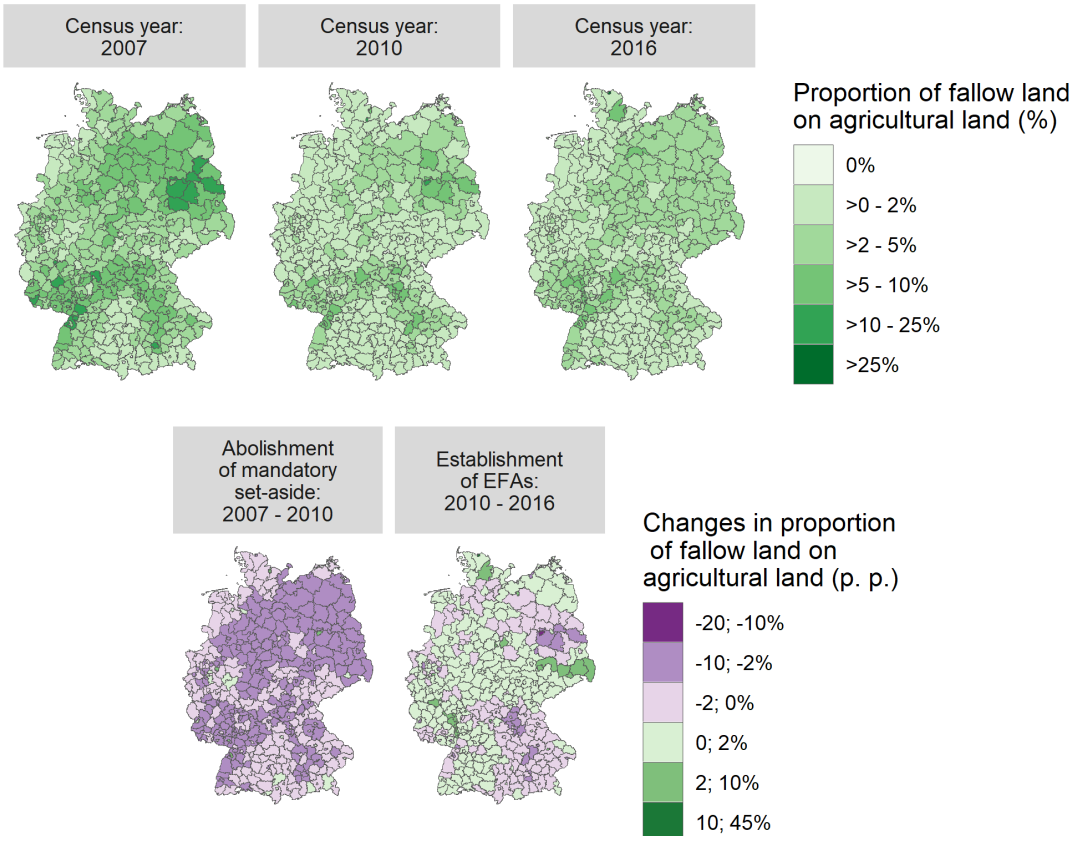


Figure 2: Effect of the proportion of fallow land on farmland bird species richness, the abundance of field- and edge-breeders and the abundance of foraging visitors conditional on landscape structural complexity (measured as edge density between agricultural land and woody features). The thick lines represent the posterior mean of the estimated effect and the dashed line the 95% credible interval around the estimated means. Note the varying range of the y-axes.

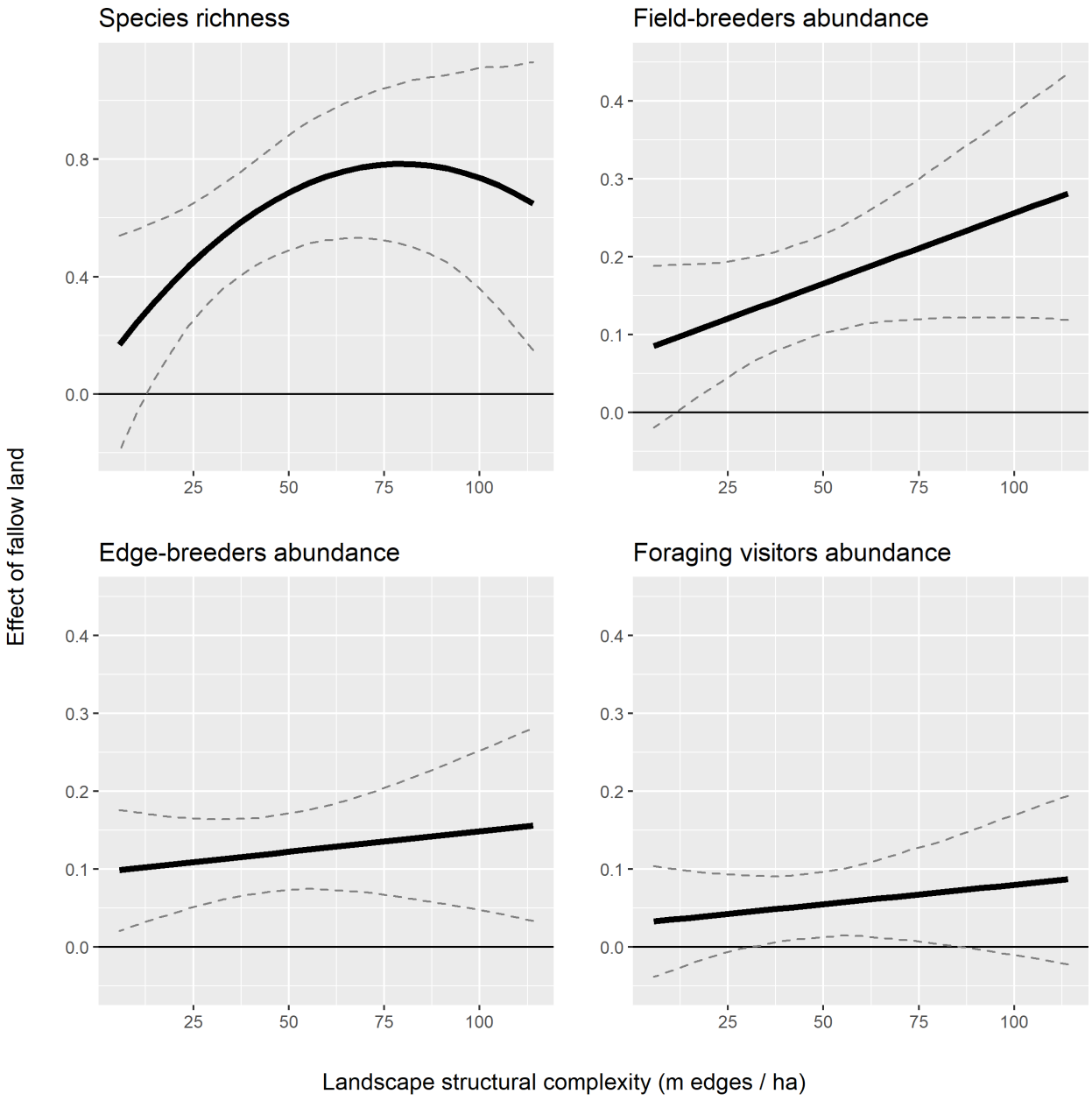
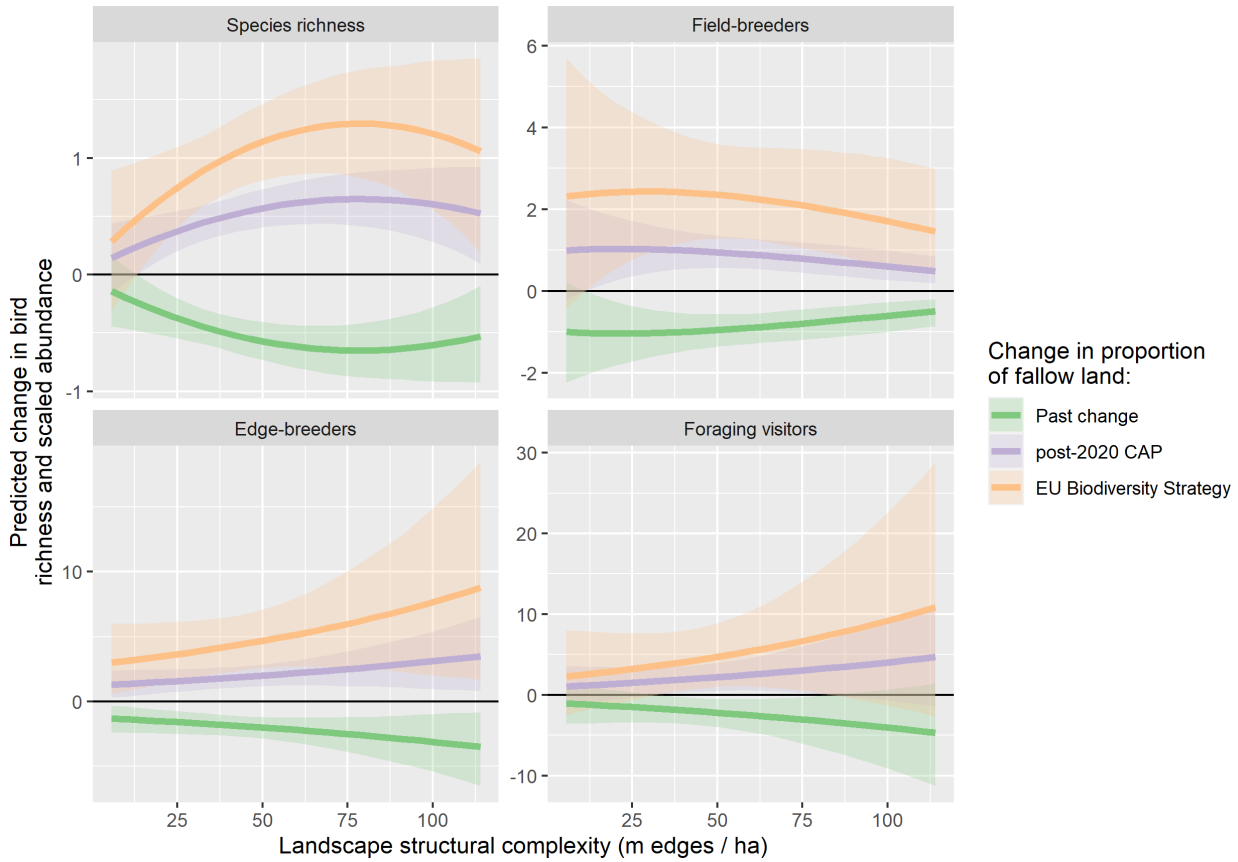


Figure 3: Projected changes in bird species richness, and the abundance of field- and edge-breeders as well as foraging visitors for the past period of fallow loss, and two future policy-based scenarios, all conditional on landscape structural complexity. The '*Past change*' scenario is the model projection reflecting a decrease in fallow land from 4 to 2% of agricultural land (the average observed across Germany for the period 2007 to 2016). '*post-2020 CAP*' scenario is the model projection for an increase in the proportion of fallow land from 2 to 4% of arable land. *'EU Biodiversity strategy*' scenario is the model projection for an increase in the proportion of fallow from 4 to 10% of arable land. Note the varying ranges of the y-axis.



566 Figure 4: Projected absolute changes in bird species richness per German district. Left – projected changes
567 based on the observed changes in the proportion of fallow land between 2007 and 2016. Centre –
568 projected changes based on comparing the 2016 observed proportion of fallow land against the '*post-*
569 *2020 CAP*' scenario with a proportion of fallow land of at least 4% in all districts. Right – projected changes
570 based on observed proportion of fallow land in 2007 against the '*post-2020 CAP*'. See appendix Figure S6
571 for projections of bird abundance.

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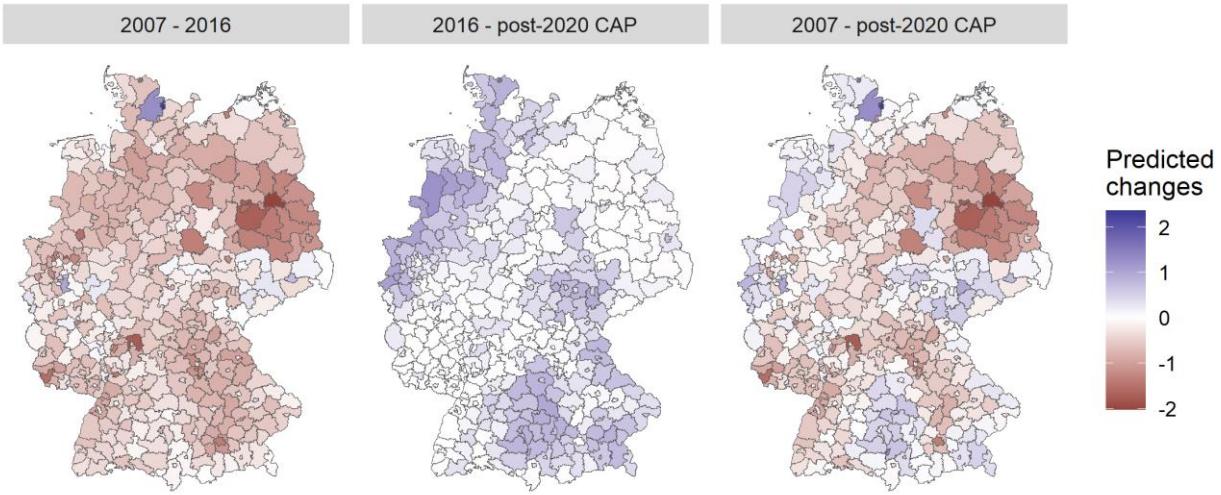

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