Ecological Indicators 150 (2023) 110197

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

A multi-scale analysis on the importance of patch-surroundings for farmland birds

Noëlle Klein [a,b,*], Adrienne Grêt-Regamey [b], Felix Herzog [a], Maarten J. van Strien [b], Sonja Kay [a]

[a] *Agricultural Landscapes and Biodiversity, Agroscope, Reckenholzstrasse 191, 8046 Zurich, Switzerland*

[b] *Chair of Planning of Landscape and Urban Systems (PLUS), Institute for Spatial and Landscape Planning, Department of Civil, Environmental and Geomatic Engineering, ETH Zurich, Stefano-Franscini-Platz 5, 8093 Zurich, Switzerland*

ARTICLE INFO

Keywords:
Agricultural management
Biodiversity
Landscape structure
Land use
Spatial
Landscape elements

ABSTRACT

Agricultural intensification has profoundly changed agricultural landscapes with important biodiversity impacts. There is increasing knowledge on the general effects of landscape structure and management practices on plant and animal species but understanding the role of surrounding landscape structure for patch-scale biodiversity is more complex. While it can be reasonably assumed, that adjacent habitats are more important than more distant ones, the importance of landscape structure has often been tested at the landscape scale but rarely at smaller scales such as patch-surroundings. We assessed the influence and interdependences of landscape composition and configuration (LCC) and land use/land cover (LULC) on bird species richness and abundance through a multi-scale analysis with specific focus on the surrounding patches. In two agricultural regions in Switzerland, we collected point data of birds on 36 transects (500 m) and combined them with detailed spatial data on LULC. Bird richness and abundance were correlated to sets of landscape metrics as proxies for LCC computed at the transect-scale as well as for the patch surroundings. We analysed patch LULC as well as the most important patch-surrounding metrics using generalized linear mixed models. The results illustrate that patch LULC is the most important predictor of bird richness and abundance. Woody structures increase bird richness, followed by extensive management on patch scale. On the transect-scale semi-natural structure and heterogeneous LCCs are beneficial for bird richness and abundance. The effect of patch-surrounding structure LCCs is only small and interacts with patch LULC. Birds in grassland benefit from fallows in the surroundings, while in cropland they tend to respond positively to surrounding extensive grassland. Our results highlight that considering surroundings can help improve patch-based biodiversity assessments, which will then better predict the consequences of farmland management and make the outcome more applicable for practice.

1. Introduction

Agricultural land is a major component of Earth's terrestrial area, making up >30% of land cover and about 50% of habitable land (FAO, 2019). In many western countries, growing urbanization is steadily shrinking this area, putting high pressures on agriculture, which simultaneously needs to ensure food supply for an ever-growing population (FAO, 2018; United Nations Economic and Social Council, 2019). In many western regions, increased agricultural productivity has often been achieved by the use of improved varieties, chemical inputs and modern machines, leading to increased field sizes and yields. These processes negatively influence plant and animal species resulting in strong population declines in the last decades (Hallmann et al., 2017; Knaus et al., 2018). Despite efforts to combat biodiversity loss, the 2020 goals to preserve biodiversity (AICHI CBD targets) have not been met in most countries nor at the global scale (Secretariat of the Convention on Biological Diversity, 2020). To improve the status of biodiversity and to sustain its associated functions and services, we need to be able to reliably understand and predict the impact of land management on farmland biodiversity.

Both land use/cover (LULC) and landscape structure are known to play an important role for farmland biodiversity (Marcacci et al., 2020). Local field-scale management effects as well as larger landscape effects on biodiversity have been thoroughly investigated (e.g. Assandri et al., 2016; Hinsley and Bellamy, 2000; Zingg et al., 2018). Yet, less is known about the intermediate scale, here defined as patch and its immediate

* Corresponding author at: Agricultural Landscapes and Biodiversity, Agroscope, Reckenholzstrasse 191, 8046 Zurich, Switzerland.
E-mail address: nklein@ethz.ch (N. Klein).

https://doi.org/10.1016/j.ecolind.2023.110197
Received 9 June 2022; Received in revised form 11 August 2022; Accepted 28 March 2023
Available online 3 April 2023

surroundings (i.e. 100 m buffers). For example, Martin et al. (2020) investigated the effect of farmland biodiversity in relation to crop diversity and found positive effects on large spatial extent, while on small spatial extent the effects were negative. These contradictory results spotlight the need to understand the intermediate scale. This scale is particularly important for practical issues, as it is the scale of farmers' decision making on management practices as fertilization and pest management (e.g. Pivato et al., 2015; Souza et al., 2015). This scale has rarely been investigated (especially for birds), even though it is assumed that nearby habitats are more important than habitats that are further away (Martin et al. 2020).

The majority of species inhabiting agricultural landscapes depend on a specific landscape composition and configuration (LCC) with specific landscape elements. They need combinations thereof as habitats for nesting, food provisioning or shelter (Chiron et al., 2014; Vickery and Arlettaz, 2012). To assess spatial characteristics of landscapes, various landscape metrics have been developed, describing their composition and configuration (McGarigal and Marks, 1994) and which are extensively used in many studies such as Evelin et al. (2009); Lausch et al. (2015); and Syrbe and Walz (2012). The predictive power of landscape metrics for farmland biodiversity, however, depends on the spatial and thematic resolution (number and type of LULC categories) of the maps that are used (Bailey et al., 2007) and may differ between species groups, depending e.g. on their mobility and activity range (Jeanneret et al., 2003).

Amongst the numerous species groups that constitute farmland biodiversity, birds are a well-monitored species group across Europe and have a long history as bioindicators (Benton et al., 2002; Temple and Wiens, 1989; Zingg et al., 2019). The close link to agriculture and their efficiency as bioindicators makes them suitable study organisms to explore the relationships between agricultural LULC patterns, patch-surrounding landscape structure and species richness (e.g. Borges et al., 2017; Hiron et al., 2015).

Generally, bird richness is higher in non-crop areas, such as hedges, extensive meadows or wildflower strips (Vickery and Arlettaz, 2012). On the broader scale, bird richness increases with higher landscape heterogeneity (Benton et al., 2003). In addition, interactions between patch LULC and surrounding LCC can be assumed. For example, hedges could play a different role for mobile species in grassland landscapes than in arable landscapes. Tschumi et al., (2020), for example, found that in cereal-dominated landscapes, woody structures were more important than semi-natural grasslands for promoting bird richness, although semi-natural grasslands had general positive effects on the landscape-scale. Bird richness, however, depended on the amount of semi-natural habitats at the landscape-scale (and on land use intensity) (Billeter et al., 2008). Thus, even though we know a lot about the impacts of patch-scale and landscape-scale agricultural management on biodiversity (e.g. heterogeneity and semi-natural structures), it is not always clear whether this is actually transferable to smaller scales (i.e. patch-surroundings). Increasing knowledge on the intermediate scale and the importance of surrounding habitats for understanding farmland biodiversity at the patch-scale can help improve impact predictions and make the outcome more applicable for practice.

The aim of our study is to analyse the importance and interdependences of landscape composition and configuration (LCC, landscape) and land use/cover (LULC, patch) on bird species richness and abundance through a multi-scale analysis. We investigate the discrete importance of I) LCC on landscape-scale (transect) and II) LULC on patch-scale. Bringing these results together, we explore the interdependency of III) LCC and LULC at intermediate scale by analysing the effect of patch-surroundings.

2. Methods

In the following, we give an overview of (1) the study areas and the sampling design, (2) the data collection, (3) the computation of the landscape metrics at three different spatial scales, and (4) the statistical analyses. The analyses were conducted on three distinct spatial scales: I) transect (100 m buffer around transect line), II) patch (here often part of an agricultural field) and III) patch-surroundings (100 m buffer around every patch). See Fig. 2 for illustration of the terminology.

2.1. Study areas and sampling design

The study was conducted in two agricultural study regions in Switzerland: The Schwarzbubenland (Canton Solothurn, SO) and the Reuss Valley (Canton Aargau, AG). While the Reuss Valley is a typical lowland landscape mainly composed of arable land and grassland, Schwarzbubenland is a hilly region with a high proportion of grassland and traditional cherry orchards.

In each study region, 18 transects (Fig. 1) of 500 m length were randomly chosen along paths (rural roads with very little traffic). The number of transects was maximised for the region, and transects were selected not to be overlapping, avoiding forest, urbanised area as well as big rivers. Transects were selected to cover the highest possible gradient of land use diversity and to provide a high variance of landscape structure.

2.2. Data collection

2.2.1. Bird data

Bird surveys were conducted three times during the breeding season between mid-April and mid-June 2020 (14.4. – 22.4, 7.5. – 20.5., 2.6. – 13.6.) up to five hours after sunrise (05:47 am – 11:29 am) under favourable conditions (no wind, no rain). The method followed protocols of the Swiss biodiversity monitoring (Schmid et al., 2004) and previous field studies on birds (Assandri et al., 2016; Marcacci et al., 2020). All transects were slowly walked by a single observer (NK) for 20–40 min per transect (as long as it took to map all birds, while keeping a standardized pace). The position of each observed bird inside a buffer of 100 m around each transect was marked on a printed map. The number of bird species (richness) and number of bird individuals (abundance) for each transect were recorded. Survey time and transect order were randomized between the surveys. Subsequently, all observation points were manually digitalized using the software ArcGIS Pro (Version 2.6.0, Esri Inc, 2021).

2.2.2. Land use/land cover (LULC) mapping

LULC (=land use/cover at the patch-scale) was mapped in a 200 m buffer around each transect (Fig. 2). The data were extracted from several map sources originating from cantonal and federal authorities (BLW, 2020). For each study area, detailed spatial information about crop cultivation, management and ecological focus area (EFA) was available at the patch-scale (i.e. a patch with a homogenous LULC, see Fig. 2). Point data of single trees were derived from the Swisstopo TLM vector layer (Bundesamt für Landestopografie, 2020). Maps were verified and completed in the field and then digitalized using aerial images with ArcGIS Pro (Version 2.6.0, Esri Inc., 2021).

LULC classes differed between cantons and were thus not uniform between the two regions. Therefore, they were harmonised and then aggregated to eight classes (woody, non-agricultural, extensive grassland (<5 trees/ha), standard grassland (<5 trees/ha), extensive orchard (>5 trees/ha), standard orchard (>5 trees/ha), fallow, and arable land). See Table 1 for details and explanations of all LULCs.

2.3. Landscape composition and configuration (LCC) indices

LCC (=composition and configuration of landscape) was expressed through a set of indices, computed for transect and patch-surrounding scales. A representative set of different landscape-level and class-level spatial metrics was chosen to evaluate LCC based on Cushman et al. (2008) and calculated for two spatial scales (transect and patch-

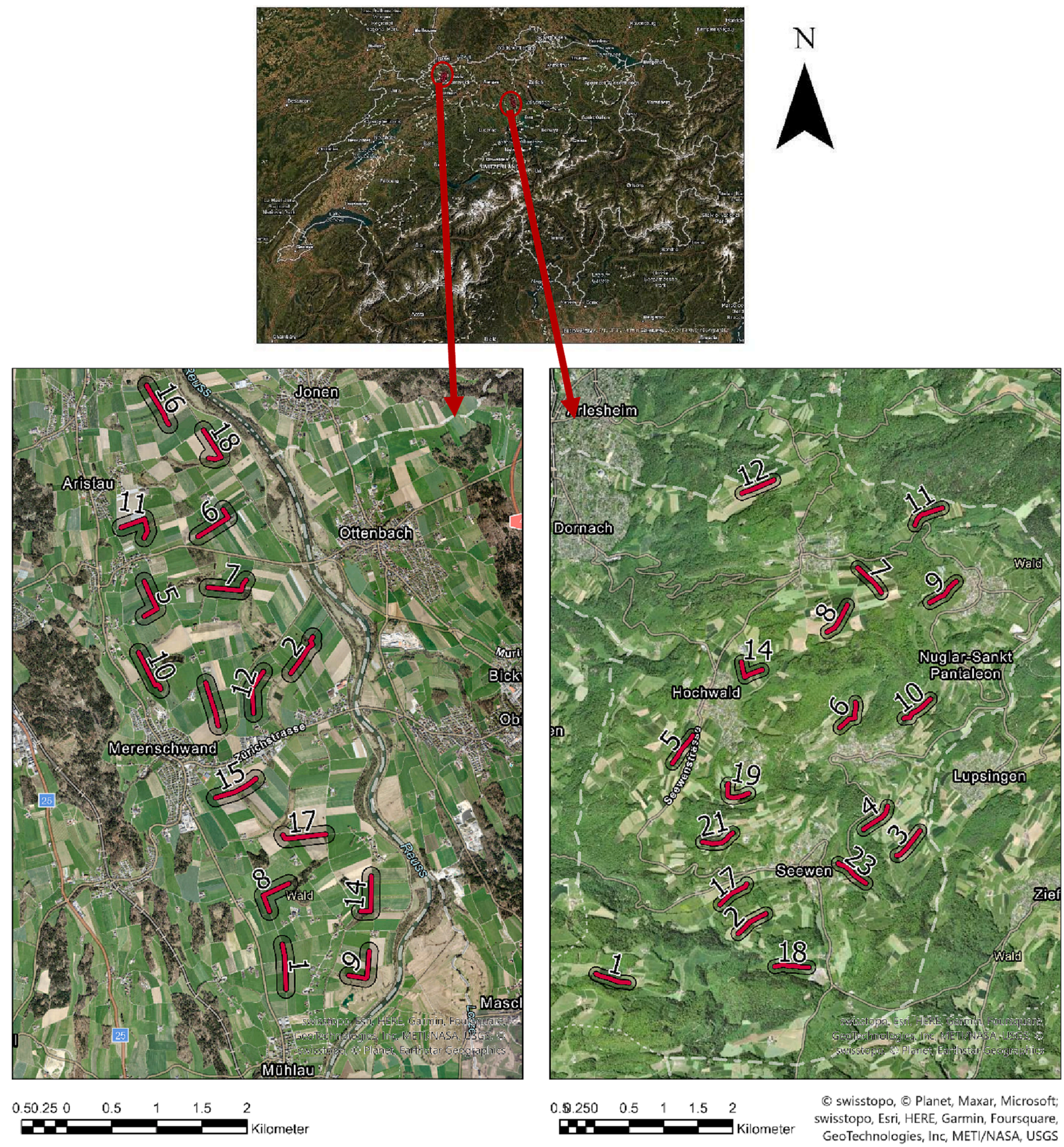

Fig. 1. Overview map of Switzerland with the two study regions, the Reusstal valley (left) and the Schwarzbubenland (right) with all 36 transects depicted.

surrounding). As landscape-level metrics, edge density (ED), largest patch index (LPI), interspersion/juxtaposition index (IJI), and shape index coefficient of variation (shape_CV) were calculated. For each of the eight LULC classes, we also calculated the mean shape index (shape_MN), aggregation index (AI), mean nearest neighbour distance (enn_MN), nearest neighbour distance coefficient of variation (enn_CV), largest patch index (LPI) and edge density (ED) (Table A.1). All metrics were computed with the "sample_lsm" function of the landscape_metrics R package (Hesselbarth, 2021), using polygon-layers (transect/patch-surrounding) on a raster (LULC, 1x1m resolution). First, the metrics were computed for "transects" (n = 36, 100 m buffers around every transect). Second, the same metrics were also computed for "patch-surroundings" (n = 903, 100 m buffers around every single patch). All metrics containing NA values were excluded from further analyses and high correlating metrics were excluded (>0.7).

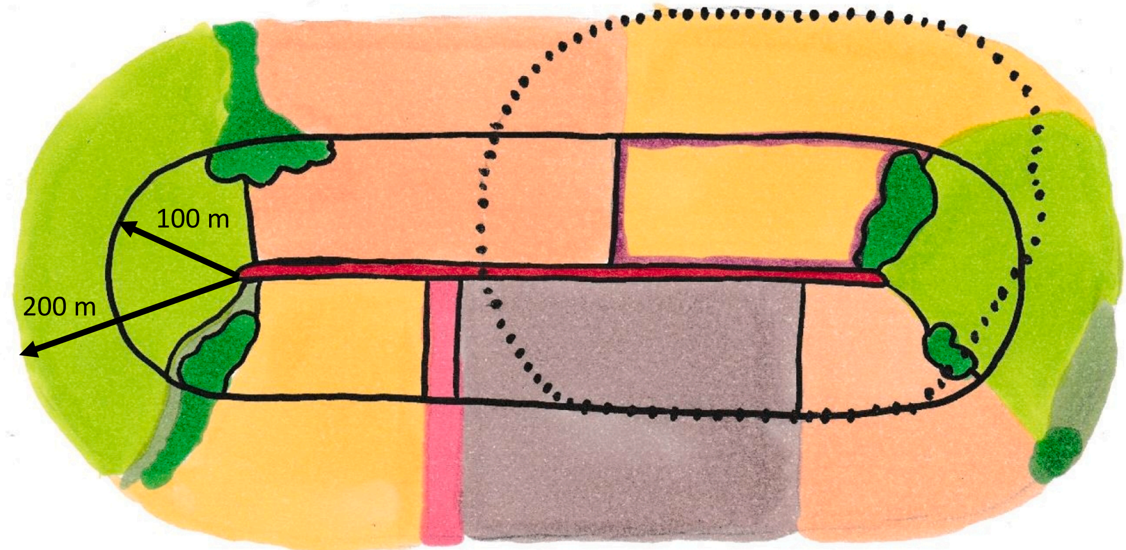

Fig. 2. Conceptual sketch of a transect, indicated as horizontal red line. Separate patches on a 100 m buffer around transects (on which birds were monitored) are delineated with black lines, while colours indicate different LULC classes (patch-scale). Transect-scale metrics were calculated for the 100 m transect buffer (n = 36), and patch-surrounding metrics were calculated on 100 m buffers around individual patches (n = 903). In the example, transect-scale metrics would be calculated for the outer black line, and patch-surrounding metrics would be calculated separately for every patch in this buffer as shown with the dotted line around the orange patch with purple border.

Table 1
LULC variables, short names and description of all explanatory variables included in the analyses. Short names were used as plot labels. N is the number of patches, classified as this specific category, with a total of 903.

Variable	Short	Description	n total
Woody	woody	Hedges, shrubs, big trees with smaller bushes underneath	**116**
Non-agricultural	non-agricultural	Urban, forest, unused land, canals along paths, standing water	**52**
Extensive grassland	ext_grass	Classified as extensively managed by canton, <5 trees per ha	**91**
Standard grassland	grass	Fertile permanent grassland, <5 trees per ha	**117**
Extensive orchard	ext_orchard	Classified as extensively managed by canton, >5 trees per ha	**38**
Standard orchard	orchard	Fertile permanent grassland, >5 trees per ha	**110**
Fallow	fallow	Flower strips, wildflower fallows, litter fields	**37**
Arable land	arable	Crop cultivation (clover, maize, oilseed rape, potatoes, sugar beet, winter cereals, summer cereals, peas, rotational grassland and other crops/grains/arable)	**342**

2.4. Statistical analyses

Bird counts were computed per transect and per patch. On transect-scale, a correlation plot was used to inspect the large-scale interactions between landscape metrics and richness/abundance. At the patch-scale, a generalized linear mixed model was built to investigate the role of LULCs for richness/abundance. For patch-surroundings, correlation plots and generalized linear mixed models were used to assess the relationships between the patch-surrounding metrics and patch richness/abundance separately for the two major agricultural LULCs: arable and grassland. All analyses were conducted using the software R (R Core Team, 2021), see Fig. 3 for an overview of all analyses and results.

2.4.1. LCC and biodiversity at transect-scale

We analysed the relationship between the different landscape-metrics and bird richness and abundance for each transect. To do so, the "corrplot" function of the Hmisc R package (Harrell, 2021) was used to build a correlation plot. As input for the plot, the function "rcorr" (Harrell, 2021) computes Pearson's correlation coefficients with their significance. For our analyses, only correlations with $p < 0.05$ were displayed, and multicollinear metrics (>0.7) with significant relationship to the response variables were removed. To limit complexity and as we focussed our analysis on the patch-surrounding scale, we did not include models for this part of the analysis.

2.4.2. LULC and biodiversity at patch-scale

To analyse the relationship between the eight LULC classes (see Table 1) and bird richness and abundance, we built models with the "glmer" function of the lme4 package (Bates et al., 2022) using richness or abundance as response and LULC as explanatory variable. Region and transect ID were included as nested random factors considering their spatial structure. To account for patch size, area was added using the "offset" function (Aarts et al., 2012; O'Hara and Kotze, 2010). We checked all models for overdispersion ("dispersion_glmer" function of the blmeco package, Korner-Nievergelt et al., 2018) and zero-inflation (comparing model predicted ("predict" function) and observed number of zeros for the model). In case overdispersion was detected in a model, negative binomial distribution was used instead of poisson, using the "glmer.nb" function of lme4 (Bates et al., 2022).

2.4.3. LCC, LULC and biodiversity at patch-surrounding scale

We investigated the relationships between patch-level richness/

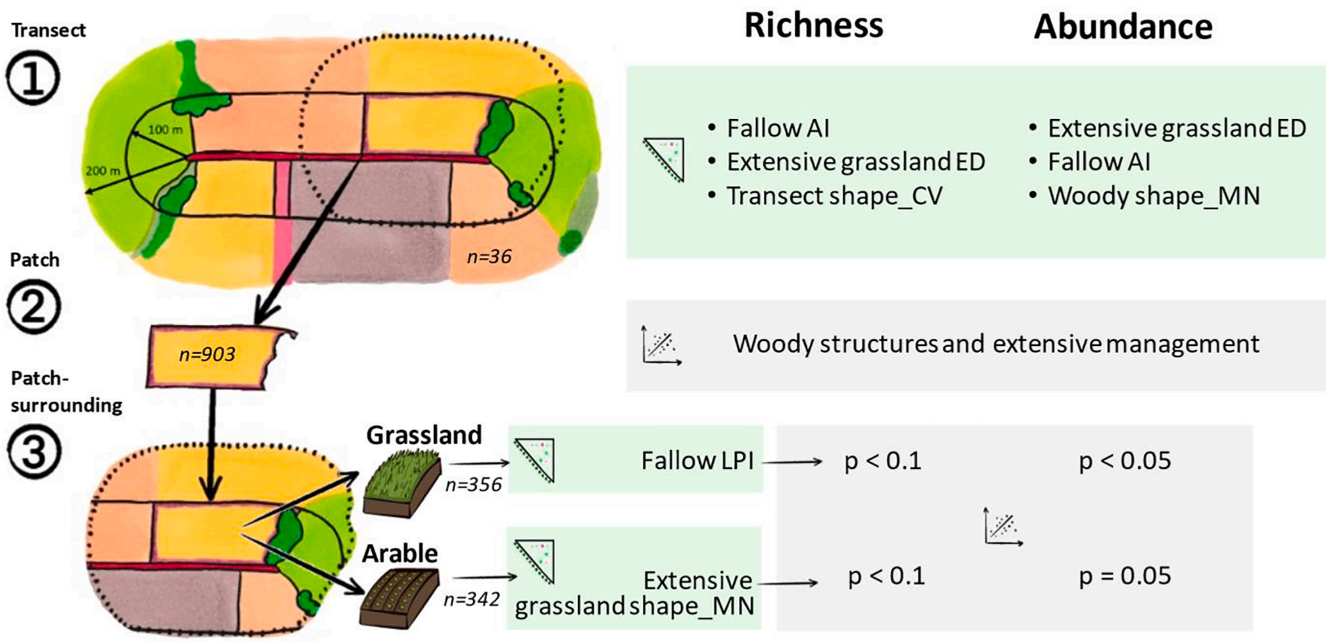

Fig. 3. Overview of the analyses and results for bird richness and abundance on all scales. 1) LCC (spatial metrics) on transect-scale, 2) LULC (land use/cover) on patch-scale and 3) LCC on patch-surrounding scale for grassland and arable land, n = sample size. Correlation analyses are summarized in green boxes, model results in grey boxes.

abundance and the landscape metrics, now computed at the patch surrounding-scale. As summarizing landscape metrics for all LULCs would balance the results out (through varying interactions of LULCs with different landscape metrics), we focussed on the two major land uses for this part of the analysis (arable and grassland). We built two separate correlation plots with the Hmisc package following the above-mentioned method and chose the metrics with the best correlation to richness/abundance.

We then built separate grassland and arable models using the "glmer" function (Bates et al., 2022) with richness/abundance as response, the respective metric as explanatory variable and region/transect ID as nested random factors. Due to the large variance of richness/abundance between different types of grassland, we additionally included grassland LULC (4 categories, Table 1) as predictor in the grassland model.

3. Results

3.1. LULC and bird data

Both regions are dominated by agriculture, with regional differences in the coverage of grasslands and substantial variation of LULC coverages within each region. In Reuss Valley (RV), transects were dominated by arable land (58–94% transect cover), followed by extensive grassland (0.12–26.3%), fallow (0–26.9%), standard grassland (0–21.2%), non-agricultural land (0–11.3%) and woody structures (0–10%). The transects in Schwarzbubenland (SBL) also mainly consist of arable land (0–90.9%) but also standard grassland (7–87.7%), followed by extensive grassland (0–44.0%), non-agricultural (0–11%), woody structures (0.05–10%) and fallow (0–8%).

The bird data consisted of 2783 individual observation points of 61 species (Table A.2). The number of species was comparable between the two regions (RV: 50, SBL: 51), with differences in individual species densities. On the transects, total bird richness ranged from 8 to 22, and total abundance (i.e. number of seen and heard individuals) from 18 to 128. On the individual patches, bird species richness ranged from 0 to 14 species and abundance from 0 to 67 individuals.

3.2. LCC correlation analyses at transect-scale

First, we explored the relationships between transect bird richness/abundance and the LCC metrics computed at the transect-scale. All significant correlations of the landscape metrics (transect ED, IJI, LPI, shape_CV; AI, ED, LPI, shape_MN, enn_MN, enn_CV, for each class) with bird richness/abundance are illustrated in the correlation plot (Fig. A1). There were four significant correlations with richness and five significant correlations for abundance. For richness, the highest correlations were found with fallow AI (0.50), extensive grassland ED (0.41) and transect shape_CV (-0.42). For abundance, the highest correlations were found with extensive grassland ED (0.49), fallow AI (0.48) and woody shape_MN (0.41). In summary, bird richness and abundance at the transect-scale were mainly correlated with each other and an aggregation of fallows (higher AI), the configuration of extensive grassland (higher ED) as well as the shape of patches in the transect (shape_CV).

3.3. LULC and biodiversity analyses at patch-scale

The patch-scale models showed significant effects of LULC class on both, richness and abundance (Table 2, Fig. 3). Both, richness-patch-model, and abundance-patch-model showed highest bird numbers in woody structures, followed by non-agricultural areas and extensive orchards, with lowest abundances in arable land.

All grassland types as well as fallows had higher richness and abundance compared to arable land. For both patch-models, the nested random factor region/transect explained only small proportions of variance, with 0.06 (0.03 only region) for the richness model, respectively 0.09 (0.08 only region) for the abundance model (Table 2). The richness-patch-model (conditional R^2: 0.69) performed better than the abundance-patch-model (conditional R^2: 0.59), but both explained major proportions of variance. Richness was modelled with poisson distribution and abundance with negative binomial, while both final models did not show signs of overdispersion or zero-inflation. In summary, at the patch-scale, LULC is the major predictor of bird richness/abundance (as is apparent from the high conditional R^2 of the models), which explains substantial differences between LULC classes and illustrates a high value of woody and (extensive) orchard LULC classes.

Table 2
Summary of the coefficients of the **patch-scale models** investigating bird richness (BD) and abundance (ABU). Predictors, estimates with confidence intervals and p-values as well as r-squared and random effects are shown, see Table 1 for details and descriptions on the LULC categories.

	BD			ABU		
Predictors	**Estimate**	**CI**	**P**	**Estimate**	**CI**	**P**
(Intercept) Arable	0.00	0.00–0.00	**<0.001**	0.00	0.00–0.00	**<0.001**
Fallow	2.35	1.67–3.30	**<0.001**	1.56	0.94–2.60	0.09
Ext_grass	1.48	1.12–1.95	**<0.05**	1.29	0.89–1.88	0.17
Ext_orchard	3.89	2.82–5.37	**<0.001**	3.92	2.41–6.38	**<0.001**
Grass	1.35	1.05–1.75	**<0.05**	1.28	0.91–1.80	0.16
Orchard	3.02	2.43–3.76	**<0.001**	3.36	2.40–4.70	**<0.001**
Non-agricultural	8.87	7.19–10.94	**<0.001**	7.62	5.15–11.28	**<0.001**
Woody	21.25	18.16–24.87	**<0.001**	21.26	16.18–27.94	**<0.001**
Conditional R^2	0.69			0.59		
Region	0.03			0.08		
Region/transect	0.06			0.09		

3.4. LCC, LULC and biodiversity analyses at patch surrounding-scale

Third, we explored the relationship between bird richness/abundance and LCC patch-surrounding landscape metrics (surrounding ED, LPI, IJI, shape_CV and shape_MN, AI, enn_MN, enn_CV, LPI, ED for each class) through correlation plots and statistical models. The correlation plots for grassland-surroundings (Fig. A2) and arable-surroundings (Fig. A3) show all significant correlations between surrounding landscape metrics and patch richness/abundance (standardized per patch area).

For grassland patches, richness/ha and abundance/ha both showed highest correlation with fallow LPI (both 0.36). For arable land patches, richness/ha and abundance/ha both showed highest correlations with extensive grassland shape_MN (both 0.18), and orchard shape_MN (both −0.18). In summary, surrounding fallow largest patch index (LPI) showed highest correlations with bird richness/abundance of grassland patches, while the surrounding shape_MN of extensive grassland and orchards had contrasting correlations with bird richness and abundance in arable patches.

From the patch-scale analysis, we chose the respective best correlating landscape metric to build the patch-surrounding models: fallow LPI for bird richness and abundance on grassland patches, and extensive grassland shape_MN for bird richness and abundance on arable patches. The abundance surrounding-model found a significant positive effect of higher fallow LPI patch surrounding-scale for grassland, while it was only marginally significant in the richness surrounding-model (Table 3). In addition, as shown in chapter 3.3, the type of grassland patch LULC influenced bird richness and abundance, with higher numbers for extensive orchard and orchard. The nested random factor region/transect explained variances of 0.09 (0.31 only region) for the richness surrounding-model and 0.15 (0.12 only region) for the abundance surrounding-model. As for the patch-scale models, the richness surrounding-model (conditional R^2: 0.52) performed better than the abundance surrounding-model (conditional R^2: 0.36). See Fig. 3 for a summary of the most significant results on all scales.

For the arable subset, richness and abundance surrounding-models both showed a positive trend (marginally non-significant) of higher mean shape index of extensive grasslands patch surrounding-scale for arable land (Table 4). The nested random factor region/transect explained only small variances of 0.06 (0.01 only region) for the richness-surrounding-model and 0.07 (0 only region) for the abundance-surrounding-model. Both arable-surrounding-models had a relatively low explanatory power (conditional R^2: 0.1 for both models). Again, no final model showed signs of overdispersion or zero-inflation. In summary, the chosen metrics with highest correlation to the response variable showed significant effects for both, grassland and arable surrounding-models, but the variance explained by both models is low.

4. Discussion

Our results illustrate that bird richness and abundance are influenced by LCC on transect-scale, and patch-scale LULC, with high importance of extensively managed and unproductive LULCs. Patch-surrounding LCC interact with patch LULC, with positive trends of surrounding fallows for grassland and extensive grasslands for arable land.

4.1. Importance of LCC on transect-scale

We found bird richness and abundance influenced by LULC structure on the transect-scale (mainly configuration of extensive grasslands, ED; aggregation of fallow, AI; and patch compactness, shape_MN). This is supported by previous research on the importance of heterogeneity on different spatial scales (Benton et al., 2003), as well as on beneficial effects of semi-natural areas (such as extensive grassland and fallows; Batáry et al., 2017; Marcacci et al., 2020). In line with our results, findings of Tschumi et al., (2020) highlighted the role of extensive grasslands for birds at the landscape-scale, which is associated with decreased mowing pressure and higher richness of plants and

Table 3
Summary of the coefficients of the **grassland patch-surrounding models** investigating bird richness (BD) and abundance (ABU). Predictors, estimates with confidence intervals and p-values as well as r-squared and random effects are shown, see Table 1 for details and descriptions on the LULC categories. LPI: Largest patch index.

	BD			ABU		
Predictors	**Estimate**	**CI**	**P**	**Estimate**	**CI**	**P**
(Intercept) Ext_grass	0.00	0.00–0.00	**<0.001**	0.00	0.00–0.00	**<0.001**
Ext_orchard	4.51	2.79–7.30	**<0.001**	2.97	1.57–5.63	**<0.05**
Grass	1.55	1.02–2.36	**<0.05**	1.06	0.62–1.83	0.83
Orchard	4.04	2.61–6.26	**<0.001**	2.92	1.64–5.20	**<0.001**
Fallow LPI	1.02	1.00–1.04	0.08	1.03	1.00–1.06	**<0.05**
Conditional R^2	0.52			0.34		
Region	0.31			0.12		
Region/transect	0.09			0.15		

Table 4
Summary of the coefficients of the **arable patch-surrounding model** investigating bird richness (BD) and abundance (ABU). Predictors, estimates with confidence intervals and p-values as well as r-squared and random effects are shown. Shape_MN: mean shape index.

	BD			ABU		
Predictors	**Estimate**	**CI**	**P**	**Estimate**	**CI**	**P**
(Intercept)	0.00	0.00–0.00	**<0.001**	0.00	0.00–0.00	**<0.001**
Ext_grass shape_MN	1.09	0.99–1.19	0.08	1.19	1.00–1.42	0.05
Conditional R^2	0.10			0.11		
Region	0.01			0.00		
Region/transect	0.06			0.07		

invertebrates. Grasslands currently defined as “extensive” still provide a high value for generalized bird richness and abundance (Eggenberg et al., 2001; Masé, 2005) and their actual configuration in the landscape is important, as illustrated by the positive effect of extensive grassland ED on bird richness/abundance. Richness and abundance were correlated with higher fallow aggregation (AI) and shape compactness (shape_MN), indicating that the spatial arrangement of fallows can influence bird richness and abundance. This result is in line with recent findings of Schoch et al. (2022), who found that flower strips have interacting effects with the surrounding landscape and are more beneficial if surrounded by high-quality semi-natural areas. Richness as well as abundance also increased with compactness of patches (shape_CV), potentially associated with higher landscape heterogeneity (i.e. more compact patches), known to positively affect birds (Vickery and Arlettaz, 2012).

4.2. Importance of LULC for biodiversity at patch-scale

At patch-scale, highest bird richness and abundance were recorded in woody structures. Woody structures are known to play an important role for biodiversity in agricultural land (Hinsley and Bellamy, 2000; Maskell et al., 2019), providing habitat to build nests, find food, or shelter (Knaus et al., 2018). The second highest richness and abundance values were found in non-agricultural areas, which in our study consisted of farmsteads, small patches of forest, unused land, canals along paths, standing water and villages. Several of these have high biodiversity values, such as forests and standing waters, small natural areas with ponds that attract water-bound species (Skórka et al., 2006). As this study focuses on farmland, we did not investigate non-agricultural patches in detail, but the relatively high bird numbers indicate that they play a role for many common bird species. The third highest richness and abundance were found in extensive orchards. In line with the high values for woody structures, higher tree counts in both extensive and other grasslands were associated with higher bird richness and abundance, similar to recent findings in grasslands with more trees (Ernst et al., 2017). The results also fit previous findings on the value of extensively managed grasslands and again confirm the importance of maintaining extensive grasslands (Assandri et al., 2019; Klein et al., 2020). In addition, fallows, namely flower strips, wildflower fallows and litter fields were recorded to have higher bird richness and abundance than arable land. This is in line with other studies that highlight the role of such structures for birds, while their actual effectiveness varies depending on the bird species (Birrer et al., 2007). Nevertheless, compared to woody structures, their overall effect seems to be modest. Yet, those differences should not be over-interpreted, as many birds require multiple habitats, e.g. using woody areas as shelter, while fallows primarily act as potential food resources. Lastly, lowest bird richness and abundance were observed in arable fields. In contrast to woody structures or trees, the structure of arable fields is more variable across the year. Starting with bare ground or low vegetation in winter, crops develop during summer or autumn. Crop fields are frequently disturbed during the season by management activities such as weed control, pest management and harvesting. Although some species are adapted to e.g. nesting in crops, such as the fieldlark (*Alauda arvensis*), most species require semi-natural habitats, or combinations of semi-natural habitats with crop fields or intensively managed grassland (Jeanneret et al., 2021). The LULC models explained major proportions of variance, indicating that local LULC is the most important factor for richness/abundance of birds, as supported by previous research (Concepción et al., 2012).

4.3. Interdependences of LCC/LULC and biodiversity at patch surrounding-scale

4.3.1. Grassland patches

The metrics describing dominance and spatial configuration of fallows (LPI, ED) showed considerably higher correlations with grassland richness and abundance than all other metrics. In addition to the correlation analysis for grassland patch-surroundings, the grassland surrounding-model showed significant differences between grassland types, illustrating positive effects of extensive management and more trees, as shown by the patch LULC model. The grassland patch-surrounding model was the only model with a substantial amount of variance explained by the random factors region and transect, in line with the higher number of (extensive) grasslands in the Schwarzbubenland region. The grassland-surrounding-model showed that bird abundance (and richness marginally) increased when fallows were more dominant on the patch surrounding-scale, even though fallows were not among the LULC classes with highest richness/abundance on patch-level. Therefore, fallows can potentially foster birds in grassland, presumably by providing food resources and shelter in their surroundings. Previous research has also shown other examples where surroundings can have positive effects on specific structures, such as hedgerows when combined with wildflower strips (Hinsley and Bellamy, 2000). Fallows had positive effects on both spatial scales, transects and patch-surroundings, supporting recent findings on the beneficial effects of (high quality) ecological focus areas on local and landscape-scale biodiversity (Schoch et al., 2022; Zingg et al., 2019).

4.3.2. Arable patches

Bird richness/abundance positively correlated with extensive grassland shape_MN, again highlighting the importance of extensive grasslands (Eggenberg et al., 2001; Masé, 2005), although the effects were not statistically significant in the models. Extensive grasslands provide high value habitats for many bird species and seem to have “spillover” effects on arable land in their surroundings, especially if they have a compact shape. In line with this, recent studies have called for diversifying agricultural landscapes through a mosaic combination of grasslands with arable land (e.g. Bretagnolle et al., 2018), which would be beneficial for landscape biodiversity on different trophic levels. Compared to the grassland surrounding LCC metrics, the correlation coefficients were quite low, which could be explained by the lower bird numbers as well as a bigger temporal and structural variance in arable land compared to grasslands.

5. Limitations

We analysed our data on patch and transect-scale to get a close link to agricultural management units while being able to compare the respective surroundings. This scale is reasonable for such analyses, especially in combination with landscape metrics (Morelli et al., 2013), and has often been used in previous studies (e.g. Assandri et al., 2016; Marcacci et al., 2020). The approach provides information that can be used for patch-based biodiversity indicators, such as LCA approaches (Souza et al., 2015) and comprehensive modelling approaches (Duru et al., 2015). A drawback of this method is the simplification when summarizing all observations per patch and summing up all species to one richness and abundance score, which does not allow to test for species-specific patterns (i.e. habitat preferences (i.e. Theux et al., 2022), but also detectability (i.e., Sanz-Pérez et al., 2020), rarefaction curves (i.e. Katayama, 2016)). Such single-species analyses could be explored in future studies to complement our results. We thus draw conclusions benefitting the majority of species, while they do not always benefit all individual species (e.g. fieldlark preferring open habitat over woody (Knaus et al., 2018)). Even though we analysed fine spatial scales, some small-scaled elements, which can influence birds, such as piles of stones or branches, pylons or road signs, could not be accounted for (Pustkowiak et al., 2021).

5.1. Potential for practical application

Statistical models can be used to predict habitat suitability for selected species (Guisan et al., 2013), investigate efficient placement of protected areas (Vincent et al., 2019), analyse the impact of land use change on species richness (Zebisch et al., 2004), or compare specific management options (Humbert et al., 2010). Nevertheless, it remains challenging to develop predictions and models that can be extrapolated and applied outside specific case studies (Duru et al., 2015), especially when these are spatially-explicit or operating at multiple spatial scales. We show that across regions, patch LULC is the most important factor to describe patch bird richness and abundance. Birds as mobile species are influenced by the LCC of agricultural landscapes, with positive effects of semi-natural structures (fallow AI, extensive grassland ED) and heterogeneity (shape_CV), at the transect-scale. These findings are in line with numerous studies on the biodiversity benefits in agriculture through active promotion of natural habitats and increased heterogeneity at the landscape-scale (Tscharntke et al., 2021).

Our investigations of the importance of surrounding habitats for predicting bird richness and abundance showed that they indeed contribute to explaining bird occurrence, even for such a mobile species group. The results underline the importance of considering the spatial context on different scales and show that surroundings have interacting effects with patch LULC, as shown also by other studies (Schoch et al., 2022; Tschumi et al., 2020). While the effects are small, as compared to patch and transect-scale, taking them into account can improve the prediction of birds on individual patches at the scale at which farmers actually operate. Individual farm and landscape management actors thus have the potential to improve patch-scale biodiversity.

6. Conclusion

Our study uses high-resolution species, LCC and LULC data to study the importance of patch-surrounding structure as a driver of biodiversity by investigating different spatial scales: landscape/transect, patch, and patch-surroundings. We show that suitable habitat (LULC) on patch-scale is the most important factor explaining bird richness and abundance. In addition, the structure of different habitat types (LCC) at transect-scale plays an important role, as birds are mobile species that move between different types of LULC. On transect-scale, most of the avian community benefits from landscape elements such as extensive grassland or fallows, as well as increased landscape heterogeneity. The influence of patch-surroundings on individual patches depends on their respective LULC. There is a positive trend on birds with nearby fallows for grasslands and nearby extensive grasslands for arable land. The results show the potential of integrating patch-surroundings into patch-scale bird predictions. Even though the effects are rather weak, adding high-resolution data on patch-surroundings can help improve biodiversity models, which ultimately inform farmers and decision makers.

Our results support the high importance of landscape structure and heterogeneity (LCC) for birds in different landscapes and at different spatial scales, thus highlighting the need for their inclusion in biodiversity models. They illustrate the high complexity of agricultural landscapes which add together a huge variety of entangled unique interactions between biodiversity and specific components of the landscape, that need to be considered on different spatial scales. Considering surroundings can help improve patch-based biodiversity assessments, which will then also better predict e.g. the consequences of agricultural management and agricultural policies. Adding context-based spatial information and disentangling components into standardized classifications that need to be considered on different spatial scales and by application of different indicators could provide huge benefits and a clear step forward to enhanced biodiversity prediction to better foster biodiversity.

CRediT authorship contribution statement

Noëlle Klein: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **Adrienne Grêt-Regamey:** Methodology, Writing – review & editing, Supervision. **Felix Herzog:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Maarten J. van Strien:** Methodology, Writing – review & editing, Supervision. **Sonja Kay:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Acknowledgements

Thanks to Aline Lüscher for her help with fieldwork and to Laura Bosco for her support with the landscape metrics analyses.

Funding

This work was part of the SALBES project funded through the 2017-2018 Joint BiodivERsA-Belmont Forum Call on “Scenarios of Biodiversity and Ecosystem services” (Grant: BiodivScen-157). Some co-authors were financially supported through the EMPHASES project funded by the Swiss National Science Foundation (Grant nr. 200021_192018), and the ValPar.ch project funded by the Swiss Federal Office for the Environment (FOEN) // Swiss Government under the project “ValPar.CH: Values of the ecological infrastructure in Swiss parks” of the Action Plan of the Swiss Biodiversity Strategy // under the Action Plan of the Swiss Biodiversity Strategy (pilot project A1.2).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.110197.

References

Aarts, G., Fieberg, J., Matthiopoulos, J., 2012. Comparative interpretation of count, presence-absence and point methods for species distribution models. Methods Ecol. Evol. 3, 177–187. https://doi.org/10.1111/j.2041-210X.2011.00141.x.

Assandri, G., Bogliani, G., Pedrini, P., Brambilla, M., 2016. Diversity in the monotony? Habitat traits and management practices shape avian communities in intensive vineyards. Agric. Ecosyst. Environ. 223, 250–260. https://doi.org/10.1016/j.agee.2016.03.014.

Assandri, G., Bogliani, G., Pedrini, P., Brambilla, M., 2019. Toward the next Common Agricultural Policy reform: determinants of avian communities in hay meadows reveal current policy's inadequacy for biodiversity conservation in grassland ecosystems. J. Appl. Ecol. https://doi.org/10.1111/1365-2664.13332.

Bailey, D., Billeter, R., Aviron, S., Schweiger, O., Herzog, F., 2007. The influence of thematic resolution on metric selection for biodiversity monitoring in agricultural landscapes. Landsc. Ecol. 22, 461–473. https://doi.org/10.1007/s10980-006-9035-9.

Batáry, P., Gallé, R., Riesch, F., Fischer, C., Dormann, C.F., Mußhoff, O., Császár, P., Fusaro, S., Gayer, C., Happe, A.K., Kurucz, K., Molnár, D., Rösch, V., Wietzke, A., Tscharntke, T., 2017. The former Iron Curtain still drives biodiversity-profit trade-offs in German agriculture. Nat. Ecol. Evol. 1, 1279–1284. https://doi.org/10.1038/s41559-017-0272-x.

Bates, D., Maechler, M., Bolker, B., Walker, S., Christensen, R.H.B., Singmann, H., Dai, B., Scheipl, F., Grothendieck, G., Green, P., Fox, J., Bauer, A., Krivitsky, P.N., 2022. Package 'lme4', Linear Mixed-Effects Models using "Eigen" and S4.

Benton, T.G., Bryant, D.M., Cole, L., Crick, H.Q.P., 2002. Linking agricultural practice to insect and bird populations: a historical study over three decades. J. Appl. Ecol. 39, 673–687. https://doi.org/10.1046/j.1365-2664.2002.00745.x.

Benton, T.G., Vickery, J.A., Wilson, J.D., 2003. Farmland biodiversity: is habitat heterogeneity the key? Trends Ecol. Evol. 18, 182–188. https://doi.org/10.1016/S0169-5347(03)00011-9.

Billeter, R., Liira, J., Bailey, D., Bugter, R., Arens, P., Augenstein, I., Aviron, S., Baudry, J., Bukacek, R., Burel, F., Cerny, M., De Blust, G., De Cock, R., Diekötter, T., Dietz, H., Dirksen, J., Dormann, C., Durka, W., Frenzel, M., Hamersky, R., Hendrickx, F., Herzog, F., Klotz, S., Koolstra, B., Lausch, A., Le Coeur, D., Maelfait, J.P., Opdam, P., Roubalova, M., Schermann, A., Schermann, N., Schmidt, T., Schweiger, O., Smulders, M.J.M., Speelmans, M., Simova, P., Verboom, J., Van Wingerden, W.K.R.E., Zobel, M., Edwards, P.J., 2008. Indicators for biodiversity in agricultural landscapes: a pan-European study. J. Appl. Ecol. 45, 141–150. https://doi.org/10.1111/j.1365-2664.2007.01393.x.

Birrer, S., Spiess, M., Herzog, F., Jenny, M., Kohli, L., Lugrin, B., 2007. The Swiss agri-environment scheme promotes farmland birds: But only moderately. J. Ornithol. 148 https://doi.org/10.1007/s10336-007-0237-y.

BLW, 2020. Nutzungsflächen - Minimale Geodatenmodelle Landwirtschaftliche Bewirtschaftung [WWW Document]. URL https://geodienste.ch/services/lwb_nutzungsflaechen.

Borges, F., Glemnitz, M., Schultz, A., Stachow, U., 2017. Assessing the habitat suitability of agricultural landscapes for characteristic breeding bird guilds using landscape metrics. Environ. Monit. Assess. 189 https://doi.org/10.1007/s10661-017-5837-2.

Bretagnolle, V., Siriwardena, G., Miguet, P., Henckel, L., Kleijn, D., 2018. Local and landscape scale effects of heterogeneity in shaping bird communities and population dynamics: Crop-grassland interactions, Agroecosystem Diversity: Reconciling Contemporary Agriculture and Environmental Quality. Elsevier Inc. https://doi.org/10.1016/B978-0-12-811050-8.00014-5.

Bundesamt für Landestopografie, 2020. SwissALTI3D - Das Topografische Landschaftsmodell TLM [WWW Document]. URL https://shop.swisstopo.admin.ch/de/.

Chiron, F., Chargé, R., Julliard, R., Jiguet, F., Muratet, A., 2014. Pesticide doses, landscape structure and their relative effects on farmland birds. Agric. Ecosyst. Environ. 185, 153–160. https://doi.org/10.1016/j.agee.2013.12.013.

Concepción, E.D., Díaz, M., Kleijn, D., Báldi, A., Batáry, P., Clough, Y., Gabriel, D., Herzog, F., Holzschuh, A., Knop, E., Marshall, E.J.P., Tscharntke, T., Verhulst, J., 2012. Interactive effects of landscape context constrain the effectiveness of local agri-environmental management. J. Appl. Ecol. 49, 695–705. https://doi.org/10.1111/j.1365-2664.2012.02131.x.

Cushman, S.A., McGarigal, K., Neel, M.C., 2008. Parsimony in landscape metrics: Strength, universality, and consistency. Ecol. Indic. 8, 691–703. https://doi.org/10.1016/j.ecolind.2007.12.002.

Duru, M., Therond, O., Martin, G., Martin-Clouaire, R., Magne, M.A., Justes, E., Journet, E.P., Aubertot, J.N., Savary, S., Bergez, J.E., Sarthou, J.P., 2015. How to implement biodiversity-based agriculture to enhance ecosystem services: a review. Agron. Sustain. Dev. 35, 1259–1281. https://doi.org/10.1007/s13593-015-0306-1.

Eggenberg, S., Dalang, T., Dipner, M., Mayer, C., 2001. Cartography and evaluation of dry grasslands sites of national importance. Nat. Landsc. Tech. Report, Environ. Ser., p. 325

Ernst, L.M., Tscharntke, T., Batáry, P., 2017. Grassland management in agricultural vs. forested landscapes drives butterfly and bird diversity. Biol. Conserv. 216, 51–59.

Esri Inc., 2021. ArcGIS Pro (Version 2.6.0).

Evelin, U., Marc, A., Juri, R., Riho, M., 2009. Landscape metrics and indices: an overview of their use in landscape research. Living Rev. Landsc. Res. 3, 1–28.

FAO, 2018. The future of food and agriculture - Alternative pathways to 2050 [WWW Document].

FAO, 2019. FAOSTAT [WWW Document]. Stat. Div. URL http://www.fao.org/faostat/en/#data/FBS.

Guisan, A., Tingley, R., Baumgartner, J.B., Naujokaitis-Lewis, I., Sutcliffe, P.R., Tulloch, A.I.T., Regan, T.J., Brotons, L., Mcdonald-Madden, E., Mantyka-Pringle, C., Martin, T.G., Rhodes, J.R., Maggini, R., Setterfield, S.A., Elith, J., Schwartz, M.W., Wintle, B.A., Broennimann, O., Austin, M., Ferrier, S., Kearney, M.R., Possingham, H.P., Buckley, Y.M., 2013. Predicting species distributions for conservation decisions. Ecol. Lett. 16, 1424–1435. https://doi.org/10.1111/ele.12189.

Hallmann, C.A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., Stenmans, W., Müller, A., Sumser, H., Hörren, T., Goulson, D., de Kroon, H., 2017. More than 75 percent decline over 27 years in total flying insect biomass in protected areas. PLoS One 12, 1–21. https://doi.org/10.1371/journal.pone.0185809.

Harrell, F.E.J., 2021. Package 'Hmisc ', Harrell Miscellaneous.

Hesselbarth, M.H.K., 2021. landscapemetrics: Landscape Metrics for Categorical Map Patterns, R package version 1.5.3.

Hinsley, S.A., Bellamy, P.E., 2000. The influence of hedge structure, management and landscape context on the value of hedgerows to birds: A review. J. Environ. Manage. 60, 33–49. https://doi.org/10.1006/jema.2000.0360.

Hiron, M., Berg, Å., Eggers, S., Berggren, Å., Josefsson, J., Pärt, T., 2015. The relationship of bird diversity to crop and non-crop heterogeneity in agricultural landscapes. Landsc. Ecol. 30, 2001–2013. https://doi.org/10.1007/s10980-015-0226-0.

Humbert, J.Y., Ghazoul, J., Richner, N., Walter, T., 2010. Hay harvesting causes high orthopteran mortality. Agric. Ecosyst. Environ. 139, 522–527. https://doi.org/10.1016/j.agee.2010.09.012.

Jeanneret, P., Schüpbach, B., Luka, H., 2003. Quantifying the impact of landscape and habitat features on biodiversity in cultivated landscapes. Agric. Ecosyst. Environ. 98, 311–320. https://doi.org/10.1016/S0167-8809(03)00091-4.

Jeanneret, P., Lüscher, G., Schneider, M.K., Pointereau, P., Arndorfer, M., Bailey, D., Balázs, K., Báldi, A., Choisis, J.-P., Dennis, P., Diaz, M., Eiter, S., Elek, Z., Fjellstad, W., Frank, T., Friedel, J.K., Geijzendorffer, I.R., Gillingham, P., Gomiero, T., Jerkovich, G., Jongman, R.H.G., Kainz, M., Kovács-Hostyánszki, A., Moreno, G., Nascimbene, J., Oschatz, M.-L., Paoletti, M.G., Sarthou, J.-P., Siebrecht, N., Sommaggio, D., Wolfrum, S., Herzog, F., 2021. An increase in food production in Europe could dramatically affect farmland biodiversity. Commun. Earth Environ. 2, 1–8. https://doi.org/10.1038/s43247-021-00256-x.

Katayama, N., 2016. Bird diversity and abundance in organic and conventional apple orchards in northern Japan. Sci. Rep. 6, 1–7. https://doi.org/10.1038/srep34210.

Klein, N., Theux, C., Arlettaz, R., Jacot, A., Pradervand, J.N., 2020. Modeling the effects of grassland management intensity on biodiversity. Ecol. Evol. 10, 13518–13529. https://doi.org/10.1002/ece3.6957.

Knaus, P., Antoniazza, S., Wechsler, S., Guélat, J., Kéey, M., Strebel, N., Sattler, T., 2018. Schweizer Brutvogelatlas 2013–2016. Verbreitung und Bestandsentwicklung der Vögel in der Schweiz und im Fürstentum Liechtenstein. Swiss Ornithological Institute, Sempach.

Korner-Nievergelt, F., Roth, T., von Felten, S., Guelat, J., Almasi, B., Korner-Nievergelt, P., 2018. Package 'blmeco'.

Lausch, A., Blaschke, T., Haase, D., Herzog, F., Syrbe, R.U., Tischendorf, L., Walz, U., 2015. Understanding and quantifying landscape structure - A review on relevant process characteristics, data models and landscape metrics. Ecol. Modell. 295, 31–41. https://doi.org/10.1016/j.ecolmodel.2014.08.018.

Marcacci, G., Gremion, J., Mazenauer, J., Sori, T., Kebede, F., Ewnetu, M., Christe, P., Arlettaz, R., Jacot, A., 2020. Large-scale versus small-scale agriculture: Disentangling the relative effects of the farming system and semi-natural habitats on birds' habitat preferences in the Ethiopian highlands. Agric. Ecosyst. Environ. 289 https://doi.org/10.1016/j.agee.2019.106737.

Martin, A.E., Collins, S.J., Crowe, S., Girard, J., Naujokaitis-Lewis, I., Smith, A.C., Lindsay, K., Mitchell, S., Fahrig, L., 2020. Effects of farmland heterogeneity on biodiversity are similar to—or even larger than—the effects of farming practices. Agric. Ecosyst. Environ. 288, 106698 https://doi.org/10.1016/j.agee.2019.106698.

Masé, G., 2005. The management of dry grassland in Switzerland. A Swiss federal program and its local practical application. Biotechnol. Agron. Soc. Environ. 9, 133–138.

Maskell, L.C., Botham, M., Henrys, P., Jarvis, S., Maxwell, D., Robinson, D.A., Rowland, C.S., Siriwardena, G., Smart, S., Skates, J., Tebbs, E.J., Tordoff, G.M., Emmett, B.A., 2019. Exploring relationships between land use intensity, habitat heterogeneity and biodiversity to identify and monitor areas of High Nature Value farming. Biol. Conserv. 231, 30–38. https://doi.org/10.1016/j.biocon.2018.12.033.

McGarigal, K., Marks, B.J., 1994. FRAGSTATS: spatial pattern analysis program for quantifying landscape structure, Version 2.0. USDA For. Serv. Gen. Tech. Rep. PNW.

Morelli, F., Pruscini, F., Santolini, R., Perna, P., Benedetti, Y., Sisti, D., 2013. Landscape heterogeneity metrics as indicators of bird diversity: Determining the optimal spatial scales in different landscapes. Ecol. Indic. 34, 372–379. https://doi.org/10.1016/j.ecolind.2013.05.021.

O'Hara, R.B., Kotze, D.J., 2010. Do not log-transform count data. Methods Ecol. Evol. 1, 118–122.

Pivato, A., Barausse, A., Zecchinato, F., Palmeri, L., Raga, R., Lavagnolo, M.C., Cossu, R., 2015. An integrated model-based approach to the risk assessment of pesticide drift from vineyards. Atmos. Environ. 111, 136–150. https://doi.org/10.1016/j.atmosenv.2015.04.005.

Pustkowiak, S., Kwieciński, Z., Lenda, M., Żmihorski, M., Rosin, Z.M., Tryjanowski, P., Skórka, P., 2021. Small things are important: the value of singular point elements for birds in agricultural landscapes. Biol. Rev. 96, 1386–1403. https://doi.org/10.1111/brv.12707.

R Core Team, 2021. R: A Language and Environment for Statistical Computing, Version 4.1.2.

Sanz-Pérez, A., Sollmann, R., Sardà-Palomera, F., Bota, G., Giralt, D., 2020. The role of detectability on bird population trend estimates in an open farmland landscape. Biodivers. Conserv. 29, 1747–1765. https://doi.org/10.1007/s10531-020-01948-0.

Schmid, H., Zbinden, N., Keller, V., 2004. Überwachung der Bestandsentwicklung häufiger Brutvögel in der Schweiz.

Schoch, K., Tschumi, M., Lutter, S., Ramseier, H., Zingg, S., 2022. Competition and facilitation effects of semi-natural habitats drive total insect and pollinator abundance in flower strips. Front. Ecol. Evol. 10, 1–11. https://doi.org/10.3389/fevo.2022.854058.

Secretariat of the Convention on Biological Diversity, 2020. Global Biodiversity Outlook 5. Montreal.

Skórka, P., Martyka, R., Wójcik, J.D., 2006. Species richness of breeding birds at a landscape scale: Which habitat type is the most important? Acta Ornithol. 41, 49–54. https://doi.org/10.3161/068.041.0111.

Souza, D.M., Teixeira, R.F.M., Ostermann, O.P., 2015. Assessing biodiversity loss due to land use with Life Cycle Assessment: are we there yet? Glob. Chang. Biol. 21, 32–47. https://doi.org/10.1111/gcb.12709.

Syrbe, R.U., Walz, U., 2012. Spatial indicators for the assessment of ecosystem services: Providing, benefiting and connecting areas and landscape metrics. Ecol. Indic. 21, 80–88. https://doi.org/10.1016/j.ecolind.2012.02.013.

Temple, S.A., Wiens, J.A., 1989. Bird populations and environmental changes: can birds be bio-indicators? Am. Birds 43, 260–270.

Theux, C., Klein, N., Garibaldi, E., Jacot, A., Eichhorn, S., Guisan, A., Pradervand, J.N., 2022. Food and habitats requirements of the Eurasian Scops Owl (Otus scops) in Switzerland revealed by very high-resolution multi-scale models. Ibis (Lond. 1859). 164, 240–254. https://doi.org/10.1111/ibi.13007.

Tscharntke, T., Grass, I., Wanger, T.C., Westphal, C., Batáry, P., 2021. Beyond organic farming – harnessing biodiversity-friendly landscapes. Trends Ecol. Evol. 2877, 1–12. https://doi.org/10.1016/j.tree.2021.06.010.

Tschumi, M., Birkhofer, K., Blasiusson, S., Martin, J., Smith, H.G., Ekroos, J., 2020. Woody elements benefit bird diversity to a larger extent than semi-natural grasslands in cereal-dominated landscapes. Basic Appl. Ecol. 46, 15–23. https://doi.org/10.1016/j.baae.2020.03.005.

United Nations Economic and Social Council, 2019. ECOSOC – Economic And Social Council. https://doi.org/10.1163/ej.9789004180048.i-962.115.

Vickery, J., Arlettaz, R., 2012. The importance of habitat heterogeneity at multiple scales for birds in European agricultural landscapes, in: Birds and Habitat: Relationships in Changing Landscapes. pp. 177–204.

Vincent, C., Fernandes, R.F., Cardoso, A.R., Broennimann, O., Di Cola, V., D'Amen, M., Ursenbacher, S., Schmidt, B.R., Pradervand, J.N., Pellissier, L., Guisan, A., 2019. Climate and land-use changes reshuffle politically-weighted priority areas of mountain biodiversity. Glob. Ecol. Conserv. 17, e00589.

Zebisch, M., Wechsung, F., Kenneweg, H., 2004. Landscape response functions for biodiversity - Assessing the impact of land-use changes at the county level. Landsc. Urban Plan. 67, 157–172. https://doi.org/10.1016/S0169-2046(03)00036-7.

Zingg, S., Grenz, J., Humbert, J.Y., 2018. Landscape-scale effects of land use intensity on birds and butterflies. Agric. Ecosyst. Environ. 267, 119–128. https://doi.org/10.1016/j.agee.2018.08.014.

Zingg, S., Ritschard, E., Arlettaz, R., Humbert, J.Y., 2019. Increasing the proportion and quality of land under agri-environment schemes promotes birds and butterflies at the landscape scale. Biol. Conserv. 231, 39–48. https://doi.org/10.1016/j.biocon.2018.12.022.