

Agricultural systems and biodiversity: evidence from European borders and bird populations

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ABSTRACT

Countries' agricultural systems have an important impact on biodiversity, for example bird populations. Here, we estimate such impacts by exploiting a natural experiment in the middle of Europe, where there is a naturally homogenous area that is divided into three countries: Switzerland, Germany, and France. These countries have markedly different agricultural systems and policies. Using a methodologically unified and unusually rich bird dataset available across these borders, both for the 2010s and 1990s, we analyze (a) whether there is a clear pattern that bird diversity systematically changes when crossing these borders and (b) whether this has changed over time. To assess bird populations, we focus on Shannon diversity, species richness and number of territories, as well as the individual effect on 29 common bird species. We find that Switzerland has systematically smaller and less diverse bird populations compared to Germany and France, driven entirely by agricultural differences. At the same time, we find that the difference between the countries was considerably more pronounced in the 1990s than in the 2010s. Yet, to reach the bird friendliness of Switzerland's neighboring countries, additional policy effort seems required, for example in the form of targeted agri-environmental payments.

1. Introduction

Biodiversity loss is currently among the most important sustainability challenges (Cardinale et al., 2012; IPBES, 2019), as recognized in the recent Kunming-Montreal Global Biodiversity Framework (UN, 2022), and it is clear that new approaches in many areas are required to limit the damage to biodiversity (Dasgupta, 2021). As one of the main drivers of environmental degradation, this especially applies to the agricultural sector. Because agriculture is transforming landscapes and ecosystems like few other sectors, the potential impact of policies and institutions is similarly great. Remote sensing imagery often shows the extent to which agricultural land use dominates many landscapes. Also often visible on such imagery are clear differences between countries. Fig. 1 shows exemplary segments of the borders of France and Switzerland (a) and Switzerland and Germany (b). In both cases, agriculture is the main land use and looks differently depending on the country.

The massive decline of European bird populations over the past decades is one manifestation of biodiversity loss in which agriculture plays

a major role (Donald et al., 2001; Donald et al., 2006; Birdlife, 2021), and where policy changes can have a major impact. Loss of bird populations is worrying beyond the intrinsic value of their presence, as bird populations are good indicators for environmental health and relevant for ecosystem services and human wellbeing (Carignan and Villard, 2002; Wenny et al., 2011; IPBES, 2019). Bird populations are also key indicators of the success (or the lack of success) of agri-environmental policies, because the health of bird populations can be an outcome of multiple steps and policies taken. However, the complex behavioral factors involved in farmer take-up of agri-environmental schemes (Alló et al., 2015), as well as the influence of country-specific socioeconomic factors and environmental heterogeneity between countries complicate policy evaluations (Huby et al., 2006). While agricultural intensification and landscape degradation have been identified as some of the main drivers of European bird decline (Mikusiński and Angelstam, 1998; Tryjanowski et al., 2011; Croci et al., 2008; Keller et al., 2020; Bowler et al., 2019), there is a need to better understand how national farming systems, and in particular policies, affect bird populations and other biodiversity outcomes.

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We contribute new empirical evidence on the effect of national agricultural systems on bird populations, based on particularly reliable, systematically and professionally collected data and an empirical approach that allows us to distinguish between the effect of national agricultural systems and environmental differences between countries. Our data covers the 1990s and the 2010s, so we are also able to quantify differences over time.

We use a high-quality dataset of observations in 202 km squares (i.e. 1×1 km) along the Swiss border, containing territory counts of 166 different bird species, amounting to a total sample size of 33'532 territory counts (i.e. count of an individual bird species at a location). These counts are based on highly standardized data collections for the Swiss Breeding Bird Atlas 2013–2016 (Knaus et al., 2018), a project realized by the Swiss Ornithological Institute in Sempach. Focusing on border regions allows us to compare populations in agricultural landscapes across borders and thus reveal country-specific system and policy effects. Based on the territory count data, we estimate differences in Shannon diversity index, species richness and number of territories, as well as difference in abundance of 29 individual common bird species between Switzerland, France and Germany. Hence, in this first step we make use of national borders to address how different agricultural systems and policies impact bird territories, which represent bird populations. In a second step, we examine how the difference in bird populations across the border has changed over time. For this, we supplement our main dataset with data from the Swiss Breeding Bird Atlas 1993–1996 (Schmid et al., 1998). This second analysis provides evidence of changes in bird populations over time, which are interpreted as being at least partially an effect of agricultural policy change.

Differences in bird populations across countries and the impact of country-specific agricultural systems on birds have been documented before, for example through the impact of European Union accession on bird populations in new member states (Sanderson et al., 2013; Reif and Vermouzek, 2019), by comparing the impact of land use change in European Union member states on bird populations (Butler et al., 2010), or by showing the effect of wildlife sanitation laws on vulture abundance across the Spanish-Portuguese border (Arrondo et al., 2018). The legacy of former national borders has also been used to conduct a natural experiment of the effect of field size on biodiversity (Batáry et al., 2017). Yet, the direct association between national agricultural policy and bird populations has not yet been established. We show that national borders can be an effective tool to evaluate the effect of country-specific agricultural systems and policies. As national borders are man-made and

often separate regions with similar or almost identical environmental conditions (which is a falsifiable assumption), there is less need for extensive controls and complex models to establish these associations. The comparison of bird populations across borders as we present it here also easily allows for quantification of the difference and thereby of the influence of country-specific factors. The high degree of association with agricultural areas we show here also allows us to narrow down potential mechanisms.

We find that bird populations are significantly smaller and less diverse in Switzerland compared to its neighbors and that this is strongly associated with agricultural land use in all three countries. Moreover, when looking at the number of territories of 29 common bird species, 19 of them are significantly smaller in Switzerland in the whole study area and 20 when including only areas with a high share of agriculture, while none of the species is ever more abundant in Switzerland. Multiple checks confirm that these differences are robust. While these results on their own paint a negative picture of Swiss land use policy in general and Swiss agriculture in particular, we also show that the difference in species richness between Switzerland and its neighbors has significantly shrunk over the previous 20 years. This pattern is consistent with relative improvements in Swiss agri-environmental policy, which might be the result of the comparably high agri-environmental payments per hectare specifically aimed at biodiversity conservation in Switzerland (Wuepper and Huber, 2021).

The rest of the paper is organized as follows: in section 2, we introduce the dataset, our econometric approach to estimate differences between Switzerland and its neighbors as well as our strategy to identify the role of agriculture. In this section, we also present the robustness checks. In section 3, we present the results of our analyses. In section 4, we discuss possible mechanisms and the implications of these results. Finally, we conclude in section 5.

2. Data and methods

2.1. Data

We base this study on a dataset of bird territories along the Swiss border with France and Germany, collected mainly between 2013 and 2016. The Swiss Ornithological Institute organized and coordinated the data collection for the Swiss Breeding Bird Atlas 2013–2016 (Knaus et al., 2018) as well as two other projects, the Common Breeding Bird Monitoring (MHB, Monitoring häufiger Brutvögel) and the Biodiversity



Fig. 1. An aerial view of Swiss border regions. a) The border region between Switzerland (right) and France (left) at Chavannes-des-Bois, near Lake Geneva. Swiss fields and forests seem very artificial, while French landscapes are uneven and broken up by hedges and smooth forest transitions. Image: ESRI 2021) The border region between Switzerland (left) and Germany (right) at the Rhine near Wallbach. Swiss fields to the lower left are again almost free of trees or hedges, while German fields on the other side of the Rhine are littered with landscape elements. Image: Bundesamt für Landestopografie swisstopo.

Monitoring Switzerland (BDM, Biodiversitätsmonitoring Schweiz). The data collection was structured as follows: first, Switzerland was divided into 10-by-10 km squares. Then, 3 to 5 smaller 1km² squares (henceforth called kilometer squares) were chosen that best represent each of the 10-by-10 km squares. While the data collection was primarily conducted to evaluate the state of Swiss bird populations, some of the 10-by-10 km squares overlapped into neighboring countries. Therefore, a number of kilometer squares was set in Switzerland's neighboring countries France, Germany, Italy, Austria and Liechtenstein. To assess bird populations, a standardized procedure was used. A route was defined within these kilometer squares and assigned to one of 750 volunteers, who then recorded bird territories along these routes following a standardized protocol. Each kilometer square was visited three times in at least one but in up to four years between 2013 and 2016 (a small number of kilometer squares was visited in 2012 for the federal scheme Biodiversity Monitoring Switzerland). Visits were scheduled and birds counted according to a standardized protocol from the Swiss Ornithological Institute (Knaus et al., 2018). The first visit was to take place between mid- and end of April, the second at the beginning of May and the third at the end of May, but no later than mid-June. This was to ensure a complete count of bird species that nest at different times. The Swiss Breeding Bird Atlas team of the Swiss Ornithological Institute then conducted a multi-layered quality control of the submitted territory mappings. Experts checked for anomalies and, if necessary, contacted the volunteers to validate observations. After each year, observations were compared to previous records to detect outliers. The dataset we employ here contains territory counts of 166 species. Based on these data, we calculated the total number of territories, total number of species and Shannon diversity index of each kilometer square. The Shannon diversity index provides a more nuanced view of diversity by taking into account both species richness and abundance, and is calculated as follows:

$$\text{Shannon index} = - \sum_{i=1}^S p_i \log(p_i)$$

Where S is the total number of species at a kilometer square and p_i denotes the share of each individual species i .

In a second step, we extend this main dataset with bird territory data collected for the Swiss Breeding Bird Atlas 1993–1996 (Schmid et al., 1998). While the count protocol is almost identical between the two time periods, there are notable differences that impose some limitations to the analysis. First, not all species were included in the period 1993–1996, which reduces the number of species to 120. Second, the count of bird territories was stopped for species when 10 territories were reached (for rarer species, this limit was 3 or 5 territories). For this part of the analysis, we are therefore required to also impose these limitations to the main dataset covering the period 2013–2016. This means, we keep only kilometer squares that have territory counts in both time periods and then “censor” the species in the newer time period to reflect the counted species in 1993–1996. Furthermore, we can only compare species richness over time, because limiting the territory count to 10 per square kilometer makes calculating total abundance and Shannon diversity impossible for the 1993–1996 period. Due to these limitations, we aim to use this dataset in an extension to the main analysis.

We focus on the border between Switzerland and its neighbors. Fig. 2 presents the spatial distribution of the kilometer squares we used. We exclude the borders with Austria, Italy and Liechtenstein as well as the section to the southeast of Lake Geneva because the high mountains and deep valleys of the Alps create very heterogeneous environmental conditions there. Thus, bird territories differ structurally at this part of the border. At the borders between Switzerland and Germany and Switzerland and France (excluding the part to the southeast of Lake Geneva) however, the environmental conditions on the two sides are very similar. We use these border strips to compare bird populations on both sides of the border.

For the main analysis covering the period 2013–2016, we include all kilometer squares in the neighboring countries and kilometer squares in Switzerland up to 2 km away from the border.

We choose 2 km to achieve a balanced sample between observations outside and inside Switzerland – there are observations on 105 kilometer squares in Switzerland, against 97 outside Switzerland¹ (60 France, 37 Germany). These 202 observations were made in 173 unique kilometer squares – nine were visited in each year between 2013 and 2016, one in 2013 and 2016 and one in 2013 and 2015. Each observation contains a complete territory count of 166 bird species per kilometer square. The summary indicators were calculated based on the territory counts of all species.

Meanwhile, in the extension comparing the periods 1993–1996 and 2013–2016, we include kilometer squares within Switzerland up to 3 km from the border. Again, this is done to achieve a balanced sample between the two regions. Filtering the kilometer squares to only include ones that occur in both time periods reduces the number of squares and necessitates the larger distance. Overall, we arrive at 167 total kilometer squares in each period, with 86 in France and Germany and 81 in Switzerland.² All kilometer squares in the 1993–1996 period were only visited in one year. If a corresponding kilometer square in the later time period was visited in multiple years, we randomly sampled one and removed the others from the data set.

To test comparability of the border regions and to control for environmental conditions, we added slope, elevation and vegetation as potential covariates. Slope and elevation data was retrieved from the Shuttle Radar Topography Mission data and averaged over the kilometer squares (Jarvis et al., 2008). We also added a proxy for the natural potential in absence of human influence averaged over each kilometer square, an index estimated combining 58 environmental indicators provided by (Bastin et al., 2019). The natural potential summarizes a comprehensive range of geographic and environmental factors and is thus a reliable indicator to detect natural differences across borders (Wuepper et al., 2020b; Wuepper et al., 2020a). As presented in Table 1, elevation, slope and natural potential are all very similar across the border. Finally, we also added land use data by calculating pixel counts per kilometer square of CORINE land use classifications (CORINE, 2018). As we are effectively comparing kilometer squares from the same regions when analyzing changes between the periods 1993–1996 and 2013–2016, we refrain from providing an additional table comparing biophysical factors of the extended dataset.

2.2. Empirical framework

To obtain a robust estimate of being on the Swiss side of the border, we employ a spatial regression model. While the limited number of observations does not allow for a regression discontinuity design (Hahn et al., 2001), we achieve some approximation of it by comparing only observations within a slim corridor along the national border. Such a methodology has been successfully applied in the past, for example when comparing field-level biodiversity across the former inner-German border (Batáry et al., 2017). For the main analysis, we use three different dependent variables expressing bird diversity and abundance. To estimate the impact on bird diversity, we use number of observed species (species richness) and the Shannon diversity index. To estimate the impact on bird abundance, we use the total number of territories at each location. Additionally, we also examine 29 common bird species individually in the main analysis. These individual species provide a more detailed picture about the differences and also serve to confirm the effect we find on summary indicators. We select these species by setting a

¹ For a complete breakdown of sample sizes, refer to Table S1 in the supplementary material.

² See Figure S2 in Supplementary Material S3 for a map of the distribution of kilometer squares

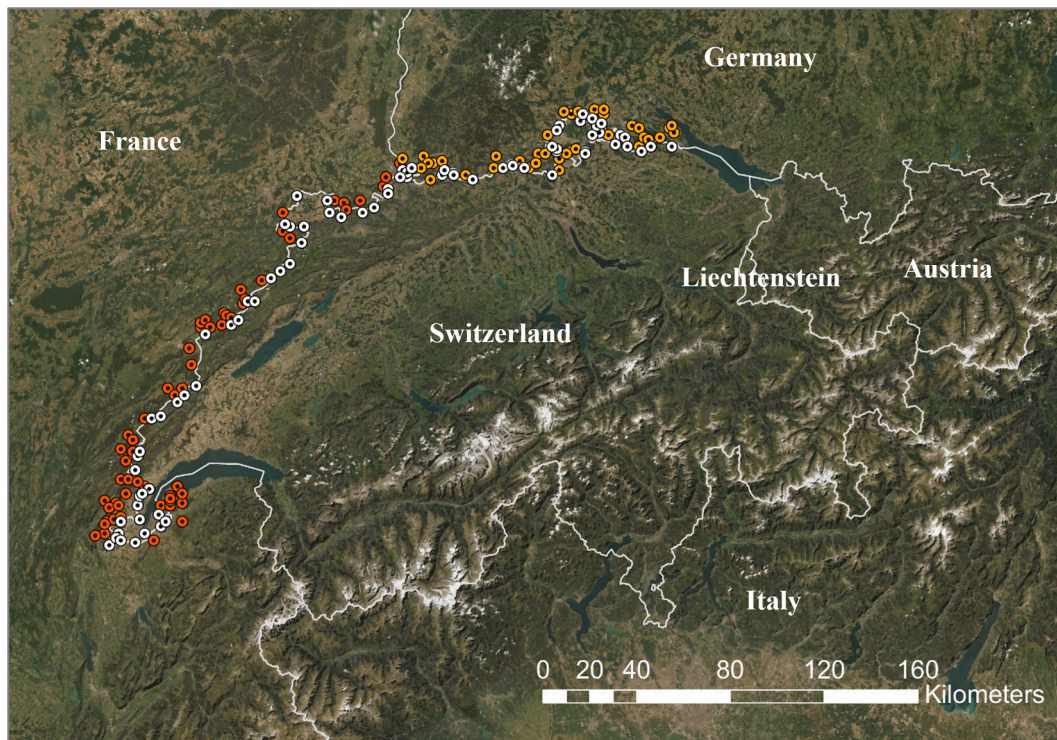


Fig. 2. An aerial view of Switzerland and its neighbors (Esri, 2020) and illustration of the spatial distribution of observations. Three characteristic geographic regions are broadly distinguishable: The Alps stretching from France through the southern half of Switzerland and northern Italy into Austria; the Central Plateau of Switzerland starting in France and continuing into Germany, and the Jura mountains along the French and German border. Orange dots indicate kilometer squares in Germany, red dots kilometer squares in France and white dots kilometer squares in Switzerland. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Comparing the border regions.

Country	Landscape and Environment		
	Elevation	Slope	Natural potential
Switzerland ($n = 105$)	m a.s.l.	degrees	Percent tree-cover
	602 (29.6)	7.35 (0.49)	75.05 (1.25)
France and Germany ($n = 97$)	660 (30.4)	7.40 (0.48)	73.16 (1.32)

The average elevation, slope and vegetation potential at the kilometer squares indicate the similarities of landscapes on both sides of the border, standard errors of the mean in brackets. Natural tree cover denotes an index combining 58 environmental indicators (Bastin et al., 2019).

minimum number of non-zero observations, because differences of rare birds with excess zero observations are difficult to capture with the models we employ here. Using a power calculation with effect size 0.5, power 0.8 and significance level 0.05, we find a minimum requirement of 63 non-zero observations, which is fulfilled by 29 species (See Table S3 in the supplementary material for a full list of species). Due to the limitations in the data mentioned above, we only compare species richness in the second part of the analysis looking at changes between the periods 1993–1996 and 2013–2016.

For summary measurements like species richness or total number of territories, we employ a Gaussian linear regression model. To estimate the impact on individual bird species we use Poisson regression, taking into account that territory numbers are count data. To determine percentage differences from Poisson estimators, we calculated incidence rate ratios. The model takes the form:

$$Y_i = \alpha + \beta \text{Switzerland}_i + \text{Biophysical}_i \gamma + \text{Coords}_i \delta + \text{Year}_i + \text{Multiple}_i + \varepsilon_i$$

where Y_i is a measure of bird diversity and abundance (total number of territories, Shannon diversity, species richness and number of territories of individual species, based on the 29 selected species) at a kilometer square i ; α is the intercept; *Switzerland* is a binary variable indicating whether a kilometer square is in- or outside Switzerland. This variable is of key interest in our analysis, as it determines the effect of across the border. *Biophysical* is a vector of environmental variables (tree cover potential, elevation and slope); *Coords* are coefficients of coordinates and interaction terms (longitude and latitude as well as their squares, and interactions of the squared longitude and latitude); *Year* are year dummies (2013–2016, 2012 as baseline); *Multiple* are dummy variables for multiple observations in the same kilometer square (first, second, third and fourth observations, single observations as baseline); and ε_i denotes the error term.

The key explanatory variable of interest is the country effect of Switzerland. Due to both France and Germany exhibiting visibly lower land use pressure as presented in the introduction and due to the limited number of observations outside of Switzerland, we primarily focus on a comparison of Switzerland with France and Germany combined and only compare Switzerland to each country individually as an additional test. With all models, we control for elevation, slope and vegetation potential to capture differences in environmental conditions. We adjust coefficients for spatial correlation by introducing controls for x- and y-coordinates and their squares, as well as an interaction term thereof. In addition, we adjust standard errors by calculating spatial standard errors clustered in 100 km squares in the linear regression model (Conley, 1999) and by generating 37 spatial clusters in the Poisson regression model using an x- and y-coordinate interaction term. We used two different clustering techniques due to the implementation of Conley (1999) not being available for Poisson regression.

In a further step, we try to establish the origin of the differences across the border. More specifically, we test agriculture as the main

explanation. To do so, we split the sample by share of agricultural area. We add up all occurring CORINE agricultural classes (arable nonirrigated, complex cultivation patterns, fruits and berries, vineyards, agriculture natural and pastures) and separate the sample into kilometer squares with a share of agricultural area larger or smaller than 50%. We then repeat the analysis using the above regressions.

Finally, we compare the change at the border between the 1993–1996 and 2013–2016 periods. We do this by running the above regression for both periods (i.e. different datasets) and comparing the coefficient of Switzerland. In addition, we compare the mean number of species of both regions over time to evaluate the origin of possible changes. The regression model used for the comparison between the two time periods is identical to the one shown above, except that dummy variables for multiple observations are not necessary, as the data is prepared in a way that each kilometer square only has a single observation per time period.

2.3. Robustness checks

One of our robustness checks is a placebo test for which we draw an arbitrary border shifted 10 km into Switzerland and repeat the analysis there. Estimating a statistically significant difference at a border that does not actually exist would suggest that also our main estimates could be caused by random chance. However, this is not what we find. For the main analysis, we designate a strip of 2 km to the left of the border as placebo-France and placebo-Germany, and a strip of 5 km on the right as placebo-Switzerland, in order to achieve a similar sample size and balance as in the main estimation: 91 in placebo-Switzerland and 88 outside of it.³ Similarly, we repeat this placebo test for the secondary analysis comparing the two time periods 1993–1996 and 2013–2016, although the distance from the border is extended to 6 km on both sides of the placebo border, again due to the lower number of kilometer squares in the dataset. Here, we compare 73 km squares in placebo-Switzerland to 78 km squares outside of it. As these placebo borders do not coincide with any national or subnational border, we expect Shannon diversity, number of species and number of territories to be the same on the two sides. Meanwhile, we expect the effect on individual species to be insignificant and the coefficients to be relatively symmetrically distributed around zero. We use the same model as presented above, the only difference being that the *Switzerland_i* binary variable designates placebo-Switzerland and placebo-Germany and placebo-France.

In the main analysis we also test, how splitting the sample into German and French border sections affects the results. To do so, we create two subsamples of the dataset, one containing all observations in France and, for those in Switzerland, west of the city of Basel (where the borders of Germany, France and Switzerland meet), and one containing all observations in Germany and east of Basel (Fig. 2, red dots denote kilometer squares in France, orange dots denote kilometer squares in Germany).

3. Results

3.1. Bird diversity and abundance

We find that Swiss bird communities are significantly smaller and less diverse than across the border in neighboring countries. This difference is associated with agricultural areas. Fig. 3 presents the results of the main estimation, the country effect of Switzerland on Shannon diversity, number of bird territories and number of bird species in the 2010s period.

Looking at the combined border sections and the full sample, all three indicators are significantly lower in Switzerland, although

Shannon diversity only at $p < 0.1$. There are 2.5 fewer species (95% CI: 0.79–4.21) and 44 fewer territories per kilometer square (95% CI: 15.06–73.86) in Switzerland compared to its neighbors. Splitting the sample into border sections, the picture is more complex, but overall remains the same. The difference to France is more pronounced than to Germany, as the effect on Shannon diversity reaches -0.09 (95% CI: -0.16 to -0.02) while there are 4 fewer species (95% CI: 2.57–5.84) and almost 50 fewer territories (95% CI: 17.08–77.18) in Switzerland. For reference, compared to the mean values in France, this is a 12% drop in number of species and 14% drop in number of territories. While the effect is weaker when only using data along the German border section, the coefficients are still negative in all cases, although not always significant. The smaller effect size and larger confidence intervals might be a result of the small sample size.

Next, we explore underlying mechanisms. When splitting the sample into kilometer squares with high and low share of agricultural areas, the results are quite striking. The size of the effect on all three indicators increases considerably when only including kilometer squares with a share of agriculture of $>50\%$, surpassing -0.1 in Shannon diversity (95% CI: -0.17 to -0.03) and -5 (95% CI: -7.82 to -2.98) in number of species, while almost reaching -80 (95% CI: -109.14 to -47.6) in number of territories. Comparing that to averages of this sample outside Switzerland, these numbers translate to 12% fewer species and 25% fewer territories. On the other hand, when limiting the sample to kilometer squares with less than half covered by agricultural areas, there is no difference in Shannon diversity and number of species across the border, and only a small but insignificant one in number of territories. It therefore seems that the overall effect is primarily driven by agriculture instead of forests or built-up areas.

As described above, we repeat the main estimation at an arbitrary placebo border to make sure that these results are not just a random occurrence due to large variation within the data. The results of this robustness check indicate that the identified border effect is indeed due to differences between Switzerland and its neighbors. Fig. 4 presents the results of the robustness check. The difference in Shannon diversity across the placebo border is effectively zero, while the number of species coefficient is only slightly negative but highly insignificant. Although number of territories is almost significant, we argue this is not a cause for concern, as this might be due to the high spatial variability of territory number. In any case, the coefficients in the main estimations are considerably larger and highly significant. Furthermore, the picture becomes much clearer when looking at territory numbers of individual species.

3.2. Individual species

In addition to the summary indicators of the previous section, we also examined the difference in territory numbers across the border of 29 individual bird species. As laid out above, the selection of these species was based on a minimum number of non-zero observations, making it an analysis of common birds. We use a Poisson model to estimate these individual species.⁴

Fig. 5 presents the results of the analysis of individual bird species. Panel A shows the effect at the real border using the full sample. The territory numbers of 19 of the 29 species, about two thirds, are significantly smaller in Switzerland. Meanwhile, only one species, the Carrion Crow, has a positive coefficient. The effect is substantial – some species have up to 40% fewer territories in Switzerland than in France and Germany – but also expected, because of the considerably lower number

⁴ We do not explicitly account for multiple hypothesis testing for two reasons. First, we are not testing new hypotheses but dissecting the effect on total number of territories. Second, the large number of species exhibiting significant effects as well as the overall pattern when comparing the actual versus the placebo border make it unlikely that the effect we find is purely coincidental.

³ See Supplementary Material S2 and S4 for an illustration.

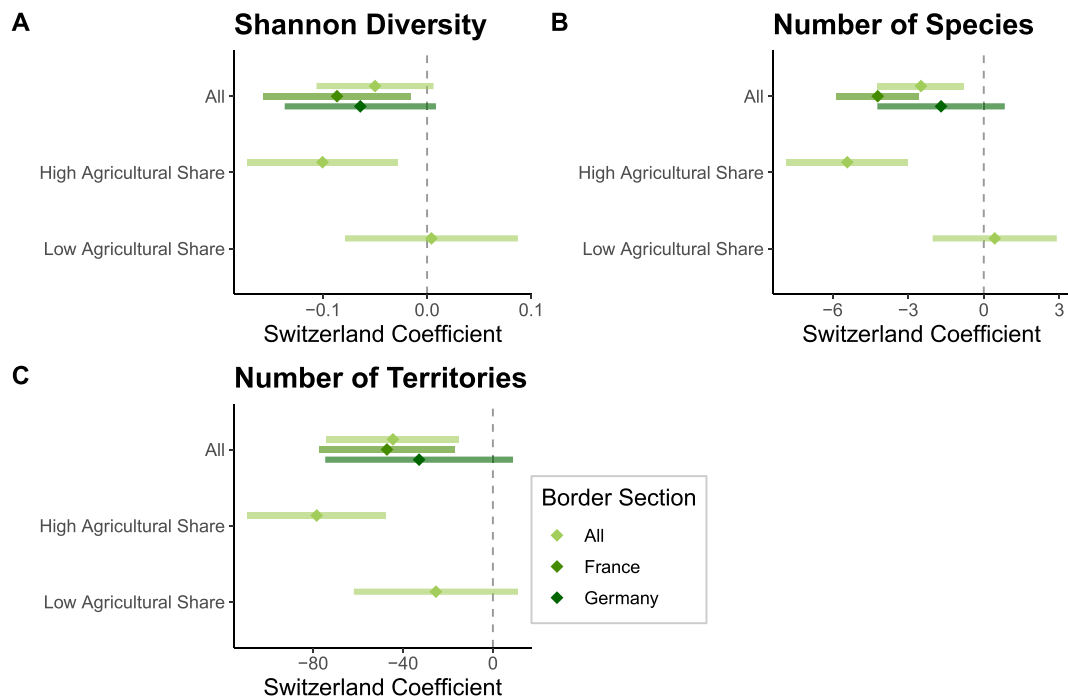


Fig. 3. The results of the main estimation. Panel A presents the effect of Switzerland on the Shannon diversity index, panel B the effect on number of species and panel C the effect on number of territories. Diamonds indicate the coefficient estimate, and bars denote 95% confidence intervals. “All” shows the effect without land use conditions, dark green including both the German and French border section, medium green only including the French and light green only including the German border section. “High Agricultural Share” shows the effect when including only kilometer squares with a share of agriculture larger than 50%, and “Low Agricultural Share” shows the effect when including only kilometer squares with a share of agriculture lower than 50%. Because splitting the sample into agriculture and non-agriculture roughly halves sample size, reducing it further to German and French border sections individually would result in a sample that is too small. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

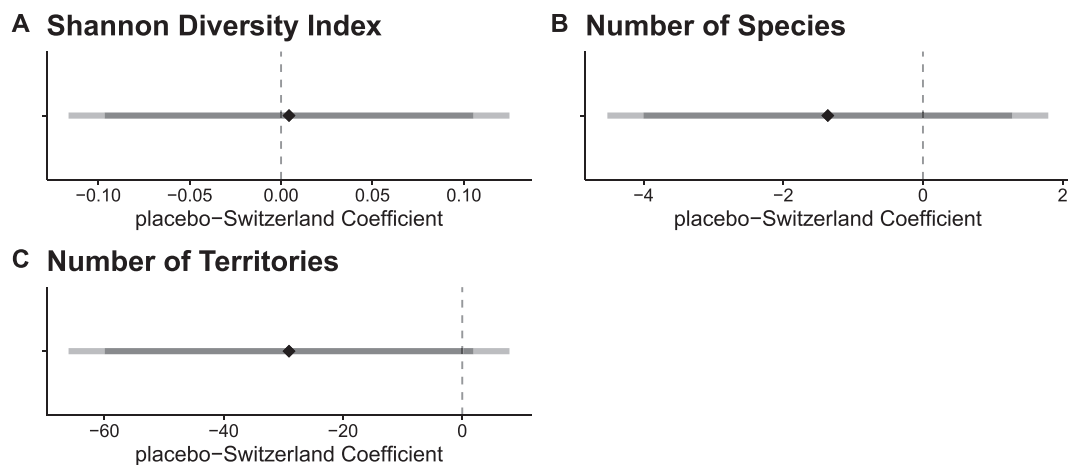


Fig. 4. The results of the robustness check. Panel A presents the effect of placebo-Switzerland on the Shannon diversity index, panel B on number of species and panel C on number of territories. All estimations using the entire border section. Diamonds represent coefficient estimates, while dark bars indicate 90% confidence intervals and light bars extend to 95% confidence intervals.

of total territories in Switzerland we found in the previous section. More surprising is the breadth of the effect. It seems that species are affected independent of habitat preferences or guild. Farmland, forest and settlement birds all have significantly smaller populations in Switzerland, exemplified by the Yellowhammer, the various Tits (Marsh Tit, Coal Tit, Great Tit, Eurasian Blue Tit) and the House Sparrow.

Fig. 5, Panel C and D present the results when splitting the sample into high and low share of agricultural areas, as done in the previous section. Although these results should be interpreted with caution, as the lower sample size reduces statistical power, the overall pattern is quite clear: 20 out of 29 species have significantly smaller populations on and

around agricultural lands, while none of the coefficients are positive, but only 6 of 29 on mostly non-agricultural land exhibit the same effect. It is again surprising that not only farmland birds, but mainly forest and settlement birds are affected, even though the sample only consists of mainly agricultural kilometer squares. This could mean that other land uses and landscape elements in agricultural areas, for example forest edges or settlement structures, are also of higher quality in France and Germany compared to Switzerland.

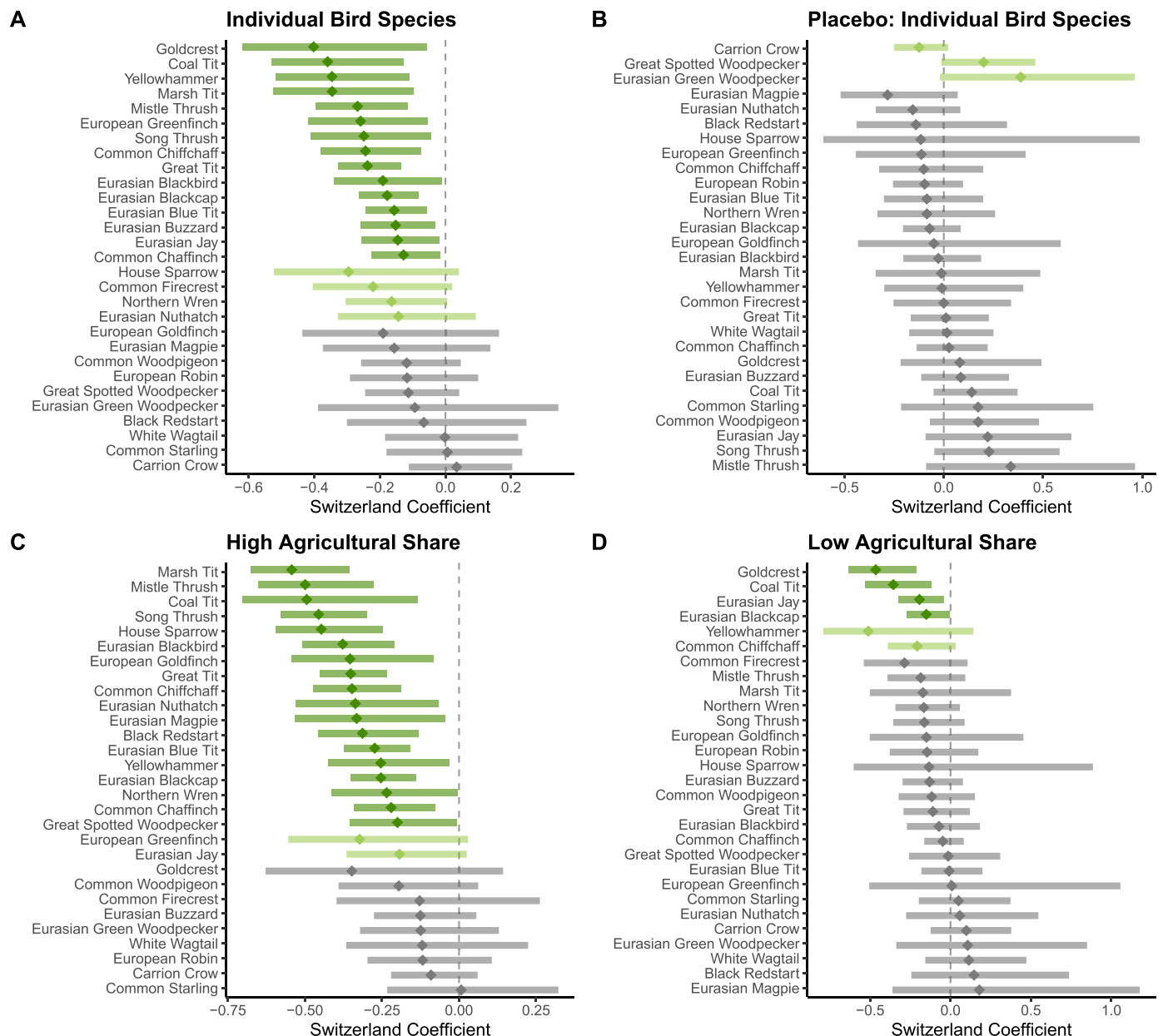


Fig. 5. The effect of Switzerland on 29 common bird species. Panel A presents the main result, the effect at the entire border with France and Germany, and panel B presents the effect at the placebo border as a robustness check. Meanwhile, panel C shows the effect when only including kilometer squares with a share of agriculture of >50%, and panel D shows the effect when only including kilometer squares with a share of agriculture of <50%. Diamonds represent the effect size (e.g. -0.2 translates to 20% fewer territories in Switzerland), bars the 95% confidence interval and colors significance levels (dark green $p < 0.05$, light green $p < 0.1$, grey $p \geq 0.1$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The results of the placebo test in Fig. 5, panel B support the findings presented so far. None of the 29 species is significantly different across the placebo border at a 5% level of significance.⁵ Furthermore, the coefficients are distributed symmetrically around zero, unlike at the real border, where all except one are negative. We interpret this robustness check as a very strong signal that we are indeed observing the effect of different countries instead of random variation. In addition, we also argue that this test confirms that the estimated effect on total number of territories is realistic, despite the placebo test of the previous section being less convincing regarding total abundance. Additionally, if we use panel B as an example of complete absence of any effect, then it seems that even on non-agricultural areas, as shown in panel D, number of

territories of some bird species are slightly lower. However, this might also be a result of the small sample size.

3.3. Effect over time

Looking at how the effect at the border developed over time, we find that it has become significantly smaller between the periods 1993–1996 and 2013–2016. In this reduced dataset with fewer kilometer squares and fewer species (after harmonizing it with the older dataset), the difference in number of species between the Swiss and neighboring border regions is not significant with a negative coefficient of -1.9 in the later period, but highly significant at -4.3 in 1993–1996 (Fig. 6, panel A). It therefore seems that the difference between the countries is slowly disappearing. When comparing the mean number of species in both regions, we see that the mean number of species in the 1993–1996

⁵ Note that 3 out of 29 species are significant at the 10% level of significance.

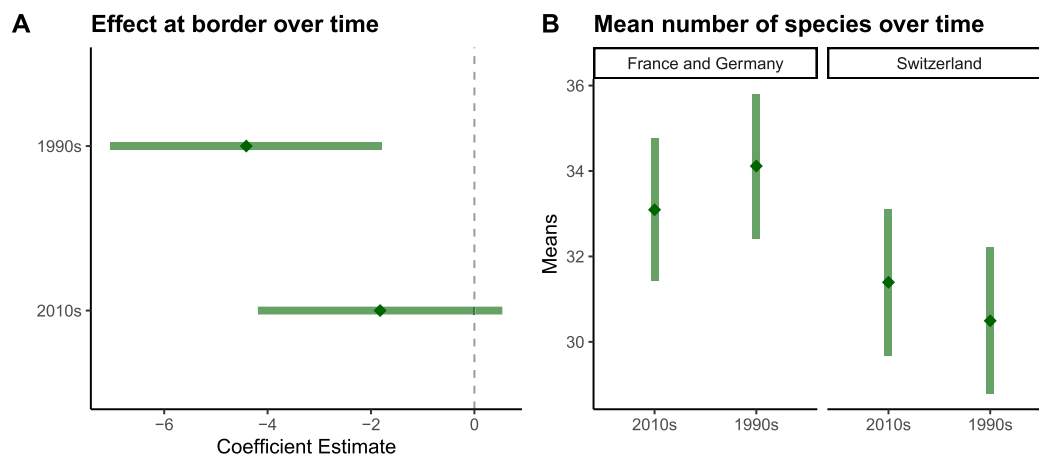


Fig. 6. The results of the comparison over time. Panel A presents the coefficient estimates of the regression estimating the effect at the border on number of species between the 1990s and 2010s. Panel B presents the mean values of number of species in the border regions of Switzerland, as well as France and Germany, respectively. Bars indicate 95% confidence intervals.

period was significantly different. Since then, the number of species has increased in Switzerland but decreased in France and Germany, closing the gap between the regions, although the Swiss mean was still about 2 species lower in the period 2013–2016. We also run the robustness check from the previous subsections, shifting the border 10 km inward Switzerland, and find that there is no effect at this placebo border for both time periods, as we would expect (see **Table S4** in Appendix S5).

4. Discussion

We find that bird populations are significantly smaller and less diverse in Switzerland compared to its neighbors France and Germany. On kilometer squares dominated by agriculture, there are 25% fewer territories and 12% fewer species, while 20 of 29 common bird species are up to 50% less abundant. Meanwhile, bird populations on areas with lower shares of agriculture are identical or only slightly smaller across the border. Farmland, forest and settlement species are similarly affected, despite the difference mainly occurring on agricultural areas. Swiss agriculture is therefore associated with a negative effect on bird populations. This may lead to negative spillovers back to agricultural production: for example, birds have been shown to support agricultural production through pest control, seed dispersal, nutrient cycling and ecosystem engineering (Wenny et al., 2011). However, we also present evidence that Swiss bird diversity has improved between the periods 1993–1996 and 2013–2016, both in absolute terms and relative to bird populations in neighboring countries. In this section, we discuss how this situation came to be, and how the further recovery of bird populations could be supported.

As presented in the introduction, a bird's eye view of border sections of Switzerland and France and Germany reveals strikingly different agricultural landscapes. Swiss landscapes appear much more artificial compared to France, where agricultural areas are broken up by hedges, tree rows and natural transitions (Fig. 1, panel A). Similarly, a comparison between Switzerland and Germany reveals a notable absence of landscape structures on Swiss agricultural areas (Fig. 1, panel B).

While these are especially dramatic examples of changes at the border, Switzerland does experience very high levels of land use pressure. As presented in Fig. 2, the Southern half of Switzerland is covered by mountains, where valleys provide only limited space for settlements and industry. Settlement and industry growth is consequently augmented in the rest of Switzerland. Agricultural areas are especially affected by expansion of built-up areas because the federal act on forest prevents almost all deforestation, so settlement and industrial zones are usually extended into agricultural areas, adding pressure on farmland

bird habitats. In the three decades between 1979 and 2009, 5.4% of agricultural areas were lost due to settlement growth and forest expansion (BFS, 2013), and agricultural areas keep shrinking by about 0.1% per year (BLW, 2020). In addition, new building and infrastructure projects are also fragmenting ecosystems and threatening biodiversity. While France and Germany are also experiencing land use pressure, their large size and comparatively low share of unproductive area might enable them to absorb it more easily. Overall, while bird species are also highly under pressure in France and Germany (Donald et al., 2001), the situation seems to be worse in Switzerland.

Between the 1950s and the 1990s, many Swiss farmland birds have experienced significant population declines, some to the point of disappearing completely (Knaus et al., 2011). Indeed, bird populations had declined to an all-time low the 1990s (Knaus et al., 2011). This development was caused mainly by the industrialization of agriculture over that period. Since then, there have been some advances in Swiss agricultural policy regarding biodiversity and the environment. While food production remains an important goal of Swiss agricultural policy, direct payments aimed at improving the environment now play an important role in the subsidy system, too (Huber, 2022). To incentivize the supply of domestic food, farmers are compensated to maintain cultivated areas and a minimum number of animals on pastures. In fact, the largest single share of direct payments (39% in 2019) was distributed as subsidies for secure supply (BLW, 2020). These payments do not necessarily encourage biodiversity-enhancing production, but all farmers have to comply with a proof of ecological performance (cross compliance) to actually receive any kind of payments. Although the share of targeted biodiversity-related payments is lower at 15% of the total direct payments, they still sum up to the considerable amount of 417 million CHF in 2019. Since 1998, farmers also must set aside 7% of agricultural areas for biodiversity conservation purposes (3.5% on areas planted with specialty crops like vineyards or vegetable plots) as part of the above mentioned proof of ecological performance. Notably, this environmental re-orientation of agricultural policy was initiated a few years after the bird count for the 1993–1996 Breeding Bird Atlas was concluded, which we use to compare changes over time⁶ (Herzog et al., 2005). While the data doesn't allow us to directly attribute the marked improvement in bird diversity since then to agricultural policy, this policy shift was one of the most significant changes in environmental legislation during this period. It has been shown that these policy changes have indeed led to

⁶ More specifically, the new direct payment systems with a proof of ecological performance is in place since 1999.

an increase in biodiversity promoting areas (Wuepper and Huber, 2021). In addition to policy incentives, also input and output prices can incentivize intensive production, i.e. lower input and higher output prices incentivize more intensive production schemes⁷ (Finger et al., 2017). Meanwhile, it took until the 2013 reform of the Common Agricultural Policy to introduce environmental payments on a large scale for farmers in the European Union. Generally, the policies of the European Union were not very effective, leading to at most small improvements (Hasler et al., 2022). This applies to both France and Germany, where agri-environmental programs only had quite small effects (Uehleke et al., 2022; Chabé-Ferret and Subervie, 2013).

While 17.6% of Swiss agricultural areas were registered as biodiversity promoting areas in 2016, the share of high quality areas adhering to outcome-based criteria was considerably lower at about a third of that (Knaus et al., 2018). Lack of hedges and landscape elements, high fertilizer and pesticide use or frequent mowing are just some of the characteristics of low quality areas. However, the effect of specific payments on biodiversity outcomes is not always straightforward. Agri-environmental policy can also have important and sometimes counter-intuitive spill-over effects. For example, payments for open landscapes, which are part of the Swiss secure supply payments, can improve biodiversity outcomes, especially when they prevent a transformation from systems with high to lower biodiversity, e.g. a transition from extensive grasslands into settlements or forests (Huber et al., 2017). At the same time, the overall intensive Swiss agricultural system creates major fertilizer and pesticide pollution that also spill over into other ecosystems (Guntern et al., 2021; Guntern et al., 2020; Finger, 2021). The link between high levels of pesticide use and bird populations has repeatedly been shown (Li et al., 2020; Morris et al., 2005; Mineau and Palmer, 2013), and there is also evidence that fertilizer use and nutrient surpluses indirectly threaten certain bird species by changing habitat structure and by decreasing invertebrate numbers (Vickery et al., 2001). Our study shows that these adverse effects could still outweigh the positive impacts of biodiversity payments in current Swiss agriculture, at least when it comes to bird conservation, as both pesticide and nitrogen pollution are higher in Switzerland than in France or Germany (Wuepper et al., 2020b; Wuepper et al., 2023).

There are several ways to further strengthen agri-environmental policies. Reducing the nutrient surpluses and pesticide use is urgently needed to improve biodiversity as well as to reach other policy goals. Moreover, existing direct payment schemes may be re-adjusted, so the emphasis is more on biodiversity conservation, while maintaining productivity and economic viability. Especially landscape level policy instruments, such as agglomeration payments, can increase the efficacy and efficiency of biodiversity related policies (Huber et al., 2021). In addition, expanding, rethinking and reforming the current biodiversity schemes may be required. For example, outcome oriented payment schemes may be enlarged to include not only plant related biodiversity outcomes (Mack et al., 2020), but also comprise other species such as birds, which only would be viable on regional levels (Burton and Schwarz, 2013; Elmiger et al., 2023). Generally, policy should increasingly focus not only on quantity, but also quality of biodiversity promoting areas. Beyond agriculture, a number of subsidies in other areas, such as transportation or tourism, have been identified as harmful to biodiversity, and demand action to be resolved (Gubler et al., 2020). As land use pressure increases in other regions of the world due to growing populations and their food and resource needs, policy requirements will also become more demanding elsewhere. For example, the European Union's Common Agricultural Policy is already deemed by many scientists as insufficient to address current and future sustainability and biodiversity challenges (Pe'er et al., 2020), also in connection with birds (Assandri et al., 2019). Switzerland as a case study (with many problems

at the interface of agriculture and the environment, but also many resources to address them) offers opportunities to identify successful policy approaches under growing land use pressure.

5. Conclusion

We here investigate how bird populations change across the border of Switzerland with France and Germany. We find that populations are smaller and less diverse in Switzerland, a difference that is associated with agricultural land use. Small and less diverse bird populations are worrying considering the role of birds as biodiversity and environmental indicators.

Our study has a number of limitations that should be acknowledged. The small number of kilometer squares outside of Switzerland does not allow for the use of a regression discontinuity approach, which would be the ideal method to establish causal inference on the differences at man-made borders. Data availability is a problem in general: as bird territory data in the past has usually been collected by national institutions for one country at a time, there is limited availability of high-quality, comprehensive bird territory data spanning across borders. This in turn reduces the number of cases in which an empirical strategy as we use it here can be applied. In addition, while we can establish an association between agriculture and bird populations, we are unable to identify the precise mechanism, mainly because a lot of detailed agricultural and socioeconomic data is not yet available in spatially explicit, high-resolution form. Another limitation is that in order to avoid the influence of potential confounding factors, we focus only on the border areas of Switzerland, France, and Germany, which potentially increases the internal validity of our results but might reduce their external validity. Most relevant policies in these three countries are national, or in the case of Germany and France, even super-national (i.e. at EU level). However, there is some variation in exact implementation, enforcement, and responses, and our data does not come from all regions of the three countries. For example, farmers in the state of Baden-Württemberg (where all German kilometer squares in this study are located) received about 25% more subsidies per hectare due to environmental payments compared to Schleswig-Holstein (the German state with the lowest subsidies per hectare), while there is also some variation in French agricultural subsidies.⁸ Finally, we only observe the change in species richness between two points in time, which is insufficient to clearly attribute any improvements to Swiss agricultural policy.

Our findings have clear implications for policy decisions. While some bird populations are slowly recovering since the low point in the 1990s, this study also shows the need for Swiss policy makers to initiate further biodiversity protection measures. Possible future approaches could include a stronger emphasis on biodiversity direct payments or extending the criteria of outcome-based direct payments from plants to insects or birds. Outside of Switzerland, this is not the time for complacency, either. Although many Swiss bird populations are slowly improving but still in a comparatively bad state, other countries are not performing well either. A recent study found that bird populations of other European countries have stalled or decreased between the 1990s and now, whereas Swiss populations have improved in certain respects, which is consistent with our findings here (Bowler et al., 2021). All around the world, countries are confronted with steeply declining agricultural bird communities and will have to find ways of reconciling agricultural production and biodiversity conservation (Lees et al., 2022). Concerted action across countries, such as initiated in the Kunming-Montreal global biodiversity framework, and tangible policy efforts are needed.

There are various promising avenues for future research. First, we

⁷ Thus, also taxes on critical inputs such as pesticides can be viable to promote better biodiversity outcomes (e.g. Finger et al., 2017).

⁸ <https://www.agrarheute.com/management/finanzen/direktzahlungen-subventionen-bekommen-bauern-meisten-581147>; <https://www.arc2020.eu/agriculture-atlas-biggest-beneficiary/> (accessed 18.02.2023)

have here quantified the effect of three different national agricultural systems, namely of Switzerland, Germany, and France. It would be important in the future to expand this to as many other countries as possible and thereby to be able to understand larger, more general patterns. Second, with currently available data, we can only say that the effects we are quantifying are mostly occurring on agriculturally dominated land, but we cannot further identify the precise mechanisms, e.g. how much this comes from pesticide and fertilizer use, structural elements between fields, crops grown, frequency of disturbances, etc. Thus, identifying mechanisms is an important task for future research. Future research shall also identify whether birds are more directly impacted, or more indirectly, e.g. via effects on insects and other food sources. Understanding all of this would be highly valuable, especially for policy.

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

See Supplementary Material.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecolecon.2023.107854>.

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