Møller *et al. Avian Res (2021) 12:43*
https://doi.org/10.1186/s40657-021-00278-1

Avian Research

RESEARCH

Open Access

# Abundance of insects and aerial insectivorous birds in relation to pesticide and fertilizer use

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**Abstract**

**Background:** The abundance of insects has decreased considerably during recent decades, resulting in current abundance showing 70–80% reductions in more than 15 studies across temperate climate zones. Dramatic reductions in the abundance of insects are likely to have consequences for other taxa at higher trophic levels such as predators and parasites. Pesticides, fertilizers and agricultural land use are likely candidates accounting for such reductions in the abundance of insects.

**Methods:** Here we surveyed the abundance of flying insects, and the reduction in the abundance of insects as a consequence of intensive reduction in agricultural practice linked to fertilizer use and pesticide use. Finally we demonstrated consistency in abundance of birds among study sites.

**Results:** We demonstrated that the use of fertilizers and pesticides had reduced the abundance of insects, with consequences for the abundance of insectivorous bird species such as Barn Swallows (*Hirundo rustica*), House Martins (*Delichon urbicum*) and Swifts (*Apus apus*). Juvenile Barn Swallows were negatively affected by the reduced abundance of insects and hence the reproductive success of insectivorous bird species. These effects imply that the abundance of insects could be reduced by the availability of insect food.

**Conclusions:** These effects of intensive agriculture on insect food abundance are likely to have negative impacts on populations of insects and their avian predators. This hypothesis was validated by a reduction in the abundance of insects, linked to an increase in the abundance of fertilizers and a general change in farming practice.

**Keyword:** Aerial insectivores, Fecundity of insects, Insect abundance, Insectivores, Insects

## Background

Traditional agriculture has affected land-use (Tucker and Heath 1994; Donald et al. 2001; Schimmelfenning and Sedelmeier 2005; Raven and Wagner 2021), and such effects combined with change in land-use and agricultural practice have affected insects and other taxa (Fox et al. 2014; Hallmann et al. 2017; Møller 2019; Tinsley-Marshall 2019), resulting in declines in abundance of insects, in particular aerial insects (Janzen and Hallwachs 2021). Furthermore, these effects of agricultural practice may have contributed to changes in the abundance of insects. Change in climate has had negative impacts on these declines in the abundance of food for insectivorous birds (Møller 2013, 2019, 2020; Halsch et al. 2021). Declines in abundance of insects have been documented across large parts of Europe, and even nature reserves now contain many fewer insects than just 50 years ago, with reductions in the

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abundance of insects as large as 80% (Hallmann et al. 2012; Møller 2019). Attempts to attribute these changes in farming practice to specific factors have been unsuccessful, mainly because some of these strongly negative effects had been observed in well studied taxa that have been strongly negatively affected (Hallmann et al. 2017; Nocera et al. 2012).

The diversity of insect taxa affected by these declines have mainly been attributed to large predatory insects. Large invertebrate taxa include large insects, but also spiders (Nyffeler and Bonte 2020). Declines in insect abundance have been well documented (Møller 2013). Declines in abundance of avian predators have often been attributed to the negative impacts of such predators on insects, but also the negative effects of agriculture on the abundance of insects (Nyffeler and Bonte 2020; Møller 2013).

Insectivorous birds have been hypothesized to be negatively impacted by pesticides and pollutants (Eurostat 2021), and the amount of fertilizer used by agriculture was initially negatively related to agricultural practice. Pollutants have reduced the abundance of flying insects (Pomfret et al. 2000; Nocera et al. 2012; Hallmann et al. 2014). Fertilizers may increase the abundance of insects if fertilizer eliminates any nutrient limitation. The distribution and abundance of insects should affect the abundance of insect predators and their performance during foraging.

Swifts (*Apus apus*), House Martins (*Delichon urbicum*) and Barn Swallows (*Hirundo rustica*) differ in their foraging height, size of prey and mode of flight (Turner 1980). Therefore, we should expect more insects captured by Barn Swallows due to large agility compared to that of House Martins and in particular than that of Swifts having the lowest level of agility (Turner 1980; Møller 1994, 2013). Recent surveys of breeding insectivorous birds have revealed that the abundance of insectivorous birds has increased with the abundance of insects on windshields (Møller 2013, 2019).

The objectives of this study were: (1) to assess the effects of pesticides on the abundance of insects with more insects hypothesized to be present in areas where fewer pesticides are used; (2) a negative impact on the amount of fertilizer on agriculture, agricultural performance and invertebrates; and (3) agricultural land-use reducing the general performance of insectivorous birds. We performed extensive surveys of insects and insectivorous birds in Europe during 3520 transects for approximately 80,000 km causing almost 125,000 insects to hit the windscreen of cars during March–September 2018–2020.

## Methods

### Study sites

This study is part of a citizen science project (Crain et al. 2014) on the determinants of the abundance of insects using the windshield of cars for sampling insects (Møller 2013, 2019, 2020). The criteria used for inclusion of human participants in this study are similar to those for inclusion of participants among ornithologists in national bird census programs, and all persons showing an interest in the project were welcome to participate.

Study sites were chosen by participants following requests for participation from amateurs who had previously expressed interest in this project. We asked more than 1000 amateurs in the amateur ornithology literature to participate, and all interested persons (50 in total) were asked to make contact through a web site.

### Methods for sampling insects and aerial insectivores

We have used novel insect surveys as sampled from the windscreens of cars across large spatial and temporal scales (Møller 2013, 2021; Tinsley-Marshall 2019).

The study took place in 3530 surveys in 16 countries with most surveys taking place in Poland 1799 surveys, Denmark 1320 surveys, Ukraine 106 surveys, Latvia 73 surveys, Spain 72 surveys and China 53 surveys. These surveys were conducted by 36 observers who participated in the study with the number of observers ranging from 1 to 505 transects, the number of transects being (SE) = 42.364 (16.807). The total number of transects was 1462 with a mean (SE) number of 22.960 insects per transect (SE = 3.992), or in total 33,568 insects. Transects were 1.2 to 1125 km long, with a mean (SE) = 24.487 km (1.390), or in total 35,800 km. Thus, there was 0 to 420.333 insects per km, on average 0.938 insects per km, SE = 0.216. Transects were made between February 3 and October 6, 2018 and 2019, mean June 15, SE = 1.1 days.

A web site named insectcount.dk was established on February 1, 2018 with information on the project in Danish and English, its purpose, a contact email address and an excel data sheet for entering data.

We also published an article in the Danish popular bird journal *Fugle & Natur* with a circulation of more than 16,000 on May 1, 2018.

We also asked national natural history or ornithology web sites for participants. These sites included web sites for citizen scientists in Finland, Belgium and Spain.

At the start of each survey the participants were asked to clear the windshield to ensure that it was completely clean. The data sheet requested information on locality, GPS coordinates as latitude and longitude for the start location, date, month, time of day, temperature (°C), wind (Beaufort units), precipitation (mm rain), cloud cover (in units of 0.125), number of Barn Swallows observed, number of Swifts observed, number of House Martins observed, number of insects counted on the windshield upon arrival, distance driven (km), speed of car (km/h), windshield area (height and width in cm) and car brand. The number of Swifts, Barn Swallows and House Martins observed from the car provided an estimate of the abundance of birds. Participants interested were asked to identify juvenile Barn Swallows and adult males and females according to the relative length of the tail with males having longer tails than females, while juveniles were aged according to them having considerably shorter outermost tails than adults (Svensson 1996; Møller 1994). Furthermore, mainly females feed the offspring, and males have considerably more rufous throat plumage than females. In addition, some were asked to record the noise when insects hit the front screen. In this way larger insects could be distinguished from smaller insects. The log number of times insects hit the front windscreen while emitting a sound was positively related to the log number of times insects hit the front windscreen [$F = 3.07$, df $= 1$, 359, $r^2 = 0.15$, $P < 0.0001$, estimate (SE) $= 0.222$ (0.028)].

Participants were only asked to survey insects when driving on roads that they would also have driven for other purposes. Hence participants were not asked to make detours in order to participate. There were no restrictions on the number of times that a survey of a given transect could be made nor to the landscapes and habitats along the roads. The number of insects on a survey was highly repeatable in an analysis of variance with the survey site being a factor (Møller 2013). Surveys were made between February and October 2018–2020 with most survey records taking place between March and September 2018.

We started a survey with a clean windscreen. Once we had terminated a survey, we carefully counted the number of insects on the windscreen. The windscreen was then cleaned again before starting a new survey. The number of bird species recorded was maximally three for a survey, and the numbers were recorded at a relatively slow speed. We used GPS to determine the exact location of a survey and this was subsequently used in Google Maps to identify the distance driven.

#### Fertilizer and pesticide use

We used data on land-use, and the amount of fertilizer and pesticides from EUROSTAT (2021) with data up to and including 2016 to allow for inclusion of data from countries beyond European countries in the European Community (EUROSTAT 2021).

We used information on chemicals for 2000–2017 derived from the following national statistics with values recorded nationally. Homepage https://ec.europa.eu/eurostat/databrowser/view/aei_pestuse/default/table?lang=en for pesticides and the following homepage for fertilizers https://ec.europa.eu/eurostat/databrowser/view/aei_fm_usefert/default/table?lang=en. Values for different years were strongly positively correlated showing that there was a high degree of consistency among years. The units for pesticides and acaricides were sales per country in kg. For nitrogen and phosphorous the units were tons per country. All official statistics were provided by EUROSTAT (2021). Information on area and area with agriculture were likewise derived from EUROSTAT (2021).

We used Principal Component Analysis to reduce the number of predictor variables from the amount of pesticides and acaricides, air pollutants, ammonium, area and agricultural area. The PCA was based on the correlation matrix with three eigenvales of 4.63, 1.20 and 1.05 accounting for 66.2%, 17.1% and 15.0% of the variance. PC1 was positively correlated with area, insecticides, air pollution and ammonia, non-methane pollutants amd ammonia with all five variables showing strong positive correlations (Table 1). This implies that PC1 showed strong positive correlations. PC2 was strongly positively correlated with fertilizer and negatively with agriculture suggesting that this variable is reflecting the amount of fertilizer relative to the area with agriculture (Table 1).

**Table 1** Principal component analysis for agro-chemicals and agricultural practice

| Loading matrix | PC1 | PC2 | PC3 | PC4 | PC5 |
|---|---|---|---|---|---|
| Fertilizer | 0.018 | **0.952** | 0.289 | 0.088 | 0.034 |
| Agriculture | − 0.117 | − 0.409 | **0.903** | 0.053 | 0.009 |
| Area | **0.950** | − 0.114 | − 0.296 | 0.092 | 0.012 |
| Insecticides | **0.949** | − 0.274 | − 0.041 | 0.091 | 0.116 |
| Air pollution | **0.961** | 0.124 | 0.191 | − 0.143 | − 0.032 |
| Non-methane pollutants | **0.983** | − 0.053 | 0.012 | 0.055 | − 0.164 |
| Ammonia | **0.962** | − 0.137 | 0.207 | − 0.88 | 0.008 |

We reduced the number of variables in a Principal Component Analysis based on the correlation matrix and the varimax rotation. The three principal components with eigenvalues larger than 1.0 are listed. The PCA resulted in three eigen-values of 4.63, 1.20 and 1.05 accounting for an accumulated amount of variance of 83.3% of the variance. The first PC had weights of 0.950 for agricultural area, 0.949 for insecticides, 0.961 for air pollution, 0.983 for non-methane and 0.962 for ammonia. PC2 had a weight of 0.952 for fertilizer and PC3 had a weight of 0.903 for agriculture. Variables larger than 0.4 are generally considered to be significant and they are highlighted in bold font

PC3 was strongly positively correlated with agricultural area thus reflecting the area of agricultural land (Table 1).

### Statistical analyses

First, we inspected the data for distribution and deviations from normality or binomial or Poisson distributions. Second, analyses of insect data and information on car features, climate and spatial and temporal variation were made using Generalized Linear Models (GLM). Third, data were inspected for goodness of fit to ensure that distributions did not deviate from normality. The PCA is reported in Table 1. The significance level was 0.05. Next, we analyzed the data using multivariate analyses of variance (MANOVA) for analysis of the data. The MANOVA was used for analyzing effects two or more factors and covariates in any single analysis. Three variables with two or more factors were used to test for interactions among variables. All analyses were made with JMP (SAS 2016).

We tested for repeatability as a measure of consistency in estimates using analyses of variance (Falconer and Mackay 1996; Bell et al. 2009).

The procedures for the statistical analyses were as follows. First, we inspected the data for distribution and deviations from normality or binomial or Poisson distributions depending on characteristics of the data. Second, analyses of insect data and information on car features (size of windshields), climate and spatial and temporal variation were made using Generalized Linear Models. Third, data were inspected for goodness of fit to ensure that distributions did not deviate from normality (or other distributions of observations). All statistical models, covariates, distributions of data link functions and fixed effects are reported in Table 1. The significance level was 0.05.

There was no evidence of collinearity between variables as revealed by variance inflation factors all being less than five (McClave and Sincich 2003). All analyses were made using JMP (SAS 2016).

## Results

### MANOVA and variation in abundance of insects among study plots

We tested for consistency in insect abundance and abundance of insectivorous birds across study sites (Table 2). There was a high consistency in insect abundance and abundance of insectivorous birds across study sites (Fig. 1).

Subsequently, we quantified the relationship between the abundance of the three species of aerial insectivorous birds (two species of swallows and a swift) and: (1) PC1 which represents air pollution such as $NO_x$, $VO_x$, ammonia and SO; (2) PC2 which represents fertilizer (nitrogen and phosphorus); and (3) PC3 represents general agricultural activity such as land-use. Table 2 is for principal components and Table 3 for multivariate analyses of variance (MANOVA). The number of Swifts decreased

**Table 2** Multi-variate analysis of variance (MANOVA) for insect in relation to the abundance of Swift, House Martin and Barn Swallow

| All between subject effects | Value | Exact *F* | Numerator df | Denominator df | *P* |
|---|---|---|---|---|---|
| All between | **2.57** | 5.22 | 421 | 853 | < 0.0001 |
| Intercept | **3.37** | 2877.39 | 1 | 853 | < 0.0001 |
| Locality | **2.56** | 5.22 | 1 | 853 | < 0.0001 |
| All within interactions | **0.09** | 4.86 | 842 | 1704 | < 0.0001 |

Effects in bold font are significant at the 5% level

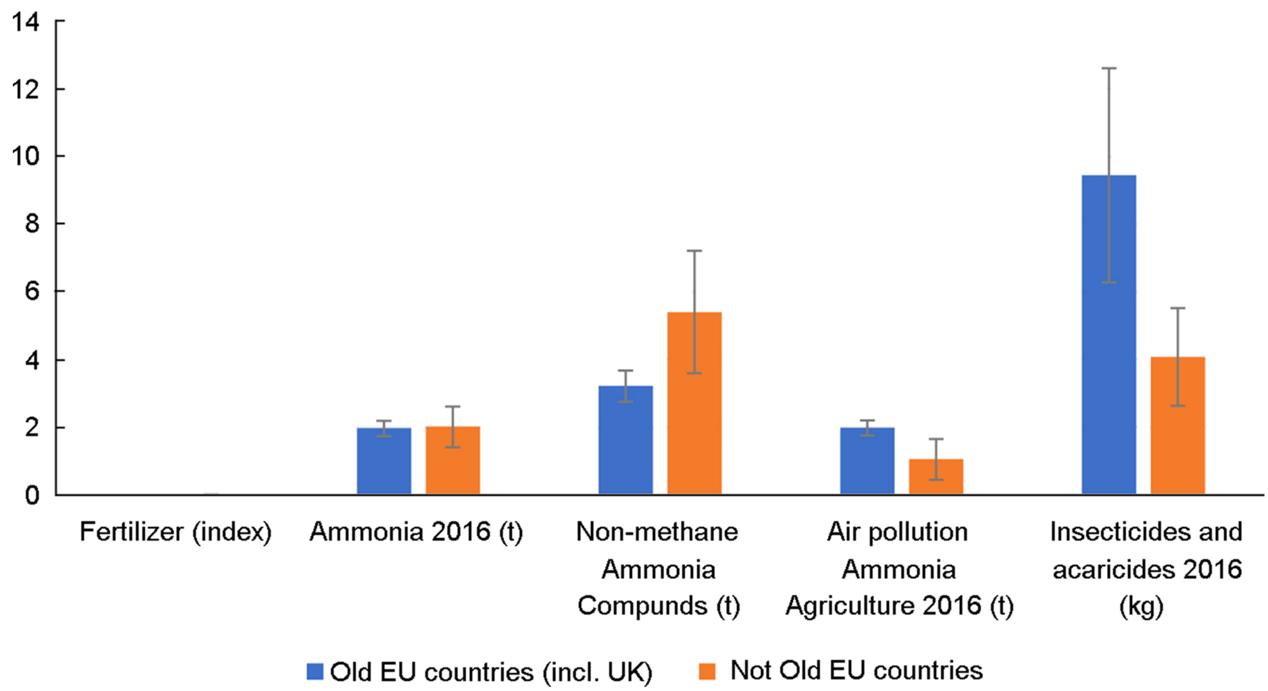


**Fig. 1** Mean (SE) fertilizer, ammonia, non-methane ammonia compounds, air pollution, ammonia and insecticides and acaricides in Old European Union (EU) countries and in recent (EU) countries. See Methods for sources

with the degree of air pollution (Fig. 2a, blue symbols and PC1), followed by the impact of fertilizer (Fig. 2a, green symbols and PC3), and by the effect of agriculture (Fig. 2a, red symbols and PC2 use). Table 3 showed significant effects of PC1 and PC3. The two-way interactions between species and PC1, PC2 and PC3, respectively, were all statistically significant (Table 3).

The number of House Martins decreased the least with pollution (Fig. 2b, blue symbols and PC1), followed by fertilizer (Fig. 2b, green symbols and PC2) and agricultural land (Fig. 2c, green symbols and PC3).

The number of Barn Swallows decreased the least with agricultural activity (Fig. 2c, green symbols and PC3), followed by the impact of fertilizer (Fig. 2b, blue symbols and PC1) and followed by the effect of agriculture (Fig. 2c, red symbols and PC2). The two-way interactions between the three bird species and PC1, PC2 and PC3, respectively, were all statistically significant (Table 3).

#### Number of insects

The slope of the relationship between the number of insects and the three principal components was independent of level of pollution (Fig. 3, blue symbols, PC1) and agricultural activity (Fig. 3, green symbols, PC3), while there was a negative correlation with fertilizer use (Fig. 3, red symbols, PC2). There were significant correlations for PC1 and PC3 (Table 4). The two-way interaction between female age and PC3 was significant (Table 4).

#### Date when insects were recorded

The date when insects were impacted by a car differed among principal components (Fig. 4). The slope of the relationship between the number of insects was related to two of the three principal components with a positive relationship with the amount of pollution (Fig. 4, blue symbols, PC1) followed by a negative impact of agricultural activity (Fig. 4, green symbols, PC2), but no correlation with fertilizer use (Fig. 4, red symbols, PC3). The two-way interactions between PC1 and PC3, on one hand, and Date were significant for pollution and agricultural practice (PC1 and Date and PC3 and Date) (Fig. 4; Tables 4, 5).

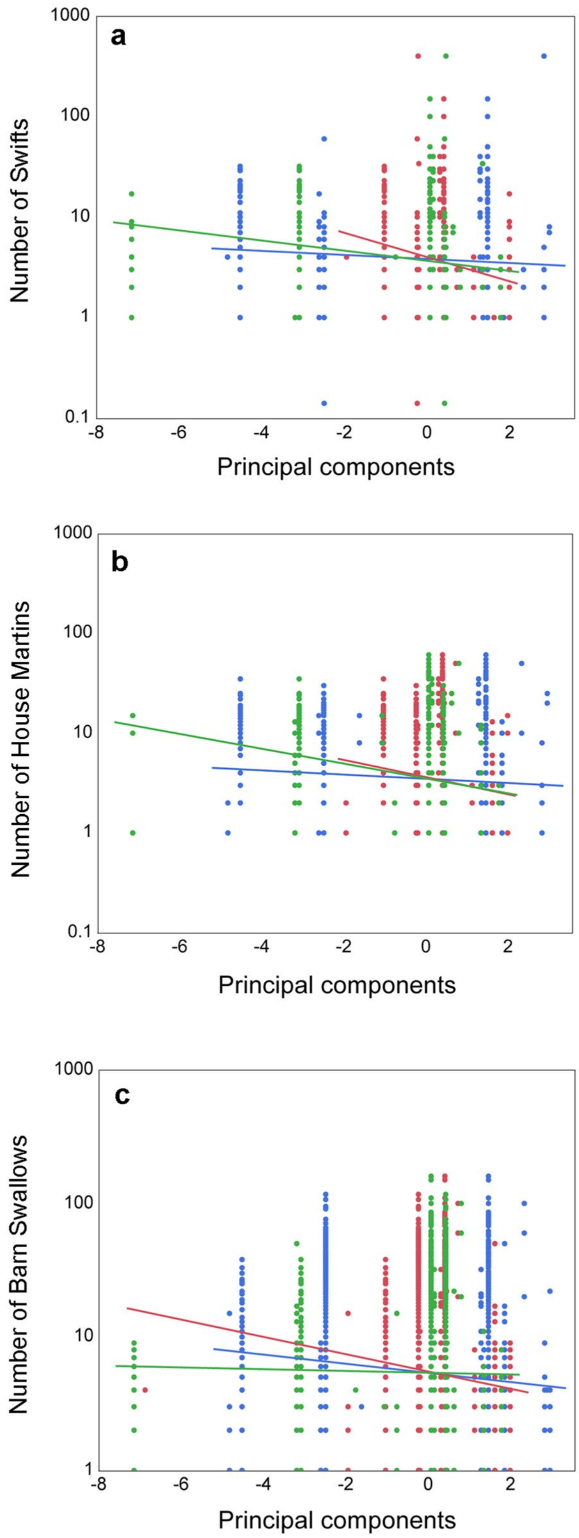


**Fig. 2** **a** The number of Swifts during surveys with cars in relation to three principal components with lines representing regression lines and SE. Red, blue and green lines represent PC1, PC2 and PC3. **b** The number of House Martins during surveys with cars in relation to three principal components with lines representing regression lines and SE. Red, blue and green lines represent PC1, PC2 and PC3. **c** The number of Barn Swallows during surveys with cars in relation to three principal components with lines representing regression lines and SE. Red, blue and green lines represent PC1, PC2 and PC3

## Discussion

The summer 2020 was by far the warmest on record during the last century (Di Liberto 2020), with expected negative correlations with phenology, fecundity, abundance and survival of vertebrates, but also invertebrates such as insects (Møller 2019). This provided beneficial conditions for studying the impact of extreme weather on the abundance of flying insects. The present study was designed to provide information on the correlation between phenology and air pollutants, fertilizer and agricultural land-use with predictions for the impact of PC1, PC2 and PC3 on abundance. The abundance of the three species of flying insectivorous birds was negatively related to farming variables with the most strongly negative correlations occurring for land-use followed by fertilizer and eventually pesticides. We analyzed differences in effects between countries, assuming that agricultural practice in the former socialist countries in Eastern Europe compared to differences between farming practice in Western European countries.

Insects have been shown to be particularly negatively affected by farming practice (Fox et al. 2014; Hallmann et al. 2014; Møller 2019; Raven and Wagner 2021). However, impacts of pesticides on insects are also likely to be negatively affected by neocotinoids (Hallmann et al. 2014) and other chemicals (Poulin et al. 2010).

We attempted to quantify the correlation between overall fecundity and mortality of insectivorous bird species due to increases in insect abundance and its component parts. We did so by investigating the correlations with abundance of juveniles and adult males and adult females, respectively, and date. Date was assumed to result in reduced fecundity due to delayed reproduction (Perrins 1965, 2009). Here we related the timing of reproduction, fecundity and survival to phenology. These correlations were partially related to pesticides, fertilizer and land-use, as we had predicted a priori.

**Table 3** Multi-variate analysis of variance (MANOVA) for principal component analysis (PCA) for pesticides, fertilizer and agricultural land-use in relation to the abundance of Swift, House Martin and Barn Swallow

| All between | Value | Exact *F* | Numerator df | Denominator df | *P* |
|---|---|---|---|---|---|
| All between-subject effects | **0.067** | **68.34** | **3** | **2957** | **< 0.0001** |
| Intercept | **0.923** | **2730.72** | **1** | **2957** | **< 0.0001** |
| PC1 | **0.017** | **48.87** | **1** | **2957** | **< 0.0001** |
| PC2 | 0.0002 | 0.74 | 1 | 2957 | 0.931 |
| PC3 | **0.022** | **66.02** | **1** | **2957** | **< 0.0001** |
| All within interactions | **0.963** | **18.85** | **6** | **5912** | **< 0.0001** |
| Species | **0.769** | **1136.57** | **2** | **2956** | **< 00010** |
| Species * PC1 | **0.026** | **37.87** | **2** | **2956** | **< 0.0001** |
| Species * PC2 | **0.011** | **16.16** | **2** | **2956** | **< 0.0001** |
| Species * PC3 | **0.016** | **23.97** | **2** | **2356** | **< 0.0001** |

Effects in bold font are significant at the 5% level

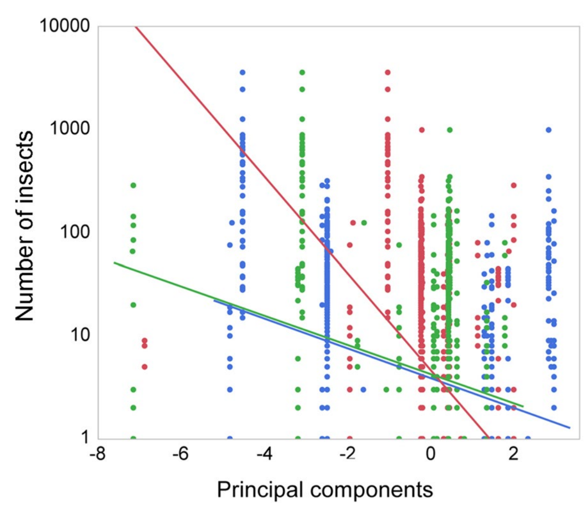


**Fig. 3** The number of insects making noise during surveys with cars in relation to three principal components with lines representing regression lines and SE. Red, blue and green lines represent PC1, PC2 and PC3

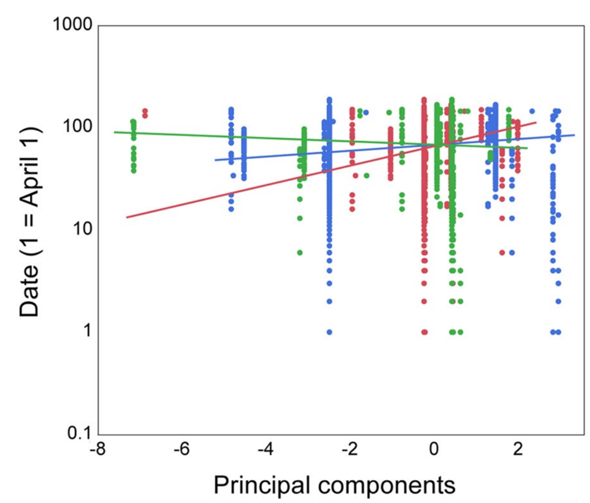


**Fig. 4** The time when recording insects on the windscreen of cars when date (1 = April 1) is related to three principal components with lines representing regression lines and SE. Red, blue and green lines represent PC1, PC2 and PC3

The present study is a unique citizen science project on the spatial correlations between current farming practices and the performance of aerially insectivorous birds. The study relies on spatial patterns of abundance of pesticides, insecticides and pollutants. We found evidence consistent with disappearance of flying insects, but also effects from altered land-use and agricultural activity on the abundance of insects killed on windscreens. These findings are consistent with multiple drivers linked to farming being responsible for these effects (Spiller and Dittmers 2019), or no effect of insect abundance on nestling survival or body mass, as shown in other studies (Imlay et al. 2017). Finally, we predict that similar effects may apply to higher trophic levels such as reductions in the abundance of predators that affect the abundance of insectivorous birds.

## Conclusions

Study plots were consistently different in relation to the number of insectivorous birds and the abundance of insects (Table 1). The effects of intensive agriculture on insect food abundance are likely to have negative consequences for population density and diversity of

**Table 4** Multi-variate analysis of variance (MANOVA) for principal component analysis (PCA) for pesticides, fertilizer and agriculture in relation to the number of juveniles and the number of adult Barn Swallows

| All between | Value | Exact *F* | Numerator df | Denominator df | *P* |
|---|---|---|---|---|---|
| All between | **0.095** | **11.84** | **3** | **374** | **< 0.0001** |
| Intercept | **0.720** | **269.31** | **1** | **374** | **< 0.0001** |
| PC1 | **0.089** | **33.47** | **1** | **374** | **< 0.0001** |
| PC2 | 0.002 | 8.68 | 1 | 374 | 0.417 |
| PC3 | **0.014** | **5.26** | **1** | **374** | **0.022** |
| All within interactions | **0.070** | **8.87** | **3** | **374** | **< 0.0001** |
| Female age | **0.580** | **216.90** | **1** | **374** | **< 00010** |
| Female age * PC1 | **0.026** | **9.63** | **1** | **374** | **0.002** |
| Female age * PC2 | 0.001 | 0.47 | 1 | 374 | 0.49 |
| Female age * PC3 | **0.045** | **16.76** | **1** | **374** | **< 0.0001** |

Effects in bold font are significant at the 5% level

**Table 5** Multi-variate analysis of variance (MANOVA) for sex of Barn Swallows in relation to principal components for pesticides, fertilizer and agriculture

| All between | Value | Exact *F* | Numerator df | Denominator df | *P* |
|---|---|---|---|---|---|
| All between-subject effects | **0.114** | **14.22** | **3** | **375** | **< 0.0001** |
| Intercept | **0.801** | **300.47** | **1** | **375** | **< 0.0001** |
| PC1 | **0.099** | **37.05** | **1** | **375** | **< 0.0001** |
| PC2 | 0.0012 | 0.66 | 1 | 375 | 0.50 |
| PC3 | **0.029** | **10.83** | **1** | **375** | **0.0011** |
| All within interactions | **0.092** | **11.52** | **3** | **375** | **< 0.0001** |
| Date | **0.003** | **1.16** | **1** | **375** | **< 0.0001** |
| Date * PC1 | **0.035** | **13.23** | **1** | **375** | **0.00003** |
| Date * PC2 | 0.006 | 2.23 | 1 | 375 | 0.14 |
| Date * PC3 | **0.015** | **5.78** | **1** | **375** | **0.017** |

Effects in bold font are significant at the 5% level

insects and their avian predators. This hypothesis was validated by showing a reduction in the abundance of insects as the intensity of agriculture increased. Furthermore, an increase in the abundance of insects was associated with an increase in the abundance of insectivorous birds. Finally, an increase in the abundance of insectivorous birds was negatively related to an increase in the abundance of fertilizers, and, a general positive change in intensity in farming practice was positively associated with a change in the abundance of insectivorous birds. These novel findings for insects and insectivorous birds have contributed to a better understanding of the factors determining the abundance of insect food for insectivorous birds.

**Acknowledgements**
Alexandr Artemyev, Jerzy Bańbura, Karen Andersen Bennedsen, Florentino de Lope, John Dowman, Pauline Dowman, Tapio Eeva, Kari Hongisto, Jianopin Liu, Jinmei Liu, Bruno Massa, Cezary Mitrus, Arne Moksnes, Federico Morelli, Zaid al Rubaiee, Diego Rubolini, Seppo Rytkönen, Nils Kristian Sallo, Chao Shen, Jacqui Shykoff, Luis Silva, Juan J. Soler, Lone Sønnichsen, Peter Teglhøj, Haitao Wang, Longwu Wang, Yuanxin Xu, Tiungting Yi, and Bo Zou kindly helped collect the extensive data. Niels Linneberg helped with establishment and maintenance of the web site.

**Data accessibility**
The data will be submitted to Dryad upon acceptance of the paper.

**Authors' contributions**
APM conceived and designed the experiments. APM, DC, EFJ, JE, KL, WL and WW performed the experiments. APM analyzed the data. APM, DC, EFJ, JE, KL, WL and WW wrote and edited the manuscript. All authors read and approved the final manuscript.

**Funding**
I.K. was supported by the Latvian Council of Science (grants lzp-2018/2- 00057 and lzp-2020/2-0271), W.L. was supported by the National Natural Science Foundation of China (Grant Nos. 31772453 and 31970427).

**Availability of data and materials**
The datasets analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Ethics approvals and consent to participate**
We only observed three species of insectivorous birds with no ethics approval being required.

**Competing interests**
The authors declare that they have no competing interests.

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Received: 4 April 2021 Accepted: 13 August 2021
Published online: 04 September 2021

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