Supplementary Material

Changing Migratory Behaviors and Climatic Responsiveness in Birds

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*Frontiers of Ecology and Evolution 7:89. (doi: 10.3389/fevo.2019.00089)*

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# Supplementary Data

Supplementary Data 1: The dataset used for phylogenetic analyses (Data Sheet 1.csv)

Supplementary Data 2: The composite phylogeny in Newick format (Presentation 1.pptx)

Supplementary Table 1: Overview of the time series used in the study (Table 1.xlsx)

# Supplementary Methods and Results

**First observation dates**

In the following analyses we addressed whether our first observation data and our conclusions are influenced by variation across species in data quality and detectability.

***Time series gaps***

The number of years with available FOD data per species in our analyzed dataset varies between 17 and 32, because some species were not detected in some years (see Supplementary Table 1 in separate file). It can be argued that missing data may bias our calculations of temporal changes in migratory behaviors. However, the number of gaps (i.e. years with missing data) per species was not correlated either with the slope of FAD over years (gaps ranging 0-15; Pearson correlation: r = -0.01, p = 0.911, N = 85) or the difference in overwintering frequency between the first and second half of the study (gaps ranging 0-2; Spearman rank-correlation: r = -0.08, p = 0.713, N = 22).

***Mode of detection***

Most of our species (N = 82) were observed both visually and acoustically, but some were typically detected by sound only (N = 25). It is possible that wintering individuals vocalize less and thereby are less likely to be detected as an overwinterer compared to species that are easy to see. However, our data do not support this concern, because the proportion of overwintering species (i.e. observed in more than one year wintering in HNP) did not differ significantly between heard-only (4/25) and seen-and-heard (18/82) species (Fisher’s exact test: p = 0.778).

***Habitat preferences***

The species’ habitat requirements may affect detectability in several ways. First, species that are associated with human settlements may be easier to detect in the winter, because such species are known to be more tolerant to the proximity of a human observer. However, the proportion of overwintering species did not differ significantly between species that do (4/12) or do not (18/95) winter near humans (Fisher’s exact test: p = 0.263). Furthermore, several human-tolerant species have increased their population sizes in human settlements recently, which might have caused higher detection probability of such species, resulting in an apparent increase in overwintering frequency or earlier arrivals. However, species that do not winter near humans and those that do did not differ significantly either in the change of overwintering frequency between the first and second half of the study (t-test: t = 0.97, df = 3.79, p = 0.389) or in the slope of FAD over years (t-test: t = 0.21, df = 7.53, p = 0.838).

Second, species that require wetland habitats may be easier to detect in HNP because a large proportion of the study area is covered by wetlands. This might result in an apparently higher overwintering frequency by waterbirds compared to species that do not require wet habitats in winter; however, our data did not support this (proportion of overwinterers among wetland species: 16/71, in non-wetland species: 6/36; Fisher’s exact test: p = 0.615).

***Population size***

Overwintering individuals as well as first-arriving migrants may be easier to detect when the population is large. We do not have data on annual population sizes of the species in our analyses, so we cannot statistically control for this effect in our calculations of FAD slopes or changes in overwintering frequency. However, we do have data on the estimated size of the European populations and on the qualitative trend of population sizes in HNP (see Methods in main text), which we included in our main analyses for the following reasons.

First, species that were observed in more than one year as overwinterers in HNP had about twice as large population size in Europe (median: 1,907,500 mature individuals) as species that were always or almost always observed as migrants (median: 986,500 mature individuals; see Table 1, Fig. 2c). Our qualitative data on HNP population sizes (i.e. small, medium or large) agree well with the numeric estimates on European population sizes (ANOVA: F2,104 = 28.01, p < 0.001; mean ± SE of log10[European population size] when HNP population is small: 4.98 ± 0.26, medium: 5.74 ± 0.16, large: 6.78 ± 0.11); all but one of our overwintering species (95.5%) have large HNP populations whereas 14.1% and 36.5% of non-overwintering species have small and medium population sizes, respectively, in HNP (χ2 test: χ22 = 15.35, p < 0.001).

Second, the apparent changes of migratory behaviors over time may be biased by changes in population size over time; for example, species with growing populations may appear to arrive increasingly earlier and/or to overwinter more often simply due to increasing chances of detection. Contrary to this expectation, we found no significant differences between species with stable, decreasing or increasing HNP populations either in FAD slope over time (ANOVA: F2,82 = 1.99, p = 0.142) or in the change in overwintering frequency (ANOVA: F2,19 = 1.46, p = 0.257). Nevertheless, the non-significant differences were in the expected direction, i.e. large population size tended to be associated with more negative FAD slopes (mean ± SE of FAD slope when HNP population is stable: -0.11 ± 0.04, decreasing: -0.03 ± 0.09, increasing: -0.23 ± 0.06) and greater increases in overwintering frequency (mean ± SE of difference in overwintering frequency between the first and second half of the study period when HNP population is stable: 0.11 ± 0.11, decreasing: 0.25 ± 0.12, increasing: 0.35 ± 0.08).

***Summary***

These results indicate that our data are appropriate for inter-specific comparisons of temporal changes in migratory behaviors. We do not claim that the factors investigated above have no effect on migration and overwintering in general; our point is that their stand-alone effects in our dataset are not strong enough to drive the patterns we found in our phylogenetic analyses, so the effects of ecological, life-history and weather-sensitivity variables cannot be attributed to time-series gaps, detection mode, or habitat type. Based on these results, we decided not to include the latter variables in our phylogenetic analyses, in order to keep the number of estimated parameters sufficiently low. We did include population size because the above analyses showed that it is a significant predictor of being detected as an overwinterer. Although the effects of population size trends were non-significant here, the tendencies in the data suggested that we might have missed some relevant variation among species due to the low resolution of our data on population trends. Considering this possibility and the fact that bias due to variation in population size is the most common criticism against first-observation data, we decided to include population trend in our phylogenetic analyses.

**Population size trends**

If Hungarian population trends in 2000-2017 were strongly related to HNP population trends in 1969-2006, the weak but non-excludable effects of population size on FOD data (see above) might confound our analysis of the relationship between migratory changes and subsequent population trends. However, we found the two datasets statistically independent, as there was no association between population trend categories during and after our study (Supplementary Table 2; Fisher’s exact test: p = 0.921).

**Supplementary Table 2.** Number of species with decreasing, stabile, or increasing population trends during our study in Hortobágy National Park and subsequently in Hungary.

|  |  |  |  |
| --- | --- | --- | --- |
| Population trends in Hungary 2000-2017 | Population trends in  HNP 1969-2006 | | |
| Decreasing | Stabile | Increasing |
| Decreasing | 2 | 9 | 10 |
| Stabile | 0 | 5 | 4 |
| Increasing | 1 | 5 | 8 |