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Supplementary material: Range and climate niche shifts in European and North American breeding birds

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Supplementary Figures

General workflow (Figure S1)

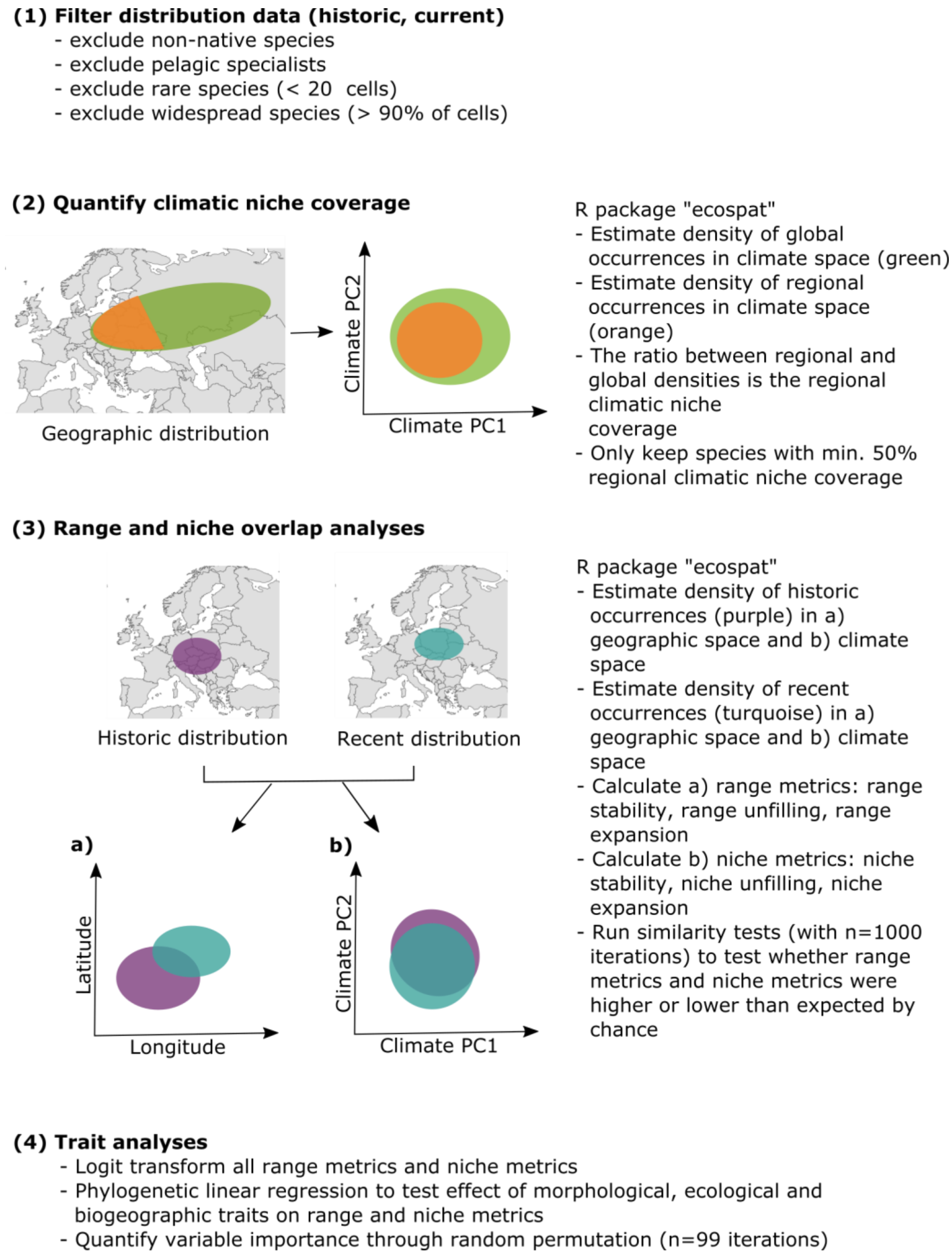

Figure S1. Overview of data preparation and data analyses steps.

Results of climatic niche coverage analyses (Figure S2)

Climatic niche coverage, meaning the proportion of the global climatic niche represented in the study region, was much lower in European breeding birds (ranging 4-100 %, mean 43 %) than in conterminous US (ranging 21-100 %, mean 88 %, Fig. S2). This is rather unsurprising as the ranges of many European breeding birds also stretch into Asia or Northern Africa.

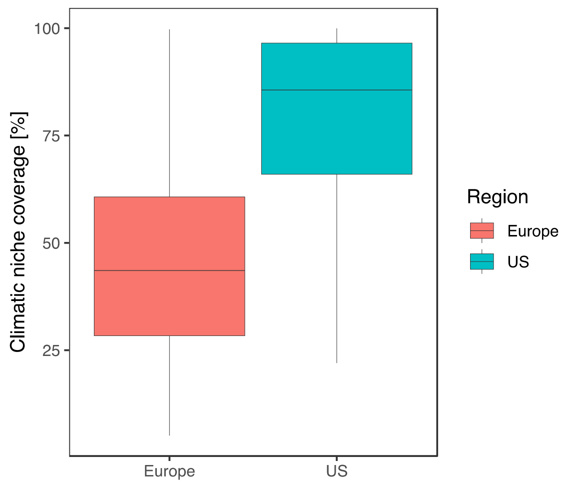

Figure S2. Climatic niche coverage calculated as proportion of global climatic niche of each species that is represented in the study region (Europe and conterminous US, respectively). The global and regional climatic niches were quantified using kernel density estimation within the first two axes of a Principal Component Analysis over the 19 bioclimatic variables.

Changes in species richness between 1980s to 2010s (Figures S3-S4)

For the remaining species, changes in species richness were observed for both regions but species gains and species losses showed large spatial variation with no clear latitudinal or longitudinal trends (Figs. S3-S4).

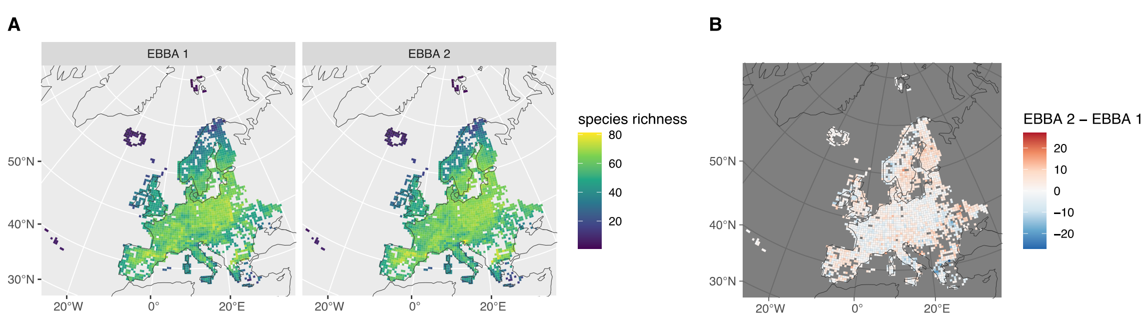

Figure S3. Species richness of European breeding birds considered in the range and niche shift analyses (n=114). (A) Species richness in the first atlas period (EBBA1, 1985-1988) and in the second (EBBA2, 2013-2017). (B) Differences in species richness between the two atlas periods (red indicates species richness gains in recent periods, blue indicates species loss).

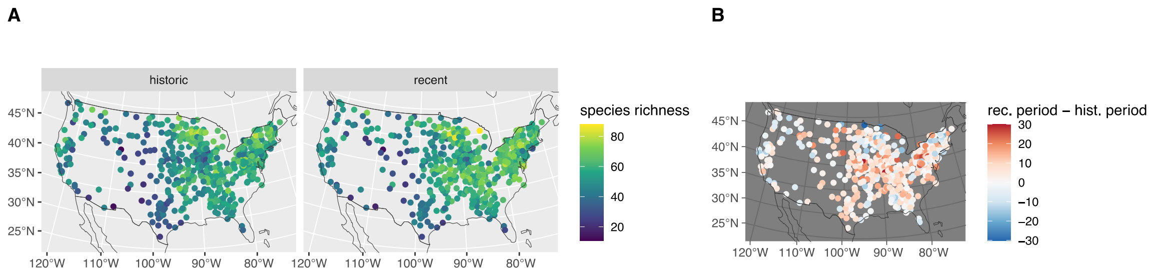

Figure S4. Species richness of (conterminous) US breeding birds along the considered routes. Only species are considered that were selected in the final range and niche shift analyses (n=195). (A) Species richness in the historic time period (1981-1983) and in the recent time period (2016-2018). (B) Differences in species richness between the two time periods (red indicates species richness gains in recent periods, blue indicates species loss).

Climate change gradients (Figures S5-S6)

In Europe, the PCA indicated a strong climatic gradient from warm-dry to cool-wet climates (PC1) and a gradient from less seasonal (with mild rainy winters) to highly seasonal climates (PC2; Fig. S5). Changes in the PCA scores over time indicated trends towards warmer and drier climate in Western Mediterranean and Central Europe and towards wetter climate in Eastern Mediterranean and Scandinavia, and a decrease in seasonality in Northern Europe. Thus, climatic changes varied from South or Southwest to North or Northeast in Europe. In North America, PCA suggested a strong climatic gradient from highly seasonal to warm-wet climates (PC1) and a gradient from cool-wet to warm-dry climates (PC2; Fig. S6). Over the study period, climate became warmer and wetter towards the East, and drier and less seasonal towards the West. Thus, there is a strong East-West gradient of climate change in North America.

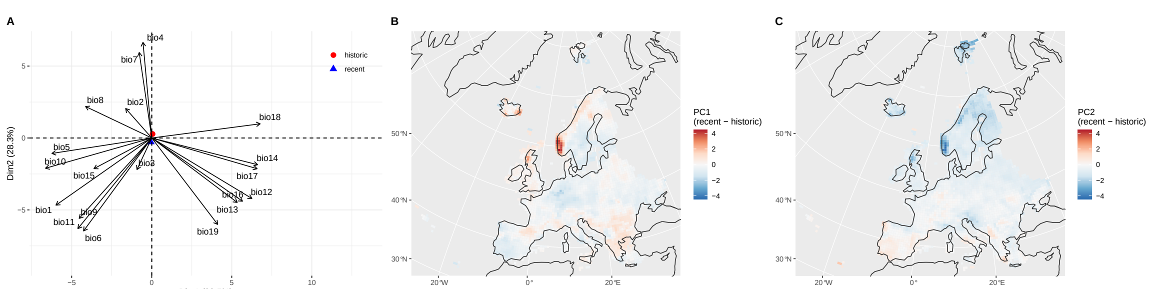

Figure S5. Changes in European climate between atlas periods. (A) Biplot of principle component analysis (PCA) of European climates. The arrows indicate the loadings of the 19 bioclimatic variables on the first two PCA axes. The points indicate the PC scores for the historic period (red; 1984-1988) and for the recent period (blue; 2012-2017). (B) shows the changes of PC1 scores and (C) of PC2 scores between the two time periods.

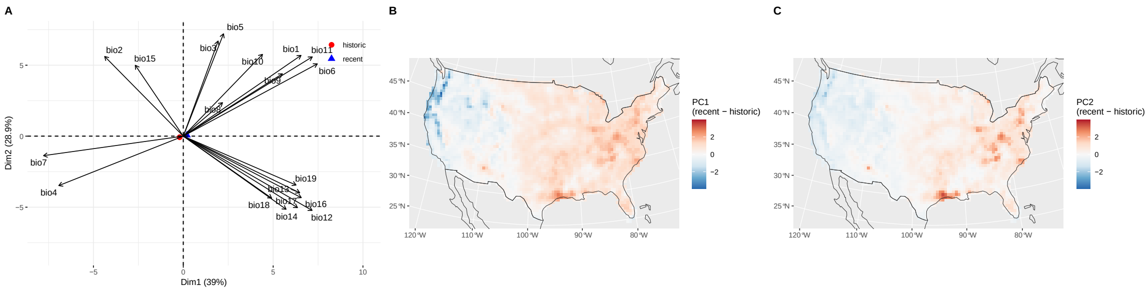

Figure S6. Changes in climate of conterminous US between two study periods. (A) Biplot of principle component analysis (PCA) of conterminous US climates. The arrows indicate the loadings of the 19 bioclimatic variables on the first two PCA axes. The points indicate the PC scores for the historic period (red; 1980-1983) and for the recent period (blue; 2015-2018). (B) shows the changes of PC1 scores and (C) of PC2 scores between the two time periods.

Observed range shifts and directions (Figures S7-S8)

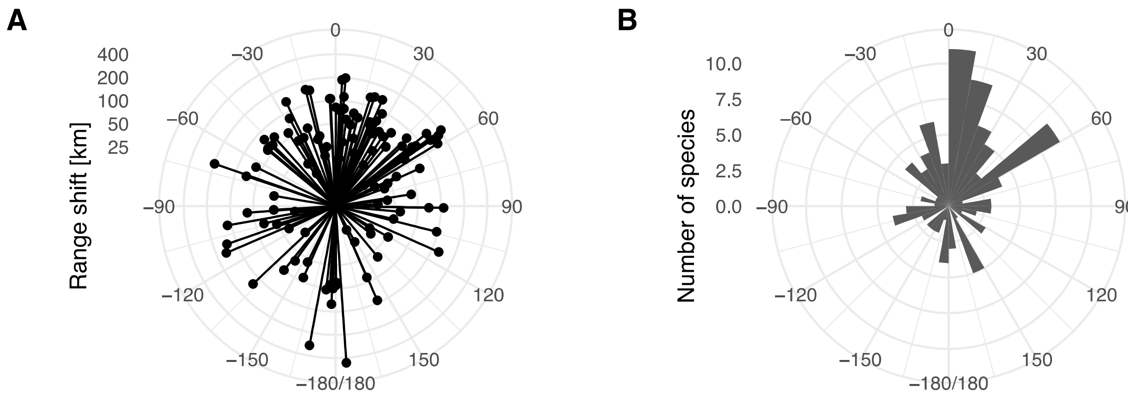

Figure S7. Range shifts of studied European breeding birds (n=114) between the first (1985-1988) and second atlas period (2013-2017). (A) shows the direction and log-transformed distances of range shifts. (B) shows the number of species per direction.

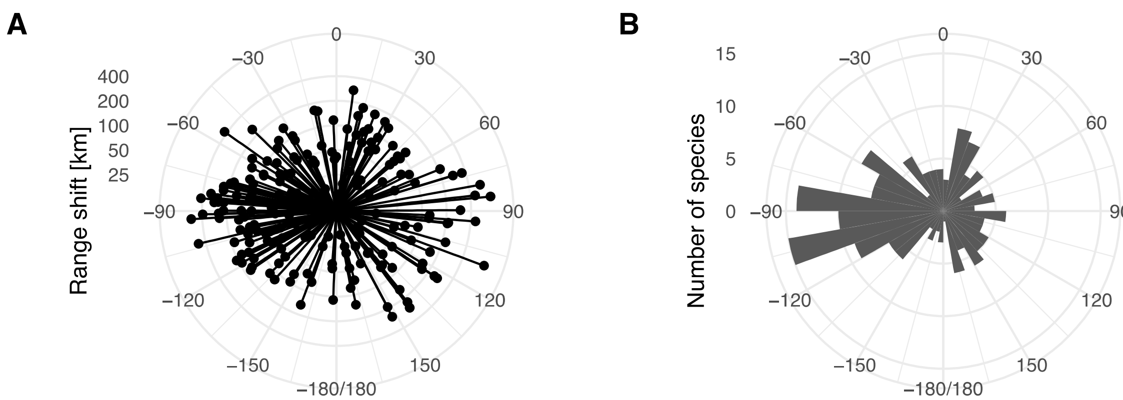

Figure S8. Range shifts of studied (conterminous) US breeding birds (n=195) between the first (1981-1983) and second time period (2016-2018). (A) shows the direction and log-transformed distances of range shifts. (B) shows the number of species per direction.

Results of range and niche overlap analyses (Figures S9-S11)

Range overlap and niche overlap estimated by Schoener's *D* between the historic and recent study periods were high in both regions, although significantly higher for European birds than for North American birds as indicated by Wilcoxon rank sum tests (Fig. S9). In Europe, almost 99-100 % of the species had significantly higher range and niche overlap than expected by chance, and in North America 98 % and 90 % of the species showed significant range overlap and niche overlap, respectively (Fig. S9). For both study regions, we found a significantly positive correlation between range overlap and niche overlap, although correlations were higher for European birds (Pearson correlation r = 0.89) than for North American birds (r = 0.54; Fig. S10).

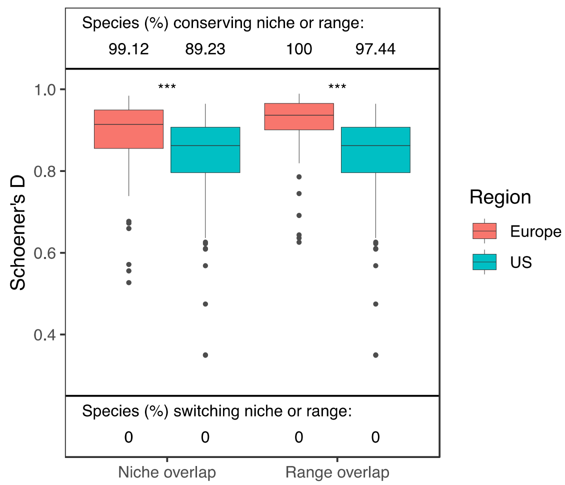

Figure S9. Niche and range overlap estimated by Schoener's *D* for European (n=114) and (conterminous) US breeding birds (n=195). Top and bottom row indicate results from similarity tests (n=1000 replicates), separately testing for significantly higher overlap than expected by chance (indicating niche or range conservatism) and significantly lower overlap than expected by chance (indicating niche or range switching). Asterisks indicate significant differences in means estimated by a Wilcoxon rank sum test (* $p < 0.001$).**

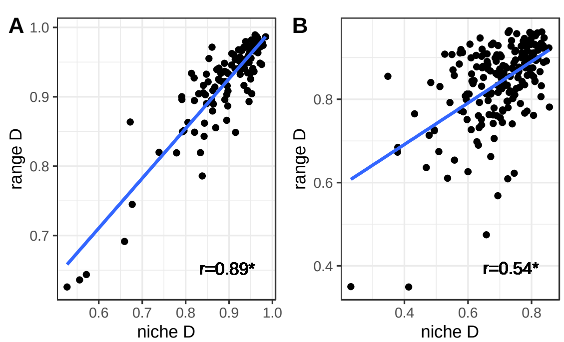

Figure S10. Correlations between niche and range overlap (Schoener's *D*). (A) Niche and range overlap for European breeding birds (n=114) between the first (1985-1988) and second atlas period (2013-2017). (B) Niche and range overlap for US breeding birds (n=195) between the first (1981-1983) and second time period (2016-2018). Each panel shows the Pearson correlation coefficient r. Asterisks indicate significant correlation (p < 0.05).

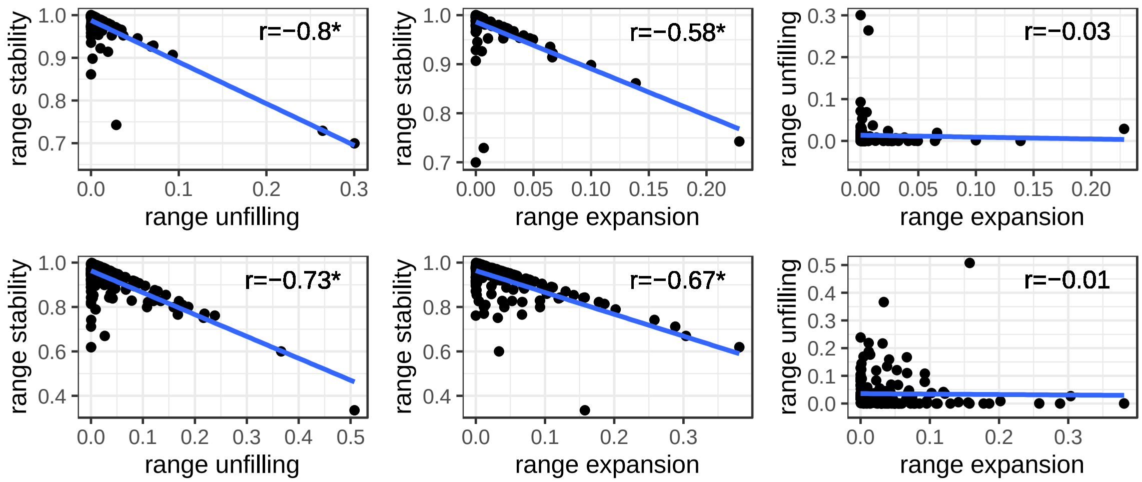

Figure S11. Correlations between different range metrics. (Top) European breeding birds (n=114) between the first (1985-1988) and second atlas period (2013-2017). (Bottom) US breeding birds (n=195) between the first (1981-1983) and second time period (2016-2018). Each panel shows the Pearson correlation coefficient r. Asterisks indicate significant correlation ($p < 0.05$).

Sensitivity analyses of range and niche dynamic metrics in US (Figure S12)

As the time difference between the historic and recent time period was slightly larger in the analyses of North American breeding birds, we repeated analyses for shorter time difference that is more comparable to the European data. Results were qualitatively similar with higher niche dynamic metrics in North American compared to Europe, although niche conservatism was slightly higher when considering a shorter period of climate change (Fig. S12).

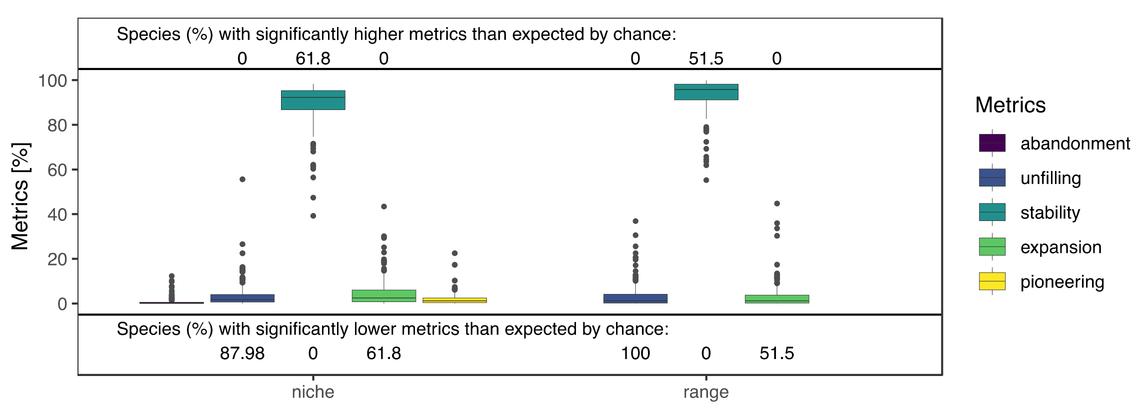

Figure S12. Niche and range dynamics for (conterminous) US breeding birds (n=195) when considering 1988-1990 as historic period. Significance was tested by similarity tests (n=1000 replicates), separately testing for significantly lower and higher metrics than expected by chance. Similarity tests cannot distinguish abandonment or pioneering from unfilling or expansion; hence they were only run for unfilling and expansion in analogue climates.

Correlations between range and niche dynamic metrics (Figures S13-S14)

We found consistent correlation patterns between range dynamic and niche dynamic metrics for the two study regions (Figs. S13-S14). Range expansion showed a significantly negative correlation with niche stability and a significantly positive correlation with niche expansion. Range stability had a significantly positive correlation with niche stability and a significantly negative correlation with niche unfilling and niche expansion. Range unfilling had a significantly negative correlation with niche stability and a significantly positive correlation with niche unfilling. There was no significant linear correlation between range expansion and niche unfilling. Nevertheless, niche unfilling only occurred when range expansion was low. Range unfilling and niche expansion showed a weak positive correlation for US breeding birds but not for European birds.

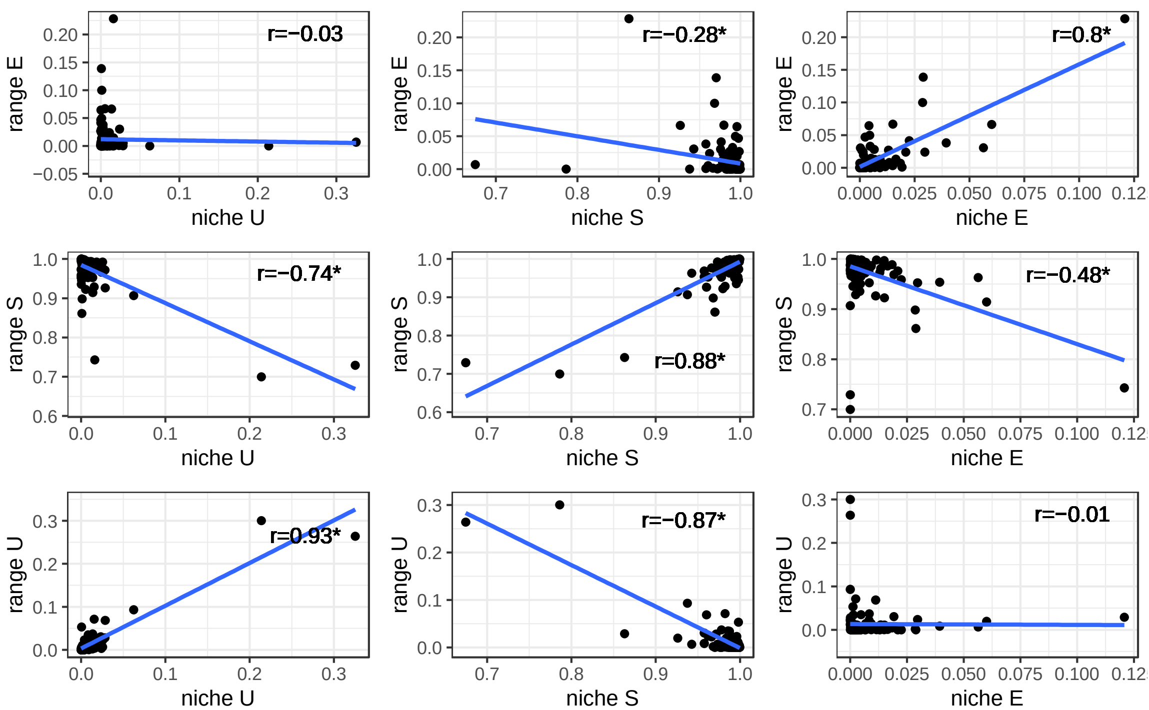

Figure S13. Correlations between niche and range metrics for European breeding birds (n=114). Range and niche metrics were calculated between the first (1985-1988) and second atlas period (2013-2017). Each panel shows the Pearson correlation coefficient r. Asterisks indicate significant correlation ($p < 0.05$).

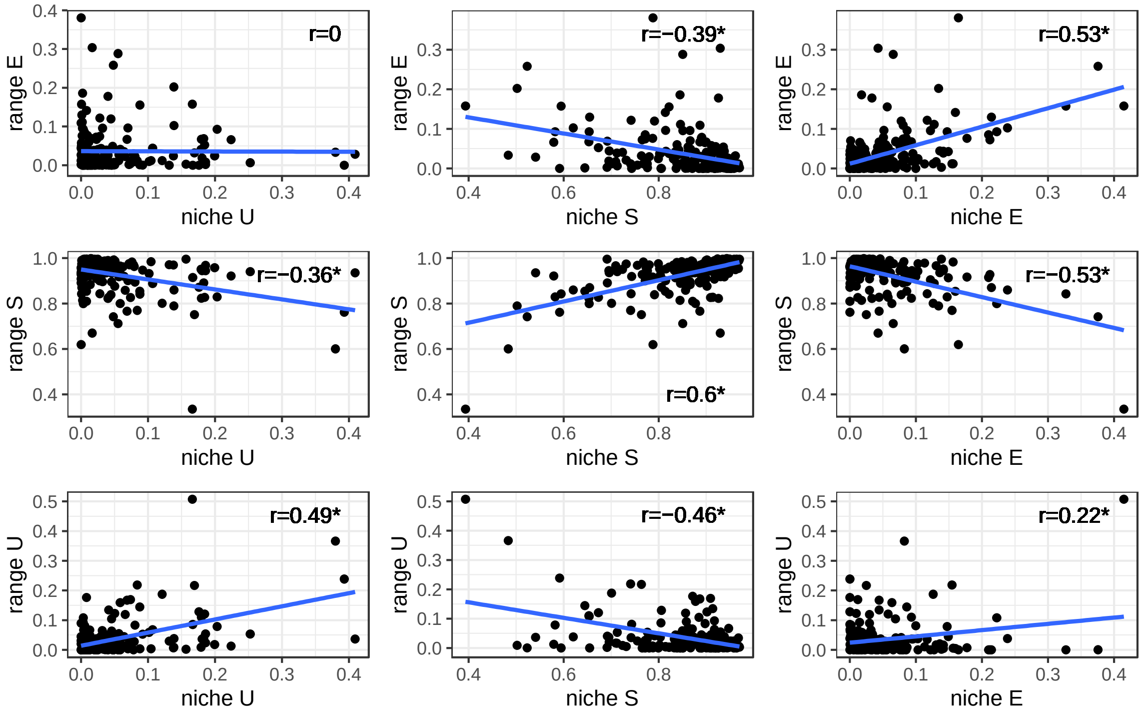

Figure S14. Correlations between niche and range metrics for North American breeding birds (n=195) in conterminous US. Range and niche metrics were calculated between the first (1981-1983) and second time period (2016-2018). Each panel shows the Pearson correlation coefficient r. Asterisks indicate significant correlation ($p < 0.05$).

Supplementary Tables

Interpretation guide for similarity tests of range and niche metrics (Table S1)

Table S1. Interpretation of similarity test for range and niche metrics. Significant range and niche conservatism are shaded in green, significant range and niche non-conservatism are shaded in red.

Metric	Similarity test results: Observed metric is significantly lower than expected by chance	Similarity test results: Observed metrics is significantly higher than expected by chance
Range overlap	Range switching	Range lagging
Range stability	Range switching	Range lagging
Range expansion	Range front lagging	Range switching
Range unfilling	Range rear lagging	Range switching
Niche overlap	Niche switching	Niche tracking
Niche stability	Niche switching	Niche tracking
Niche expansion	Niche tracking	Niche switching
Niche unfilling	Niche tracking	Niche switching