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Original Research Article

Identifying global hotspots of avian trailing-edge population diversity

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A B S T R A C T

Climate change is causing the ranges of many species to shift poleward and to higher elevations. Trailing-edge populations near the low-latitude edge of a shifting range are predicted to be at high risk of climate-induced extinction, but conservation efforts are hindered by a lack of information about the global distribution of trailing-edge populations. We used a large spatial dataset on the ranges of nearly all extant avian species to identify potential hotspots where trailing-edge populations represent a large proportion of the total avifauna. We identified potential trailing-edge population hotspots by isolating and overlaying low latitude regions of species' ranges, and computing the proportion of total species richness in a location comprised of low-latitude populations. We identified potential hotspots on all continents other than Antarctica. Potential trailing-edge population diversity was highest near the equator, low-latitude margins of mountain ranges, desert edges, and along coastlines. Because a potential trailing-edge population hotspot might not be an actual trailing-edge population hotspot if the low-latitude populations are not declining, information on population trends is necessary for confirmation. As a case study, we focused on one of the identified hotspots, the Southern Appalachian Mountains, where our analysis indicated that 30 bird species have potential trailing-edge populations. Even though more population studies have been conducted in the Appalachian Mountains than in most of the other potential hotspots that we identified, there was insufficient information available from the high elevations where these species occur to make strong inferences about population declines. Our research highlights the need for a concerted effort to gather more information about population trends in the regions we identified as potential hotspots of trailing-edge population diversity.

Global environmental change is causing the ranges of many species to shift poleward and to higher elevations (Parmesan and Yohe, 2003; McDonald et al., 2012; Morelli et al., 2012; Auer and King, 2014; Mason et al., 2015). Although range shifts are expected to become more pervasive, their outcomes and consequences are difficult to predict without a thorough understanding of the underlying ecological processes. Several studies have investigated recent range shift dynamics by focusing on high-latitude, leading-edge populations, but little work has been done on trailing-edge populations (Angert et al., 2011; Cahill et al., 2014; Beauregard and de Blois, 2016). Trailing-edge populations are populations near the receding margin of a shifting species range (Hampe and Petit, 2005), and information about trailing-edge populations is needed because they are predicted to be at high risk of climate change induced extinction (Cahill et al., 2014).

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Although it has been argued that conservation efforts should not target low viability populations (Gilbert et al., 2019), loss of trailing-edge populations could negatively affect regional biodiversity because they represent a large portion of species richness in some regions (Cahill et al., 2014). Additionally, loss of trailing-edge populations could have detrimental impacts on species-level genetic diversity because these populations are often older and more genetically diverse than populations at the range center or leading-edge (Hampe and Petit, 2005; Ferrari et al., 2018). Conservation of trailing-edge populations requires information about their global distribution, but distributional data is lacking. Although there is a dearth of spatial data available on trailing-edge population distributions, their distributions must be shaped by the same factors that influence species' range limits, which is a subject that has been extensively studied for over a century (Darwin, 1859; MacArthur, 1972; Gross and Price, 2000).

The relative influence of biotic interactions and abiotic conditions on species distributions often varies spatially and among species, making it difficult to predict where the diversity of trailing-edge populations is likely to be highest. At a coarse scale, range limits are often shaped by continental geology. For example, in the Americas, physical features such as the Andes and the Rocky Mountains influence the longitudinal range boundaries of many species (Baselga et al., 2012). Conversely, in the Eurasian landmass, longitudinal limits are often shaped by the east-west orientation of mountain ranges (Baselga et al., 2012). Latitudinal limits often occur in the absence of predominant physical landforms, potentially as the result of competition and other biotic interactions (MacArthur, 1972; Cahill et al., 2014). However, for species adapted to cool climates, low-latitude range limits regularly occur near the southern terminus of mountain ranges (Stefanescu et al., 2004; Wilson et al., 2005).

Their unique genetic structure and high extinction risk make trailing-edge populations an important conservation priority, but no studies have attempted to document the global diversity and distribution of trailing-edge populations. One challenge that hinders efforts to identify the global distribution of trailing-edge populations is that spatial datasets on ranges are not available for many species. Birds are an exception, and we used a large dataset on the global distribution of nearly all extant avian species to identify potential trailing-edge population hotspots: regions where trailing-edge populations comprise a large portion of the local avifauna. Birds are also a useful taxonomic group to focus on because they occur on all continents. One difficulty associated with identifying trailing-edge population hotspots is that a population can only be considered a trailing-edge population if the population is declining. We therefore sought to confirm the status of one potential trailing-edge hotspot, the Southern Appalachian Mountains, where we expected to find more information on population trends than in other parts of the world.

1. Methods

1.1. Identifying potential trailing-edge population hotspots

We identified regions of high trailing-edge population diversity using range maps provided by BirdLife International for nearly all extant avian species (Birdlife International and Handbook of the Birds of the World, 2018). The BirdLife International range map dataset was provided as a collection of polygon shapefiles. For migratory species, separate range maps were provided for breeding and non-breeding season ranges. For simplicity, we discarded range maps for migration routes and nonbreeding grounds, although shifting nonbreeding ranges are certainly important from a conservation standpoint. We limited our analysis to terrestrial species because range maps for pelagic species are often more indicative of foraging locations than of breeding sites. We converted polygons to rasters with 1.2 km resolution using the 'raster' package (v 2.7—15) in R (Hijmans et al., 2018; R Core Team, 2018).

Because temperature niches appear to be shifting to higher latitudes, with species expected to follow, we identified potential trailing-edge population hotspots by isolating low-latitude portions of species' ranges. We used two thresholds, the 5th and 10th percentiles, to crop the low-latitude region of each species' range. Specifically, our algorithm involved: (1) computing the area of the entire range, (2) computing the area of a subset of the range defined by an increment of one degree of latitude from the equator, and (3) computing the percentage of the range within this subset. The algorithm stopped if the percentage of the area of the subset was greater than the threshold at the end of step (3). Otherwise, steps (2) and (3) were repeated by adding an additional increment of one degree of latitude. In some cases, for example when a species' range was restricted to a small island, the entire range of a species occurred within a single degree of latitude. We discarded these species because the designation of a trailing-edge population is arbitrary for such a small range. After running the algorithm for all species, we overlaid each subset and computed the total number of low latitude populations at each cell of 1.2 km resolution global raster layer. We designated potential trailing-edge population hotspots as regions where 15% of the avifauna was comprised of low-latitude populations and where at least 10 low-latitude populations were present.

1.2. Trailing-edge populations in the Southern Appalachian Mountains

A population can be classified as a trailing-edge population if it occurs near the receding edge of a shifting range, which by definition, suggests that trailing-edge populations are experiencing local population declines (Hampe and Petit, 2005; Koen et al., 2014; Mota et al., 2015). Without knowledge of global population trends, we refer to the regions identified above as *potential* trailing-edge population hotspots. To confirm whether a potential hotspot could be considered an actual trailing-edge population hotspot, we focused on the Southern Appalachian Mountains of the United States, one of the most diverse regions in the temperate zone and a region where long-term trend data is available (SAMAB, 1996; Riddell et al., 2018).

The region is large, covering over 37 million acres and encompassing the headwaters of several major rivers (SAMAB, 1996). Forests in this region are diverse, ranging from bottomland hardwoods at low elevations to spruce-fir forests at high elevations (Yarnell, 1998). They are distinct from the northern Appalachian Mountains because they escaped glaciation during the last glacial maximum (Walker et al., 2009).

To verify that the potential trailing-edge populations have been experiencing population declines, we used publicly available Breeding Bird Survey (1966–2015) estimates to assess population trends of birds in the Southern Appalachian Mountains (Sauer et al., 2015). We subsetted trend estimates by bird species and by region. Regions included the Appalachian Mountains (S28), Alabama (ALA), Georgia (GA), North Carolina (NC), Tennessee (TEN), West Virginia (WV), and Virginia (VA). The Appalachian Mountain region (S28) also includes Kentucky, Ohio, Pennsylvania, New Jersey, and New York which are not considered part of the Southern Appalachian Mountains. We assessed the regional credibility measure codes for each trend estimate. Credibility measures are as follows: G – representing the highest quality data, described as having at least 14 samples over the entire study period; Y – Data with a deficiency, such as low abundance estimates, fewer than 14 routes sampled, or imprecise results; R – Data where regional abundance estimates are very low, fewer than 5 routes sampled, or results are extremely imprecise.

2. Results

2.1. Potential trailing-edge population hotspots

All terrestrial avian populations along the equator are, by definition, potential trailing-edge populations because they occur at the lowest possible latitude at similar elevations (Fig. 1a–b). Thus, it is unsurprising that areas near the equator had the highest trailing-edge population diversity. Specifically, equatorial South America, equatorial east Africa, and Indonesia had the highest diversity of potential avian trailing-edge populations. Equatorial South America and Africa had just under 500 species with trailing-edge populations identified using the 10th percentile threshold, and approximately 330 bird species identified using the 5th percentile threshold (Fig. 1a, Appendix 1a).

Beyond the equatorial zone, regions with high potential avian trailing-edge population diversity occur near low-latitude margins of mountain ranges, deserts, and coastlines (Fig. 1a–c). In addition, northern Australia and southern India were highlighted as having high potential avian trailing-edge population diversity with 100–120 species. Other hotspots include southern Iran and Pakistan, the northwest coast of Africa, the southern coast of California, the Central Rocky Mountains, the Southern Appalachian Mountains, the Gulf Coast of North America (including S. Florida), the northern Andes, the Southern Himalayan mountains, the Korean Peninsula, and the Indochina Peninsula (Fig. 1d).

2.2. Trailing-edge populations in the Southern Appalachian Mountains

Our results indicate that the Southern Appalachian Mountain region is a hotspot of trailing-edge population diversity, with 30 species of birds having their low-latitude breeding range limit occurring in this region (Fig. 2). The Southern Appalachian Mountains had many more potential trailing-edge populations than in the surrounding Piedmont, Coastal Plain, and Alleghany Plateau (Figs. 2 and 3). Approximately 20% of the avifauna in the Southern Appalachian Mountains is comprised of species with potential trailing-edge populations in the region (Fig. 3).

We found Breeding Bird Survey (BBS) population trend estimates for 29 of the 30 bird species on our list of species with trailing-edge populations in the Southern Appalachian Mountains (Table 1). There were no estimates for northern saw-whet owl (*Aegolius acadius*). For some species, like black-throated green warbler (*Setophaga virens*) and blue-headed vireo (*vireo solitarius*), trend estimates were available for every state in the region (Sauer et al., 2015). For other species, like Canada warbler and dark-eyed junco, trend estimates were available for only a few states, even though these species are known to breed in most states in the region (Nolan et al., 2002; Reitsma et al., 2009; Sauer et al., 2015). Breeding Bird Survey data indicate that five of the 29 bird species showed negative trends and two showed positive trends (95% CIs excluding zero) in the Appalachian Mountains during the most recent decade (2005–2015, Table 1). Three of the five negative trends and both positive trends were reported to have at least one data deficiency, as described in the Methods section. Twenty-two species had population trends with 95% CIs including zero. Four species showed a decline, and 14 increased (95% CIs excluding zero), over the entire 49-year study period (Table 1, Sauer et al., 2015). Unfortunately, 21 of 29 trend estimates were reported as having one or more data deficiencies over the time period. These estimates are from a region which includes states north of the Southern Appalachian Mountains, but data sparsity and data quality issues became even more problematic when we tried to conduct an analysis of state-level trends. Specifically, many species on our list were not sampled in every state although they are known to breed there. This is likely because most BBS routes do not sufficiently sample high elevations. Additionally, 95% of state level trend estimates had at least one data deficiency or were not available for some species (Appendix 4).

3. Discussion

Conserving global biodiversity requires more than preventing species-level extinctions. The high levels of genetic and phenotypic diversity among populations within species indicates that attention must be given to the most vulnerable population segments within a species' range (Hughes et al., 1997). Trailing-edge populations are predicted to be the most

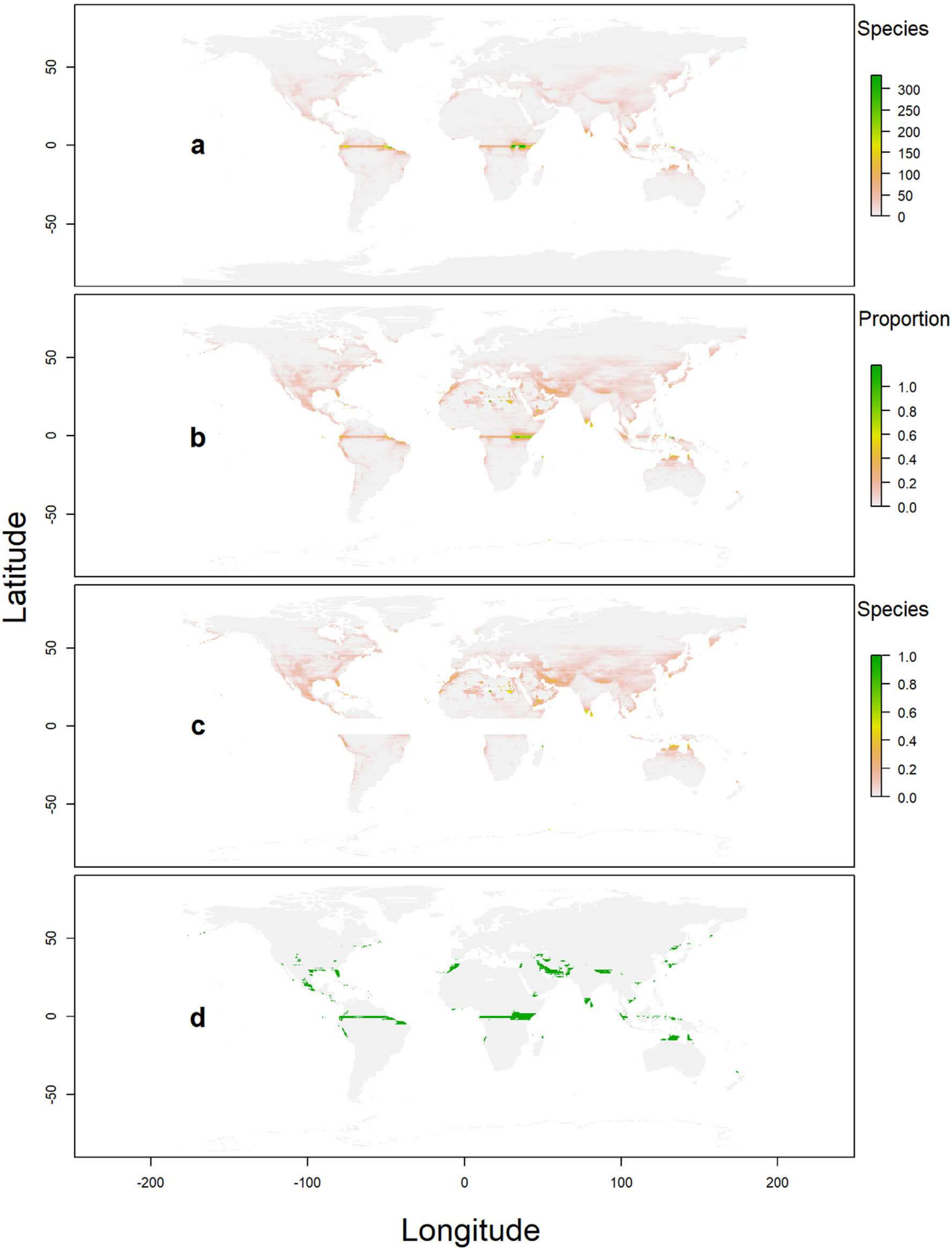

Fig. 1. Global diversity and distribution of potential trailing-edge populations of bird species represented by (a) species richness and (b) proportional richness of local avifauna. Regions within five degrees of latitude north or south of the equator are removed in panel (c). Panel (d) indicates regions where ≥15% of the local avifauna is comprised of potential trailing-edge populations, excluding areas with fewer than 10 species. Low-latitude range segments were defined as the lower 5th percentile of each species' range. See Appendix 1 for low-latitude segments using 10th percentiles of each species' range.

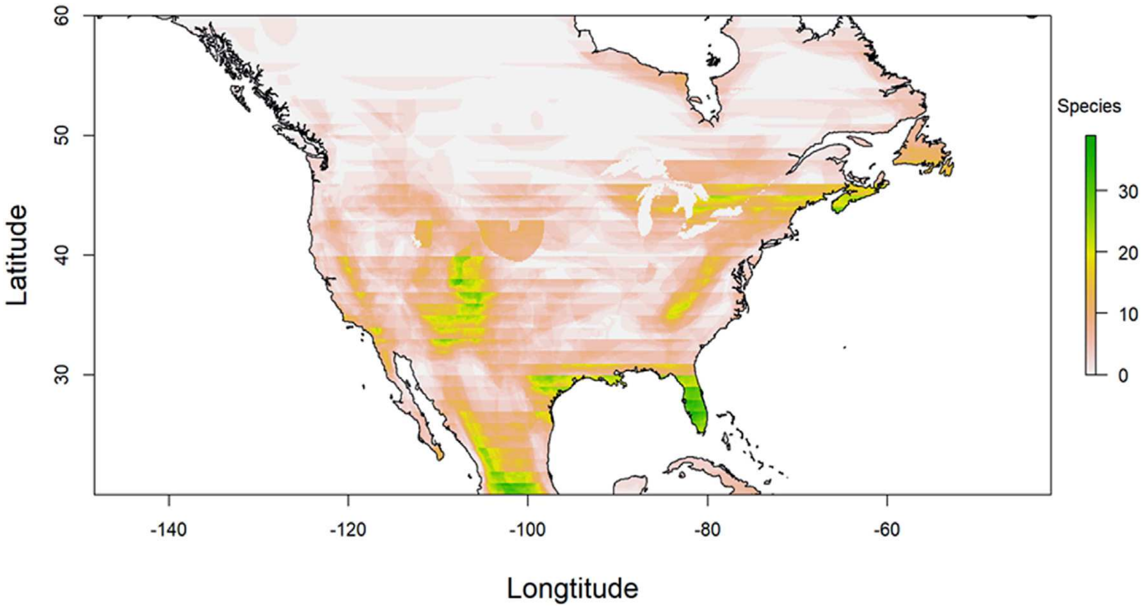

Fig. 2. Distribution of potential avian trailing-edge populations in North America. Colors indicate the number of species with low-latitude range segments at each terrestrial location. Low-latitude range segments were defined as the lower 5th percentile of each species' range. See Appendix 2 for low-latitude segments using 10th percentiles of each species' range. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

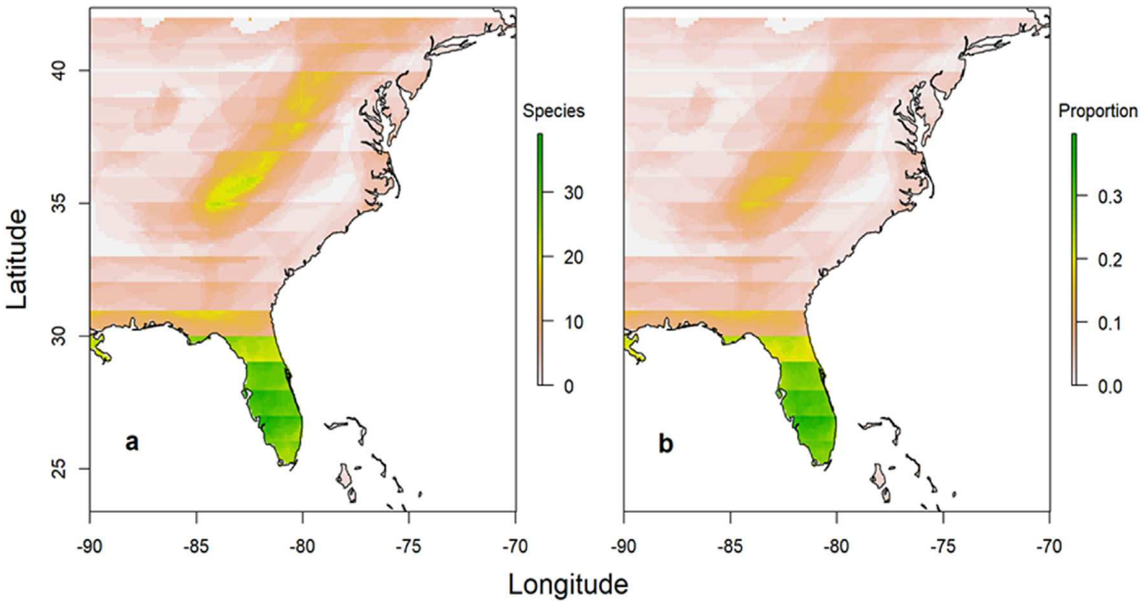

Fig. 3. Diversity and distribution of trailing-edge populations in the Southeastern United States, represented by (a) species richness and (b) the proportion of the local avifauna comprised of potential trailing-edge populations. Both figures used the lower 5th percentile to designate low-latitude range segments for each species. See Appendix 3 for low-latitude segments using 10th percentiles of each species' range.

vulnerable population segments to climate-induced extinctions, and our results represent the first effort to describe the global distribution of trailing-edge populations and to identify trailing-edge population diversity hotspots (Hampe and Petit, 2005).

Our analysis of the ranges of all extant terrestrial bird species indicated that the highest diversity of potential trailing-edge populations occurred along the equator, where overall vertebrate biodiversity is greatest (Pianka, 1966; Myers et al., 2000; Pimm et al., 2014). We also found that trailing-edge population diversity was high near the low-latitude margins of mountains, deserts, and coastlines. Many of these regions are also recognized as important hotspots of species-level

Table 1
Breeding Bird Survey trend estimates, 95% credible intervals, and regional credibility measure codes (*G − representing the highest quality data, described as having at least 14 samples over the entire study period; Y − Data with a deficiency, such as low abundance estimates, fewer than 14 routes sampled, or imprecise results; R − Data where regional abundance estimates are very low, fewer than 5 routes sampled, or results are extremely imprecise*) for bird trailing-edge populations in the southern Appalachian Mountains. For all species a trend estimate is available for the entire Appalachian Mountain range (Sauer et al., 2015). See Appendix 4 for state-level trend estimates.

Species	1966–2015 Trend Est. (CI)	2005–2015 Trend Est. (CI)	Regional Credibility Measure
Sharp-shinned hawk(*accipter striatus*)	1.51 (0.40, 2.44)	1.94 (−0.92, 4.66)	R
Ruffed grouse (*Bonasa umbellus*)	−1.55 (−3.09, −0.11)	−0.83 (−4.91, 3.05)	R
Yellow-bellied sapsucker (*Sphyrapicus varius*)	5.81 (4.30, 7.20)	1.02 (−1.92, 3.91)	Y
Alder flycatcher (*Empidonax alnorum*)	2.77 (1.62, 3.99)	−0.31 (−3.46, 2.65)	Y
Least flycatcher (*Empidonax minimus*)	−2.46 (−3.04, −1.93)	−2.49 (−4.15, −0.85)	G
Blue-headed vireo (*Vireo solitarius*)	3.16 (2.15, 4.09)	1.42 (−0.32, 3.20)	Y
Common raven (*Corvus corax*)	4.48 (3.37, 5.45)	5.59 (3.11, 7.97)	Y
Black-capped chickadee (*Poecile atricapillus*)	0.65 (0.19, 1.11)	−0.97 (−2.39, 0.36)	G
Red-breasted nuthatch (*Sitta canadensis*)	4.10 (2.71, 5.47)	3.89 (−0.33, 8.03)	R
Brown creeper (*Certhia Americana*)	0.47 (−0.90, 1.81)	0.93 (−2.72, 4.05)	Y
Winter wren (*Troglodytes hiemalis*)	2.74 (1.16, 4.30)	−3.50 (−7.83, 0.19)	Y
Golden-crowned kinglet (*Regulus satrapa*)	1.13 (−0.83, 3.12)	0.36 (−5.99, 5.42)	R
Veery (*Catharus fuscescens*)	−0.32 (−0.68, 0.04)	0.34 (−0.54, 1.36)	G
Hermit thrush (*Catharus guttatus*)	2.31 (1.28, 3.39)	0.19 (−2.44, 2.85)	Y
Swainson's thrush (*Catharus ustulatus*)	2.04 (−0.63, 4.94)	1.27 (−7.15, 6.98)	R
Cedar waxwing (*Bombcilla cedrorum*)	1.64 (1.00, 2.24)	1.31 (−0.49, 3.13)	G
Golden-winged warbler (*Vermivora Chrysoptera*)	−8.56 (−9.77, −7.29)	−7.65 (−10.95, −3.05)	Y
Chestnut-sided warbler (*Setophaga pensylvanica*)	0.00 (−0.68, 0.58)	−0.63 (−1.89, 0.55)	G
Magnolia warbler (*Setophaga magnolia*)	2.39 (1.63, 3.15)	2.65 (0.26, 4.62)	Y
Black-throated blue warbler (*Setophaga caerulescens*)	0.22 (−0.93, 1.22)	−0.25 (−2.09, 1.46)	Y
Blackburnian warbler (*Setophaga fusca*)	−0.16 (−1.31, 0.84)	−3.01 (−5.39, −0.68)	Y
Yellow-rumped warbler (*Setophaga coronate*)	2.13 (0.23, 4.00)	−5.86 (−10.50, −1.19)	Y
Black-throated green warbler (*Setophaga virens*)	1.19 (0.53, 1.82)	0.3 (−1.10, 1.71)	G
Northern waterthrush (*Parkesia noveboracensis*)	−1.52 (−3.27, 0.28)	−0.62 (−4.97, 4.94)	R
Mourning warbler (*Geothlypis philadelphia*)	−0.38 (−2.58, 1.21)	0.13 (−3.76, 3.63)	Y
Canada warbler (*Cardellina canadensis*)	−1.00 (−2.32, 0.16)	−0.19 (−2.20, 1.85)	Y
Rose-breasted grosbeak (*Pheucticus ludovicianus*)	−0.82 (−1.35, −0.28)	−2.64 (−4.37, −1.03)	G
Dark-eyed junco (*Junco hyemalis*)	1.36 (0.62, 2.06)	1.36 (−0.27, 2.93)	G
Purple finch (*Haemorhous purpureus*)	0.02 (−0.73, 0.74)	−1.03 (−3.37, 1.13)	Y

biodiversity (Myers et al., 2000). For example, Brazil's Atlantic Coast, Caucasus, Mesoamerica, South-Central China, and Western Ghats/Sri Lanka are all listed by Myers et al. (2000) as being important biodiversity hotspots. However, several regions that we identified as potential trailing-edge population hotspots are not considered to be biodiversity hotspots, including northern Australia, northwestern Africa, eastern Asia, southeastern United States (primarily Florida), and the central Rocky Mountains of the United States. The discordance between trailing-edge population hotspots and overall biodiversity hotspots highlights the need for conservation efforts to focus on both population-level and species-level patterns of diversity.

Our method of identifying potential hotspots of trailing-edge population diversity relied on range maps and an algorithm based on latitude. Consistent with previous efforts to identify hotspots (Marchese, 2015), our aim was not to model species distributions, only to identify where potential trailing-edge populations occur. Indeed, range maps can be regarded as outcomes of simple species distribution models, and we therefore did not use climate variables or elevation in our analysis because the effects of these variables are already represented in species range maps. Additionally, we only focused on the lowest-latitude portions of the range and not the entire low-latitude margin of a species' range, which might span thousands of miles, because the most sensitive populations to climate change are predicted to be at the lowest latitudes of the existing range (Cahill et al., 2014). An alternative approach to identify trailing-edge populations could have focused on both low latitudes and low elevations; however, the effect of elevation can be negligible in some parts of a species' range, suggesting that an algorithm based on an interaction between latitude and elevation would be necessary. We did not have sufficient data to parameterize such an algorithm. Finally, non-breeding season distributions are important to the viability of many species (Marra et al., 2015; Taylor and Stutchbury, 2016) and investigating their response to environmental change should be a focus of future research.

Our results demonstrate that the Southern Appalachian Mountains harbor a high diversity of potential avian trailing-edge populations. However, trend estimates in this region are based on sparse data that were not sufficient for making strong inferences about population declines. For example, state-level trend estimates are unavailable for many bird species, and over half of the estimates for birds with trailing-edge populations in the Southern Appalachian Mountains had a data deficiency. This was especially apparent at high elevations, indicating that this region would benefit from additional high elevations routes or that different survey methods may be necessary. Even though data quality was poor in this region, it can still be considered data rich compared to other regions around the world where trend estimates are completely unavailable.

Although we have made progress towards identifying the global distribution of trailing-edge hotspots, much of the information needed to guide conservation efforts in the face of rapid environmental change is lacking. Specifically, most of the forecasts of range shifts have not been based on mechanistic models that include ecological processes (Iverson et al., 2008; Matthews et al., 2011; Prasad et al., 2013). Understanding how population processes such as survival, recruitment, and movement are affected by environmental and biological change is key to future conservation efforts and should be a research priority (Chandler et al., 2018). It is also unknown how biotic interactions, like competition and predation, will affect these populations or whether trailing-edge populations are able to adapt fast enough to changing biotic and abiotic pressures (Sekercioglu et al., 2008; Riddell et al., 2018; Urban, 2015). In addition, a greater understanding of the physiology of species at their low-latitude range limit is needed because many populations at range boundaries occur near their physiological limits (Riddell et al., 2018).

To advance knowledge of trailing-edge populations and the ecological processes contributing to range shifts, we suggest a global-scale research initiative is needed to evaluate hypotheses by coupling observational studies with manipulative experiments (Cotterill and Foissner, 2010). To properly identify causes of range shifts at low latitudes, observational data is needed to quantify long-term trends in population parameters. Furthermore, the addition of occupancy, mark-recapture, and natural history data would allow for inference on spatial and temporal variation in demographic processes contributing to these shifts (Royle et al., 2013). While collecting these data at large spatial scales is difficult, it may be possible to pair this data with count or rapid assessment data (Chandler et al., 2018). Although it would be logistically challenging, combining large scale observational work with manipulative experiments may be the best approach to identifying the causal relationships underlying range shifts.

Our work provides a first glimpse into the global diversity and distribution of trailing-edge populations, but additional research is needed. By following the research agenda outlined above, the understanding of how climate change impacts range shifts can be advanced beyond simple identification and forecasts of species distributions. Moving beyond conventional species distribution modeling to understand the demographic mechanisms involved with range shifts at the trailing-edge, and at other portions of the range, will provide the information necessary to inform conservation efforts aimed at mitigating the impacts of climate change on global biodiversity.

4. Data availability

The avian range data used in this analysis is available by request from BirdLife International. USGS Breeding Bird Survey data is publicly available at https://www.pwrc.usgs.gov/bbs/

Author contributions

S.A.M. wrote and formatted the manuscript, formatted the data, and conducted the analysis. R.B.C. conceived the ideas, planned the analysis, and edited the manuscript.

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.

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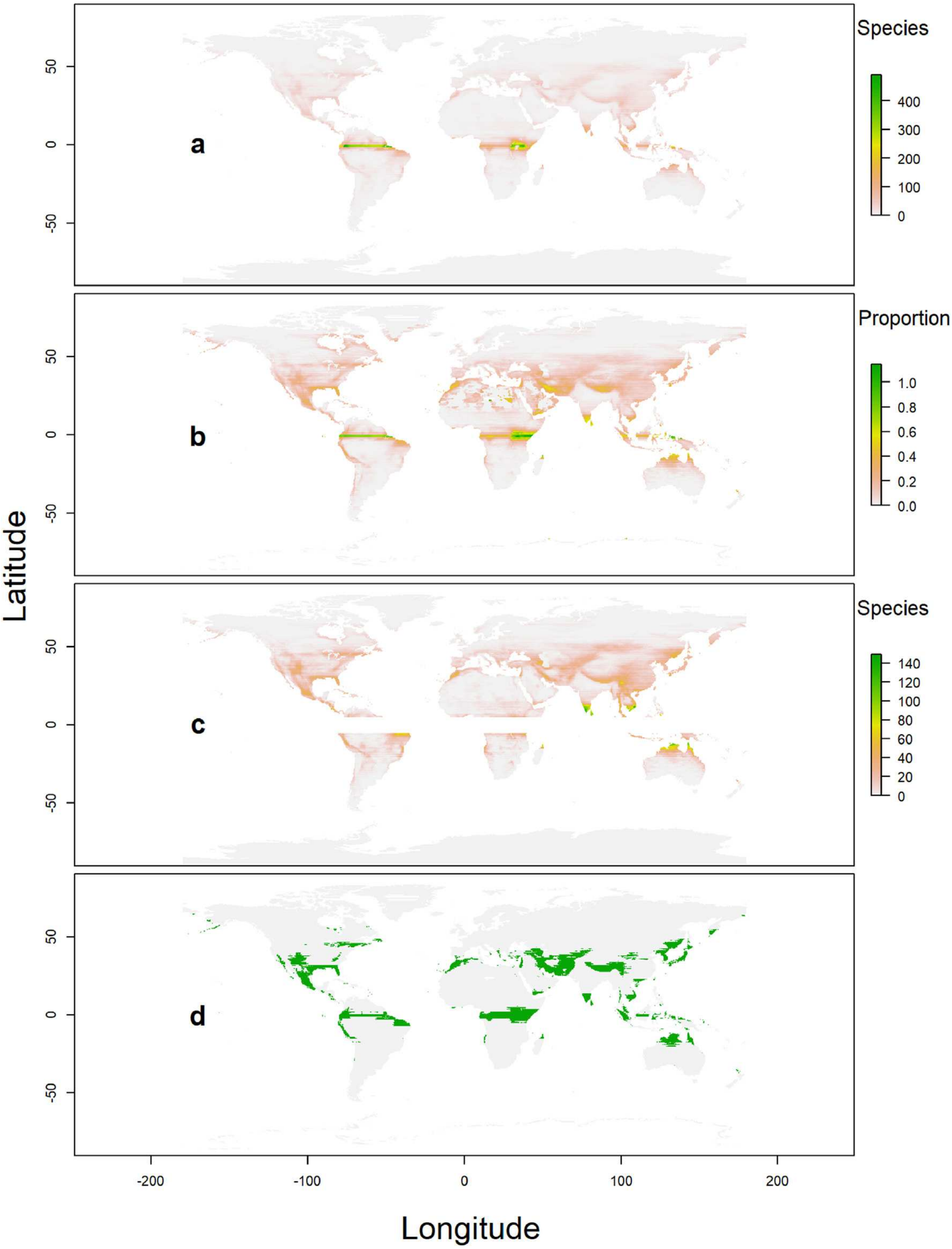
Appendix A. Supplementary data

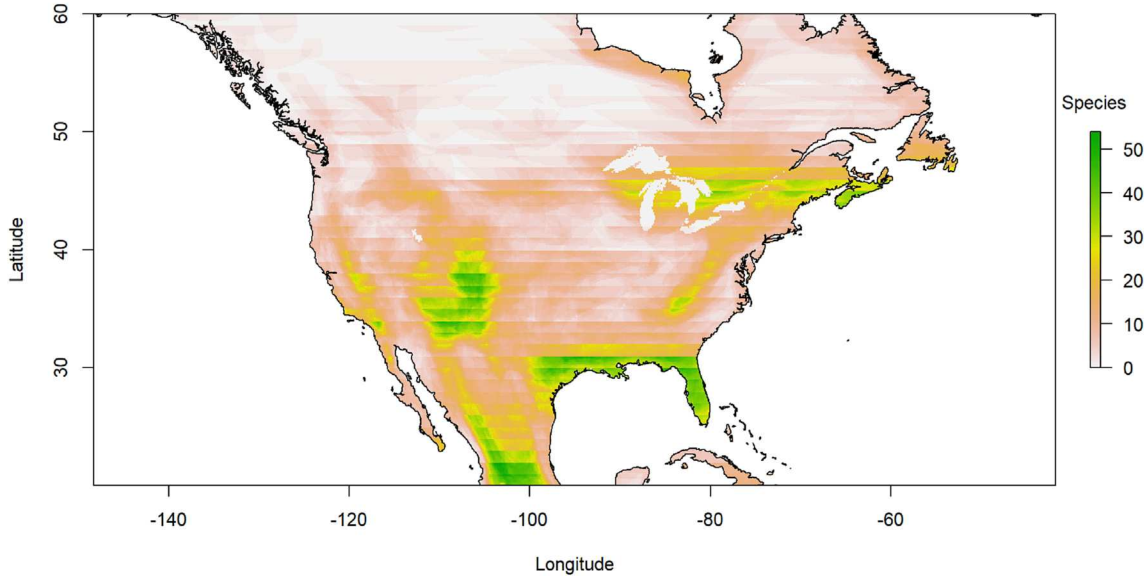
Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2020.e00915.

Appendix



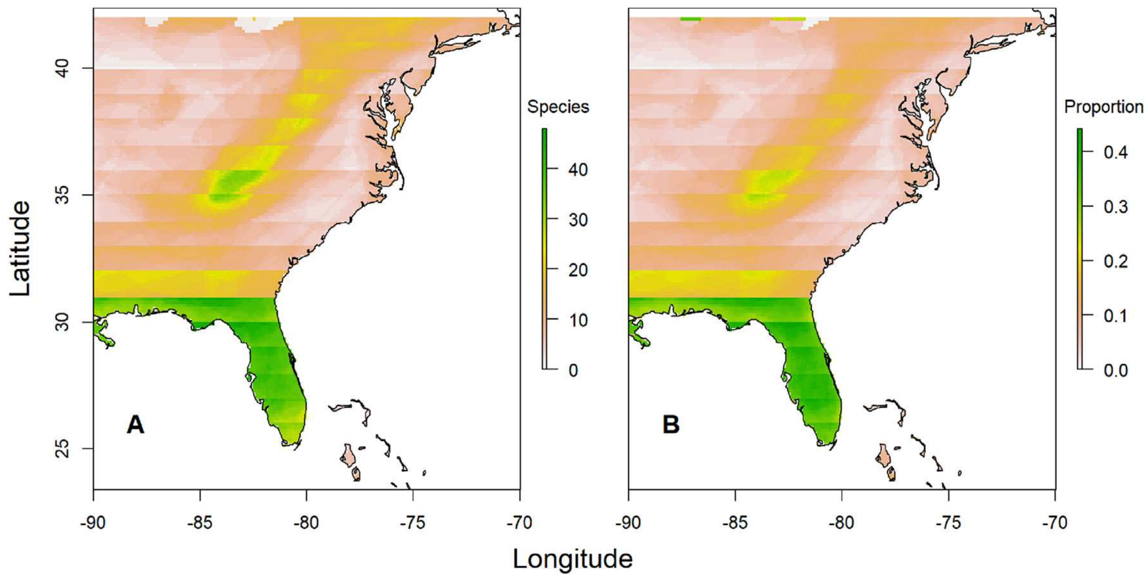
Appendix 1

Global diversity and distribution of potential trailing-edge populations of bird species represented by(a) species richness and (b) proportional richness of local avifauna. Regions within five degrees of latitude north or south of the equator are removed in panel (c). Panel (d) indicates regions where ≥15% of the local avifauna is comprised of potential trailing-edge populations, excluding areas with fewer than 10 species. Low-latitude range segments were defined as the lower 10th percentile of each species' range.



Appendix 2

Distribution of potential avian trailing-edge populations in North America. Colors indicate the number of species with low-latitude range segments at each terrestrial location. Low-latitude range segments were defined as the lower 10th percentile of each species' range.



Appendix 3

Diversity and distribution of trailing-edge populations in the Southeastern United States, represented by (a) species richness and (b) the proportion of the local avifauna comprised of potential trailing-edge populations. Both figures used the lower 10th percentile to designate low-latitude range segments for each species.

Appendix 4: Breeding Bird Survey trend estimates, 95% credible intervals, and regional credibility measure codes (G − representing the highest quality data, described as having at least 14 samples over the entire study period; Y − Data with a deficiency, such as low abundance estimates, fewer than 14 routes sampled, or imprecise results; R − Data where regional abundance estimates are very low, fewer than 5 routes sampled, or results are extremely imprecise) for bird trailing-edge populations in the southern Appalachian Mountains. For all species a trend estimate is available for the entire Appalachian Mountain range. For some species, state-level trend estimates are also available (Sauer et al., 2015).

Species	Region	1966–2015 Trend Est. (CI)	2005–2015 Trend Est. (CI)	Regional Credibility Measure
sharp-shinned hawk	Appalachian Mtns	1.51 (0.40, 2.44)	1.94 (−0.92, 4.66)	R
(*Accipter striatus*)	Alabama	1.22 (−1.25, 3.46)	1.82 (−3.76, 9.15)	R
	Georgia	2.24 (−2.43, 7.25)	2.75 (−10.60, 14.61)	R
	North Carolina	−0.84 (−5.15, 2.46)	0.43 (−7.13, 12.27)	R
	Tennessee	2.80 (0.14, 5.62)	4.06 (−5.16, 10.78)	R
	Virginia	1.22 (−2.31, 4.53)	0.98 (−12.01, 9.48)	R
	West Virginia	1.29 (−1.88, 4.05)	1.49 (−9.59, 12.98)	R
ruffed grouse	Appalachian Mtns	−1.55 (−3.09, −0.11)	−0.83 (−4.91, 3.05)	R
(*Bonasa umbellus*)	Virginia	−5.55 (−10.61, −0.62)	−5.43 (−19.84, 9.88)	R
	West Virginia	−3.34 (−6.69, −0.27)	−3.55 (−14.82, 5.25)	R
yellow-bellied sapsucker	Appalachian Mtns	5.81 (4.30, 7.20)	1.02 (−1.92, 3.91)	Y
(*Sphyrapicus varius*)	West Virginia	3.97 (−4.91, 18.64)	1.30 (−28.75, 19.80)	R
alder flycatcher	Appalachian Mtns	2.77 (1.62, 3.99)	−0.31 (−3.46, 2.65)	Y
(*Empidonax alnorum*)	West Virginia	0.09 (−4.72, 4.54)	0.08 (−9.54, 13.56)	R
least flycatcher	Appalachian Mtns	−2.46 (−3.04, −1.93)	−2.49 (−4.15, −0.85)	G
(*Empidonax minimus*)	North Carolina	−4.11 (−6.62, −1.55)	−4.13 (−8.06, −0.28)	Y
	Tennessee	−1.13 (−5.09, 2.83)	−1.35 (−10.14, 5.11)	R
	Virginia	−8.56 (−14.30, −3.14)	−10.12 (−26.79, 5.05)	R
	West Virginia	−0.41 (−1.64, 0.93)	0.14 (−2.62, 4.31)	Y
blue-headed vireo	Appalachian Mtns	3.16 (2.15, 4.09)	1.42 (−0.32, 3.20)	Y
(*Vireo solitarius*)	Alabama	6.37 (1.93, 10.92)	6.56 (−0.48, 14.11)	R
	Georgia	7.11 (4.06, 10.45)	6.69 (−0.96, 12.39)	R
	North Carolina	2.29 (0.42, 4.02)	2.47 (−0.27, 5.73)	Y
	Tennessee	0.09 (−2.11, 2.28)	0.03 (−4.49, 4.18)	Y
	Virginia	5.51 (3.38,7.56)	4.74 (−1.86, 9.03)	Y
	West Virginia	4.11 (2.44, 5.93)	4.77 (0.61, 9.37)	Y
common raven	Appalachian Mtns	4.48 (3.37, 5.45)	5.59 (3.11, 7.97)	Y
(*Corvus corax*)	North Carolina	4.00 (0.25, 7.98)	6.44 (−1.49, 16.88)	R
	Virginia	0.56 (−1.37, 2.47)	2.23 (−3.11, 9.05)	Y
	West Virginia	6.21 (4.37, 8.10)	5.72 (1.03, 10.48)	Y
black-capped chickadee	Appalachian Mtns	0.65 (0.19, 1.11)	−0.97 (−2.39, 0.36)	G
(*Poecile atricapillus*)	Virginia	−0.03 (−2.39, 2.41)	−0.23 (−7.22, 6.41)	Y
	West Virginia	0.41 (−0.70, 1.49)	0.93 (−2.06, 4.32)	G
red-breasted nuthatch	Appalachian Mtns	4.10 (2.71, 5.47)	3.89 (−0.33, 8.03)	R
(*Sitta canadensis*)	West Virginia	5.40 (1.63, 9.54)	6.02 (0.65, 17.14)	R
brown creeper	Appalachian Mtns	0.47 (−0.90, 1.81)	0.93 (−2.72, 4.05)	Y
(*Certhia Americana*)	West Virginia	0.28 (−5.52, 6.51)	−0.62 (−13.22, 7.72)	R
winter wren	Appalachian Mtns	2.74 (1.16, 4.30)	−3.50 (−7.83, 0.19)	Y
(*Troglodytes hiemalis*)	West Virginia	1.52 (−0.84, 3.61)	1.32 (−5.95, 6.67)	R
golden-crowned kinglet	Appalachian Mtns	1.13 (−0.83, 3.12)	0.36 (−5.99, 5.42)	R
(*Regulus satrapa*)	West Virginia	1.67 (−1.28, 4.73)	1.65 (−4.89, 8.17)	R
veery	Appalachian Mtns	−0.32 (−0.68, 0.04)	0.34 (−0.54, 1.36)	G
(*Catharus fuscescens*)	North Carolina	0.89 (−1.75, 3.52)	0.88 (−2.84, 4.26)	Y
	Virginia	1.34 (−3.15, 7.00)	1.87 (−4.23, 10.48)	R
	West Virginia	3.81 (2.60, 5.10)	3.90 (0.58, 7.46)	Y
hermit thrush	Appalachian Mtns	2.31 (1.28, 3.39)	0.19 (−2.44, 2.85)	Y
(*Catharus guttatus*)	West Virginia	4.62 (1.74, 7.69)	5.50 (−1.09, 14.88)	R
Swainson's thrush (*Catharus ustulatus*)	Appalachian Mtns	2.04 (−0.63, 4.94)	1.27 (−7.15, 6.98)	R
cedar waxwing	Appalachian Mtns	1.64 (1.00, 2.24)	1.31 (−0.49, 3.13)	G
(*Bombcilla cedrorum*)	Alabama	6.93 (1.24, 13.65)	−0.16 (−13.59, 15.47)	R
	Georgia	6.80 (1.67, 12.81)	−5.58 (−17.76, 10.58)	R
	North Carolina	2.04 (−0.10, 4.23)	−3.00 (−7.71, 1.48)	Y
	Tennessee	5.13 (2.67, 7.89)	−7.31 (−13.14, −1.25)	Y
	Virginia	3.78 (1.47, 6.20)	−0.89 (−6.70, 5.26)	Y
	West Virginia	2.6 (1.36, 3.93)	1.29 (−2.47, 5.10)	G
golden-winged warbler	Appalachian Mtns	−8.56 (−9.77, −7.29)	−7.65 (−10.95, −3.05)	Y
(*Vermivora Chrysoptera*)	North Carolina	−11.48 (−16.23, −6.62)	−11.68 (−18.50, −4.87)	Y
	Tennessee	−8.43 (−12.10, −5.37)	−7.99 (−18.21, 2.96)	Y
	Virginia	−8.67 (−12.11, −5.12)	−8.61 (−15.47, −1.89)	R

(*continued*)

Species	Region	1966–2015 Trend Est. (CI)	2005–2015 Trend Est. (CI)	Regional Credibility Measure
	West Virginia	−8.59 (−10.34, −6.53)	−7.84 (−12.90, 0.64)	Y
chestnut-sided warbler	Appalachian Mtns	0.00 (−0.68, 0.58)	−0.63 (−1.89, 0.55)	G
(*Setophaga pensylvanica*)	North Carolina	−3.63 (−5.27, −2.02)	−4.16 (−8.18, −1.28)	G
	Tennessee	−4.86 (−7.30, −2.55)	−5.35 (−12.79, −1.16)	Y
	Virginia	−4.27 (−7.02, −1.20)	−3.22 (−9.24, 11.36)	Y
	West Virginia	1.79 (0.41, 3.19)	−0.06 (−4.25, 3.83)	Y
magnolia warbler	Appalachian Mtns	2.39 (1.63, 3.15)	2.65 (0.26, 4.62)	Y
(*Setophaga magnolia*)	West Virginia	6.22 (4.06, 8.13)	5.41 (−2.76, 9.16)	Y
black-throated blue warbler	Appalachian Mtns	0.22 (−0.93, 1.22)	−0.25 (−2.09, 1.46)	Y
(*Setophaga caerulescens*)	North Carolina	−1.12 (−2.99, 0.81)	−0.69 (−3.39, 3.03)	Y
	Virginia	−3.45 (−6.71, −0.01)	−2.70 (−8.62, 9.69)	Y
	West Virginia	1.70 (0.10, 3.16)	1.46 (−2.44, 4.37)	Y
blackburnian warbler	Appalachian Mtns	−0.16 (−1.31, 0.84)	−3.01 (−5.39, −0.68)	Y
(*Setophaga fusca*)	North Carolina	−0.47 (−4.69, 3.90)	−0.74 (−6.98, 5.79)	Y
	Virginia	−7.72 (−10.37, −4.76)	−7.95 (−13.41, −2.47)	Y
	West Virginia	1.25 (−1.13, 3.59)	1.44 (−2.47, 6.28)	R
yellow-rumped warbler(*Setophaga coronate*)	Appalachian Mtns	2.13 (0.23, 4.00)	−5.86 (−10.50, −1.19)	Y
black-throated green warbler	Appalachian Mtns	1.19 (0.53, 1.82)	0.3 (−1.10, 1.71)	G
(*Setophaga virens*)	Alabama	−1.10 (−3.57, 1.20)	−1.89 (−7.69, 2.40)	Y
	Georgia	4.10 (1.30, 7.31)	2.11 (−6.49, 7.58)	Y
	North Carolina	1.54 (−0.45, 3.45)	1.18 (−1.94, 4.22)	Y
	Tennessee	−1.86 (−3.41, −0.40)	−1.85 (−6.13, 2.22)	Y
	Virginia	2.13 (−0.23, 4.79)	1.69 (−4.29, 7.98)	Y
	West Virginia	2.70 (1.27, 4.00)	2.91 (−0.98, 6.74)	Y
northern waterthrush	Appalachian Mtns	−1.52 (−3.27, 0.28)	−0.62 (−4.97, 4.94)	R
(*Parkesia noveboracensis*)	West Virginia	−4.4 (−11.27, 1.93)	−6.25 (−28.52, 8.07)	R
mourning warbler	Appalachian Mtns	−0.38 (−2.58, 1.21)	0.13 (−3.76, 3.63)	Y
(*Geothlypis philadelphia*)	West Virginia	−3.46 (−7.15, −0.01)	−4.48 (−15.81, 6.39)	Y
Canada warbler	Appalachian Mtns	−1.00 (−2.32, 0.16)	−0.19 (−2.20, 1.85)	Y
(*Cardellina canadensis*)	North Carolina	−1.6 (−4.86, 1.73)	−1.56 (−5.74, 2.70)	Y
	West Virginia	2.81 (0.33, 5.15)	2.91 (−2.53, 8.59)	Y
rose-breasted grosbeak	Appalachian Mtns	−0.82 (−1.35, −0.28)	−2.64 (−4.37, −1.03)	G
(*Pheucticus ludovicianus*)	North Carolina	−3.39 (−6.05, −0.66)	−2.27 (−7.28, 8.52)	Y
	Virginia	−1.85 (−4.38, 0.38)	−2.03 (−9.29, 3.11)	Y
	West Virginia	1.72 (0.32, 3.41)	1.30 (−3.13, 5.76)	Y
dark-eyed junco	Appalachian Mtns	1.36 (0.62, 2.06)	1.36 (−0.27, 2.93)	G
(*Junco hyemalis*)	North Carolina	0.94 (−1.19, 3.11)	0.69 (−2.38, 3.35)	Y
	Virginia	2.54 (−0.30, 5.64)	2.62 (−3.18, 10.20)	Y
	West Virginia	3.15 (1.54, 4.62)	3.01 (−0.97, 6.21)	Y
purple finch	Appalachian Mtns	0.02 (−0.73, 0.74)	−1.03 (−3.37, 1.13)	Y
(*Haemorhous purpureus*)	West Virginia	0.96 (−4.05, 7.11)	0.55 (−13.61, 17.37)	R

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