**A model for estimating regional and range-wide population trends based on migration counts: a case study with Blackpoll Warbler (*Setophaga striata*)**

David T. Iles1, Erica H. Dunn2, Steven Van Wilgenburg3, Kevin J. Kardynal4, Danielle Ethier5, Adam C. Smith1, Charles M. Francis1

1 Canadian Wildlife Service, Environment and Climate Change Canada, Ottawa, ON, Canada

2 Canadian Migration Monitoring Network, Birds Canada, Port Rowan, ON, Canada

3 Canadian Wildlife Service, Environment and Climate Change Canada, Saskatoon, SK, Canada

4 Wildlife Research Division, Environment and Climate Change Canada, Saskatoon, SK, Canada

5 Birds Canada, Port Rowan, ON, Canada

\*Corresponding author; Email: david.iles@ec.gc.ca

D.T.I. ORCID: 0000-0002-7251-4938

Research paper for submission to *Avian Conservation and Ecology*

15 January 2024

**Acknowledgements**

We thank the countless volunteers and employees who contributed to the operation of monitoring stations and collection of data that made these analyses possible. Canadian data were obtained through the NatureCounts website, while data from U.S. observatories were obtained through Evan Dalton, Luke DeGroote, Kim Gaffert, Maren Gimpel, Trevor Lloyd-Evans, Peter Paton, Steven Rienert, Mark Shieldcastle and Claire Stuyck.

**Abstract**

Large portions of the boreal forest are inaccessible, leading to highly uncertain assessments of North America’s landbird populations based on breeding season surveys. However, systematic monitoring of bird populations during migration has the potential to inform regional trend estimates for species that are otherwise data deficient. A network of bird observatories across North America have collected decades of standardized daily counts during fall and spring migration seasons with a goal of monitoring avian population dynamics, but statistical approaches to appropriately weight station-level trends in regional-scale analyses have not yet been developed. Here, we describe a multi-level statistical model that estimates population trends across a species’ breeding range by integrating migration count data with estimates of station-level “catchment” based on stable isotopes in feather samples. We applied this model to Blackpoll Warbler (*Setophaga striata*), a species of conservation concern, and compared migration-based population trend estimates to those from the North American Breeding Bird Survey (BBS). Migration-based and BBS-derived trend estimates were strongly negative for the portion of the species’ boreal breeding range east of the Great Lakes, where populations have likely declined by over 20% from 2008-2018. In contrast, migration analyses suggested that populations were stable or increasing in western Canada, though BBS suggested populations likely declined, possibly owing to spatial biases in breeding season surveys in that region. Our approach yields trend estimates that are independent from other breeding season survey programs, and can be used to validate conventional breeding surveys for which spatial biases in data collection are a major concern. Application of our method to other species inadequately monitored throughout their life cycle could be an important advance for North American landbird monitoring.

**Keywords** *Bayesian analysis,* *breeding origins,* *hierarchical model, migration monitoring, population trend, stable isotopes, status assessment*

**Introduction**

North America’s boreal forest supports billions of breeding birds from more than 300 species (Niemi et al. 1998). However, increasing industrial development in this region (Hobson et al. 2013; Mahon et al. 2014), changing forest dynamics due to rapid rates of climate change (Stralberg et al. 2015), and numerous pressures during nonbreeding periods (i.e., migration, wintering; Kirby et al. 2008) have led to concern over the status of boreal avian populations. Recent studies suggest that boreal birds appear to have experienced among the steepest population declines of any avian group, owing to large declines of several previously abundant and widespread species (Rosenberg et al. 2016, 2019). There is therefore an urgent need to develop more effective avian monitoring in the boreal forest (Cumming et al. 2010).

Population trends for most North American landbirds are derived from the North American Breeding Bird Survey (BBS), but this roadside survey has limited coverage in the mostly roadless core of the boreal zone. Consequently, the BBS samples a biased collection of boreal habitats (Van Wilgenburg et al. 2015), leading to potentially unrepresentative trend estimates for boreal species (Machtans et al. 2014). Many boreal-breeding species migrate to neotropical regions that are not adequately monitored by nonbreeding (i.e., ‘wintering’) surveys such as the Christmas Bird Count (CBC). Thus, while there are substantial data with which to estimate population status in select regions of northern forest, range-wide trends of most boreal species are lacking (Dunn et al. 2005).

There has long been interest in using standardized counts of migrating birds to evaluate population change for species that are not well-monitored during the non-migratory part of their life cycle (Francis and Hussell 1998; Dunn et al. 2005). Counting migrants for use in population monitoring is a specific goal of The Canadian Migration Monitoring Network, a collaborative initiative of bird observatories across Canada, Birds Canada, and Environment and Climate Change Canada (Canadian Migration Monitoring Network 2021), and similar data are collected by several long-running migration monitoring stations in the United States. However, migration monitoring data have typically been analyzed on a station-by-station basis due to lack of knowledge of the breeding ground origins of migrants passing count stations. This gap in knowledge precludes appropriate weighting of site-specific trends in combined analyses to derive regional or range-wide trends, while also hampering appropriate targeting of conservation action.

Advances in probabilistic origin assignments using stable hydrogen ratios in feathers, have led to cost-efficient methods for broadly determining the breeding ground origins (hereafter ‘catchment areas’) of birds captured at migration count sites (Van Wilgenburg and Hobson 2011, Hobson et al. 2015, Dunn et al. 2023). Knowledge of catchment areas provides a powerful opportunity to appropriately weight information across a network of migration monitoring stations and to estimate large-scale patterns in population trends. This is particularly relevant to boreal-breeding birds that are not well-monitored by other methods, thereby delivering enhanced information for conservation decision-making.

Blackpoll Warbler (*Setophaga striata*) is an abundant Nearctic-Neotropical migrant landbird species that breeds mostly in the northern boreal forest, where breeding season surveys are extremely limited in geographic coverage. Trends derived from roadside BBS surveys suggest populations have declined by over 90% since 1970; among the steepest declines of any landbird during that period (Rosenberg et al. 2016, Sauer et al. 2020). However, the reliability of these trend estimates is uncertain owing to the absence of BBS coverage throughout the core of the species’ breeding range (Environment and Climate Change Canada 2019). Migration monitoring methods provide an attractive alternative method for tracking population status in boreal species, because individuals from all parts of the breeding range must pass through southern areas during migration, allowing count sites to sample birds from every part of their respective catchment areas.

Here, we develop a Bayesian integrated population model to estimate regional and national population trends using standardized daily counts of migrants from a series of monitoring stations, combined with estimates of station catchment areas from feather stable isotope analysis. Our method synthesizes trend information at a range-wide scale by weighting information from migration monitoring stations based on their catchment area, thereby moving beyond station-by-station analyses. We apply this analysis to Blackpoll Warbler and compare the resulting trend estimates to those from conventional Breeding Bird Survey analysis. We also describe how this analytical framework can be readily applied to other migratory boreal species to generate estimates of range-wide population trends, and we provide fully documented R code and recommendations for expanding this method to other species.

**Methods**

*Description of statistical model*

We developed a hierarchical model to estimate temporal patterns of population change within discrete geographic strata, from which birds arriving at migration monitoring stations have originated. The model simultaneously estimates annual indices of bird abundance at each migration monitoring station, as well as the proportion of birds at each station that have arrived from each stratum. We fit models separately to data collected during pre-breeding migration (i.e., the northward migration of breeding birds during North American spring) and post-breeding migration (i.e., the southward migration of adult and newly fledged juvenile birds during the North American fall season). Equations and priors underlying the statistical model are described in Tables 1 and 2.

Quantities in the model are indexed by geographic stratum (*j*), year (*y*), monitoring station (*s*), and day of year (*d*). The highest level of the model (equation 1) describes the temporal pattern of population change in each geographic stratum *j* starting from a baseline year . Our model assumes that abundance within each stratum () changes according to a log-linear trend.

The next level of the model (equation 2) describes the expected number of migrants () arriving from each geographic stratum to each migration monitoring station during each year. is modeled as a product of annual stratum abundances and station-level migration parameters () that describe the contribution of stratum *j* to station *s* in year *y*. The parameters therefore convert indices of abundance in each stratum to number of birds arriving at each station in each year. In cases where a migration monitoring station is known (or assumed) to exclusively capture birds from a subset of strata, the relevant parameters () are fixed to zero for the strata that are not monitored by the station. We note that stratum abundances in the baseline year of the model (i.e., ) are not estimable with migration data alone, because infinite combinations of and migration parameters ( would be equally consistent with the observed data. Thus, we fix such that the model estimates change relative to the start year within each stratum, ensuring all parameters are theoretically identifiable.

We model the index of expected annual abundance at each station () as the sum of across strata multiplied by a yearly station-specific random effect (). The term in equation 3 acknowledges that there is annual variation in the total number of migrants arriving at each station, beyond that which is attributable to changes in (e.g., additional variation could be driven by year-to-year fluctuations in migration pathways).

The next level of the model (equation 4) distributes the migrants arriving at the monitoring station among days of the season. This component of the model is necessary because some monitoring stations are only operational for a subset of days per season; the model can therefore accommodate missing data within a season. Migration of individuals past monitoring stations is assumed to follow a symmetric seasonal pattern around a peak date. We therefore described the seasonal pattern of counts at each station using a normal probability density function that integrates to 1 across all days in a season. The parameter is the date of the seasonal peak of migration at station , while describes the temporal dispersion of the migration period at that station (i.e., approximately 95% of the station’s migration period occurs within 1.96 on either side of ). In our application of the model, was estimated separately for each migration monitoring station but was estimated as a shared parameter across stations.

The final level of the model describes the observed count data (equation 6) and breeding origin estimates (equation 7). To describe migration count data, the number of birds counted on each day of the season () at each station () in each year () was modeled as an over-dispersed Poisson process with median equal to . We assumed log-normal variance for unexplained ‘noise’ in daily counts at each station (e.g., owing to weather conditions that affect daily migration behavior). Equation 7 also includes an offset equal to log(net hours) to account for spatio-temporal variation in monitoring effort.

We use a multinomial distribution to model breeding origins of migrants at the stations where they were collected (equation 7). In this equation, is a vector (denoted by bolded font) containing the number of sampled birds assigned to each of the strata at a station in a year. The vector of probabilities describing the multinomial distribution (i.e., ) therefore allow station-level dynamics to be linked to stratum-level dynamics.

Finally, estimates of percent population change in a stratum (indexed by *j*, Table 1) relative to a baseline year (in this study, relative to the year 2000), are calculated as:

|  |  |
| --- | --- |
|  | (7) |

where is an index of abundance in the final year (). Following the the North American Breeding Bird Survey (Smith et al. 2014), we defined population trend as the geometric mean rate of change between two points in time, where:

|  |  |
| --- | --- |
|  | (8) |

Estimates of change and trend for the continental population can be calculated by summing across strata before applying equations 7 and 8 (Table 1). However, since our implementation of the migration model requires that (such that and are identifiable), independent estimates of relative abundance in each stratum are required in order to re-scale estimates of and thereby appropriately weight changes in abundance within each stratum at a continental scale. For example, a 1000% increase in a stratum containing only a few individuals will have a miniscule impact on continental change compared to a 10% decrease within a stratum containing the majority of the continental population.

*Application to Blackpoll Warbler: data and model parameters*

We applied our statistical model to time series of standardized daily migration counts of Blackpoll Warblers collected from 1998-2018 at permanent monitoring locations across Canada and the United States (see summary of data in Appendix 1). Canadian sites are members of the Canadian Migration Monitoring Network, which use station-specific standards to collect avian counts during the pre-breeding (‘spring’) and/or post-breeding (‘fall’) migration seasons. The most used count approaches include banding captures using mist nets and visual counts (hereafter ‘censuses’) that record all birds detected in a specified area during a specified time. Banding at most sites is for 6 hours starting a half-hour pre-dawn at fixed net locations. The length of census counts can vary from one hour (e.g., counting birds along a fixed route) to more than six hours (e.g., continuous counts from a fixed point). Count protocols vary among stations, but within a station the count methods and daily effort are standardized and remain consistent over time (Canadian Migration Monitoring Network 2021). Data from U.S. bird observatories consist of daily captures with mist-nets, usually with fixed locations and operated for similar hours as at Canadian sites for least 5 days per week during spring and/or fall migrations. Because some U.S. stations had variable daily hours and/or number of nets, daily number of net-hours was used as a statistical offset in analyses.

Daily counts for Blackpoll Warbler were available for 13 monitoring sites during pre-breeding migration and 18 sites in post-breeding migration (Appendix 1). Data from each site were restricted to dates that were sampled in at least two-thirds of years in which the station operated. Within those date limits, daily samples had to have been made during at least 75% of days within local migration season for blackpolls. Specific days with <50 total net hours were omitted from analyses. For sites with notable changes in count effort between 1998 and 2018, data were limited to the years within which coverage was standardized.

We split the boreal breeding range of the Blackpoll Warbler into two geographic strata: ‘West’ and ‘East’ (Figure 1), based on feather stable hydrogen isotope analysis and other information in Dunn et al. (2023). Those authors defined three strata, but we combined the two covering all areas west of the Great Lakes into our single West stratum due to sample size considerations, and to ensure migrants could assigned to each stratum with high precision. Breeding ground origins of individual Blackpoll Warbler can be confidently assigned to one or the other stratum based on stable hydrogen isotope ratios in their tail feathers (Dunn et al. 2023). The boundaries of these strata are also consistent with other knowledge of Blackpoll Warbler migration routes, based on banding, geolocator, and additional stable isotope studies (DeLuca et al. 2015; Holberton et al. 2015, Morris et al. 2016; Covino et al. 2020).

With a few exceptions, we used the feather isotope results from Dunn et al. (2023) as data in our statistical population model to indicate the proportion of migrants originating from East and/or West strata. Stable hydrogen isotope ratios in parts of Alaska have the same values as expected in the East stratum, but because migrants captured far west of the Great Lakes can safely be assumed to have originated from the West stratum we fixed the West proportion at 100% without regard to isotope results. Elsewhere, we assigned values based on isotope results from the nearest location within 250 km for which isotope results were available, though several sites had no data for estimating West *versus* East proportions of migrants. The values assigned to each site in each season and the basis for each selection are shown in Appendix 1.

For an estimate of relative abundance in the East and West strata for Blackpoll Warbler, we used predictions based on eBird (Fink et al. 2023; see map in Appendix 2), in which high-resolution rasters (2.96 km pixel width) describe model-derived predictions of relative abundance across North America during the breeding season). We obtained a relative abundance raster for Blackpoll Warbler using the ‘*ebirdst’* package in R (Fink et al. 2023), cropped this raster to the boundary of each stratum, and summed pixel values to yield estimates of relative abundance. eBird relative abundance rasters indicated that Blackpoll Warbler is currently 1.46 times more abundant in the East stratum than in the West We therefore re-scaled estimates of based on these values, using , where was 1.46 and 1 for the East and West, respectively.

We fit the statistical model in a Bayesian framework using JAGS version 4.3.0 (Plummer 2003), interfaced with the R programming language version 4.0.2 (R Core Team 2024) using the jagsUI library version 1.5.2 (Kellner 2021). We specified vague priors on all model parameters (Table 2). After a burn-in of 10,000 iterations, we stored every 100th iteration until we accumulated 1000 posterior samples from each of three MCMC chains. We assessed chain convergence by visual examination of MCMC traceplots and by evaluating that the Gelman–Rubin convergence statistic was close to 1 for all model parameters. Code to repeat these analyses is available at https://github.com/davidiles/BLPW-migration-trends.

We assessed goodness-of-fit by evaluating the correlations between observed seasonal totals at monitoring stations and the expected counts generated by the fitted models. We also conducted posterior predictive checks to confirm that the distribution of simulated counts based on the fitted statistical model were consistent with the distribution of observed counts at each station. Using simulation we also evaluated whether the migration model was able to generate unbiased estimates of regional population trends across a wide range of regional trajectory scenarios, and tested model sensitivity to changes in fixed parameter values. Goodness-of-fit assessments and more detailed simulation details are provided in Appendix 3.

*Comparison to trend estimates from the North American Breeding Bird Survey*

We compared regional trend estimates from our model to those derived from the North American Breeding Bird survey to evaluate differences between conventional breeding season analyses and our migration analysis. We fit a Bayesian hierarchical model to BBS time series from 1998 to 2018 (the same period as our migration analysis), using analytical strata implemented by the United States Geological Survey (USGS) for continental analysis. We specified a ‘first difference’ population process model (Link et al. 2017; Smith and Edwards 2021), which is widely used in standard continental analysis of BBS data. We fit the model and extracted output using the ‘bbsBayes’ package in R (Edwards and Smith 2020), specifying a 50,000 iteration burn-in period, after which we stored every 100th posterior sample until we accumulated 2000 posterior samples from each of 3 MCMC chains.

We calculated estimates of continental change based on analysis of the BBS, using methods described in Link et al. (2017) and Smith and Edwards (2021). To derive regional trend estimates from the BBS, we assigned BBS analytical strata into East and West categories based on geographic overlap with the strata we used for migration analysis (illustrated in Appendix 2). This allowed us to calculate ‘post hoc’ synthetic estimates of regional population trends by summing annual indices from the fitted model across analytical strata that overlapped with the coarse East and West strata used for the migration monitoring analysis. Detailed methods for estimating population trajectories and trends within custom strata are described in the bbsBayes package (Edwards and Smith 2020).

**Results**

Simulations confirmed that the statistical model produces regional trend estimates that are identifiable and unbiased under a wide range of simulated population trajectories and data collection scenarios (Appendix 3).

Blackpoll Warbler migration monitoring from 1998 to 2018 suggested similar population trends in the western population stratum based on independent analyses of pre- and post-breeding data (Table 3, Figure 2). We detected moderate evidence of population increases in the western stratum based on pre-breeding migration (0.92 probability of positive trend), and weak evidence of population increases based on post-breeding migration (0.79 probability of positive trend). In contrast, analysis of the BBS indicated a high probability that western populations had declined over the 20-year period (0.97 probability of negative trend).

We detected strong evidence of large declines in eastern Blackpoll Warbler populations based on pre-breeding migration monitoring (<0.01 probability of positive trend), with a median trend estimate of -4.6% per year leading to a decline of -37.8% over 10 years (95% CRI = -53.3% to -18.7%). BBS also suggested there was a high probability (0.97) the trend was negative, and the magnitude of the BBS trend estimate was similar to that from pre-breeding migration monitoring. The eastern population trend estimated from post-breeding migration was extremely imprecise because few stations were captured eastern migrants during post-breeding migration (Figure S2.2), and signals of eastern population changes were largely swamped by migrants originating from the western stratum. However, the median estimate of the trend was consistent with that from pre-breeding migration and BBS (Figure 2) and the analysis indicated eastern population declines are twice as likely to have declined than to have increased over the monitoring period (probability of decline = 0.69).

Continental population trend estimates derived from pre-breeding migration monitoring and BBS were highly consistent with each other and yielded strong evidence for highly negative continental population trends (Table 3), primarily due to declines in eastern North America. Trend estimates based on pre-breeding migration and BBS each suggested there was more than a 0.4 probability the population declined by more than 30% over 10-years. Continental change estimates from post-breeding migration were highly uncertain owing to extreme imprecision in the eastern trend estimate, but also nevertheless suggested moderately strong evidence of negative continental population trends (0.70 probability the trend was negative).

**Discussion**

Our study fulfills a longstanding need for North American landbird monitoring by facilitating large-scale population trend assessments for migratory species, particularly for the approximately 80 species that primarily breed in the core of the boreal forest (Dunn et al. 2005). Our model synthesizes information from across an international network of more than 20 long-term migration monitoring stations, and therefore represents an important step beyond analysis of migration trends on station-by-station basis (Canadian Migration Monitoring Network 2021).When trends in the number of migrants vary among stations, our model attempts to partition these discrepancies into contributions from differences in regional population trends, differences in station-level catchment, and multiple sources of unexplained spatial and temporal variation. Since many species are difficult to survey during the non-migratory periods of their life cycle, migration monitoring may therefore be crucial for assessing the conservation status of those species.

In general, confidence in a scientific finding is enhanced when multiple independent lines of inquiry converge on a shared conclusion through so-called ‘methodological triangulation’ (Heesen et al. 2019). For North American landbirds, there are now multiple survey programs from which population trends can potentially be estimated and compared. Large-scale, long-term, semi-structured community science programs such as the BBS and the Christmas Bird Count can provide valuable insights into population trends for species inhabiting the roaded portions of North America (Link et al. 2006; Sauer et al. 2020). Provincial and state breeding bird atlases (Dunn et al. 2008), along with a suite of other regional monitoring programs (e.g., Pavlacky et al. 2017; Hill 2023) can provide finer-scale inference in locations that may otherwise be data-deficient. eBird also provides estimates of local and regional population trends over the last 10 years across portions of North America, based on unstructured volunteer data analyzed with machine-learning algorithms designed to minimize biases inherent in opportunistically collected datasets (Fink et al. 2023). Range-wide migration monitoring, in combination with stable isotope analysis, can provide a powerful complement to these other survey programs because it relies on a fundamentally different methodology: the capture of migrating birds using standardized protocols, assignment of those individuals to regional catchment areas, and integrated analysis of data using hierarchical models. Migration monitoring has an additional advantage in that pre- and post-breeding migration seasons can be analyzed independently from each other (as in our current analysis), providing a further check on consistency in estimates. Consilience between population trend estimates from each migration season and other relevant breeding and non-breeding surveys could greatly strengthen confidence in species status and trend assessments. Conversely, lack of consilience may help identify weaknesses in a particular survey approach or suggest new avenues for research.

For Blackpoll Warbler, multiple lines of evidence indicate that severe population declines have recently occurred in eastern North America. Independent analysis of pre-breeding migration and BBS suggest that eastern populations have declined at rates of approximately -4% per year (Table 3). While trend estimates could not be precisely estimated from post-breeding migration, the analysis nevertheless suggested that declines were more likely to have occurred than population increases. Congruent with these findings, Mountain Birdwatch, which monitors montane breeding bird communities in the eastern United States, also estimated Blackpoll Warbler population declines of approximately -4.5% per year (80% CI = -5.2% to -3.8) from 2010 to 2023 (Hill 2023). Strong declines in Blackpoll Warbler breeding occurrence were also detected in New Brunswick and Cape Breton Island in Nova Scotia between the first (1990) and second (2010) Maritimes Breeding Bird Atlases (Stewart 2015). eBird trend estimates differ from these other programs and suggest Blackpoll Warbler populations in eastern Canada were stable or increasing between 2012 and 2022 (Fink et al. 2023); the cause of this discrepancy is unclear. Provincial breeding bird atlases currently underway in Ontario and Quebec are collecting boreal avian data using a nationally standardized framework (Van Wilgenburg et al. 2020) and are expected to provide critical insights into population changes that have occurred in eastern Canada since the early 2000s. Simultaneously, these efforts will provide another independent test of the ability of our model to track regional changes in population size.

Pre- and post-breeding migration analysis independently suggested that populations of Blackpoll Warbler west of James Bay have likely increased slightly or remained stable over a 20-year period. In contrast, the BBS suggested that populations have likely declined in this region over the same period. eBird also reports evidence of recent populations declines in western Canada and Alaska (Fink et al. 2023). Because of their reliance on volunteers, data from BBS and eBird are heavily biased towards roadsides and human settlements, and therefore sample an incomplete and biased portion of the western boreal forest (Machtans et al. 2014; Van Wilgenburg et al. 2015). BBS and eBird are also unable to estimate population trends in the Northwest Territories and Nunavut where long-term breeding season surveys are exceedingly sparse, yet a substantial proportion of the continental population of Blackpoll Warbler breeds. The migration monitoring network likely captures substantial numbers of individuals from those regions, particularly during post-breeding migration when the entire continental population passes through eastern North America (Holberton et al. 2015) and is thus theoretically capable of monitoring population trends in these remote areas. However, it is also possible that migration trends could be biased, particularly if “western” birds captured at migration monitoring stations originate from a small or unrepresentative portion of the boreal forest (e.g., where local trends are unrepresentative of regional dynamics).

Our statistical model makes several important assumptions that warrant consideration. First, migration counts at each station are driven by a complex product of both variation in regional population sizes and the probability that migrating individuals are observed at particular stations (Dunn 2005). Importantly, our model is unable to account for long-term directional changes in migration pathways, which would impose spurious signals of population change if migrants increasingly avoid particular monitoring stations. This could occur if the landscape surrounding a migration monitoring station changes considerably over time, resulting in long-term changes in the probability that migrants stop over (Francis and Hussell 1998). However, network-wide trend analyses should be robust to this bias if many stations capture birds from each region, reducing the influence of single stations on overall trend estimates. Additionally, pre- and post-breeding migration seasons have different collections of stations contributing data to their trend estimates, and the loop migration behaviour of Blackpoll Warbler also implies that each station can have different regional catchments in each season (Holberton et al. 2015). Together, these factors should increase confidence in migration-based trend assessments when trends from each migratory period are estimated independently but are nevertheless consistent with each other.

Second, daily migration counts are also extremely stochastic and difficult to characterize parametrically (Crewe et al. 2016). Unrealistic error distributions could result in poor goodness-of-fit metrics in some years at some stations (e.g., Appendix 3) and credible intervals that are potentially too narrow. However, this phenomenon is not unique to our migration monitoring analysis, and iterative improvements in model structure are almost always necessary for hierarchical analyses of long-term, large-scale monitoring data (Link et al. 2016).

Third, the current structure of our population process model only includes a log-linear trend and does not attempt to estimate annual process variation in regional population sizes from migration monitoring. This assumption may be justified for a wide-ranging, highly abundant species like Blackpoll Warbler, where large-scale regional trajectories derived from the BBS resulted in relative smooth trajectories (Figure 2). However, in cases where regional populations fluctuate substantially between years (e.g., for nomadic or irruptive populations), confidence intervals on trend estimates from our model will likely be too narrow because random temporal variation in population dynamics is not being fully accounted for. In those cases, annual assessment of catchment at a subset of monitoring stations could help to disentangle station-level variation from regional variation. However, annual analysis of feather isotopes across a network of stations may be cost prohibitive and alternative methods for estimating station catchment could also be considered (e.g., Meehan et al. 2022).

Application of our method to a larger number of boreal breeding species could yield novel insights into the population status of boreal-breeding migratory species. Our analytical approach could potentially be extended to other groups of birds that are more reliably covered on migration or at stopover sites, such as shorebirds (Smith et al. 2023) and raptors (Farmer et al. 2007), provided that regional catchment can be estimated at survey locations. Our model could also potentially be extended to incorporate non-standardized migration count data from citizen science networks such as eBird, conceptually equivalent to adding thousands of migration monitoring ‘stations’ across the continent. This would have numerous advantages including more comprehensive coverage of migratory populations and reducing the influence of individual monitoring stations on regional trend estimates. However, reliance on citizen science information requires careful screening of data and appropriate accounting of changes in observer effort over time (e.g., through modeling; Fink et al. 2023). Nevertheless, continued efforts to implement and improve range-wide trend analyses from migration surveys hold considerable promise for North American landbird monitoring.

**Authors’ Contributions**

DTI developed the statistical model, led analysis, and wrote the initial manuscript drafts. EHD and DE compiled and cleaned migration count data. All authors contributed throughout to ideas, discussion, and editing.

**Data Accessibility**

Canadian migration count data are publicly available at the NatureCounts portal (https://www.bsc-eoc.org/birdmon/cmmn/datasets.jsp), managed by Birds Canada. US migration counts are available upon request from individual migration monitoring stations. All isotope data, code, and Bayesian posterior samples associated with these analyses will be archived in Dryad Digital Repository upon acceptance of this manuscript.

**Conflict of Interest**

The authors declare they have no conflict of interest.

**Compliance with Ethical Standards**

The authors declare that they have complied with ethical standards.

**Literature Cited**

Canadian Migration Monitoring Network. 2021. The Canadian Migration Monitoring Network - Réseau canadien de surveillance des migrations: Researching Canada’s Landbirds for Twenty Years. *CMMN-RCSM Scientific Technical Report, 3.*

Covino, K., Morris, S., Shieldcastle, M., and Taylor, P., 2020. “Spring Migration of Blackpoll Warblers across North America.” *Avian Conservation and Ecology 15* (1).

Crewe, T., Taylor, P. and Lepage, D., 2016. Temporal aggregation of migration counts can improve accuracy and precision of trends. *Avian Conservation and Ecology*, *11*(2).

Cumming, S.G., Bayne, E., Schmiegelow, F.K.A., Fontaine, T., Song, S.J. and Lefevre, K., 2010. Toward conservation of Canada's boreal forest avifauna: Design and application of ecological models at continental extents. Avian Conservation & Ecology*, 5(2).*

DeLuca, W.V., Woodworth, B.K., Rimmer, C.C., Marra, P.P., Taylor, P.D., McFarland, K.P., Mackenzie, S.A. and Norris, D.R., 2015. Transoceanic migration by a 12 g songbird. *Biology Letters*, *11*(4).

Dunn, E.H., 2005. Counting migrants to monitor bird populations: State of the art. *USDA Forest Service General Technical Report PSW-GTR-191*, pp.712-717.

Dunn, A.M. and Weston, M.A., 2008. A review of terrestrial bird atlases of the world and their application. *Emu-Austral Ornithology*, *108*(1), pp.42-67.

Dunn, E.H., Kardynal, K.J., Covino, K.M., Morris, S.R., Holberton, R.L. and Hobson, K.A., 2023. Feather isotopes (δ 2 H f) and morphometrics reveal population-specific migration patterns of the Blackpoll Warbler (Setophaga striata). *Avian Conservation and Ecology*, *18*(2).

Edwards, B.P. and Smith, A.C., 2020. bbsBayes: An R package for hierarchical Bayesian analysis of North American breeding bird survey data. *Journal of Open Research Software 9(1).*

Environment and Climate Change Canada. 2019. “Blackpoll Warbler.” Status of Birds in Canada. 2019. https://wildlife-species.canada.ca/bird-status/oiseau-bird eng.aspx?sY=2019&sL=e&sM=a&sB=BLPW.

Farmer, C.J., Hussell, D.J. and Mizrahi, D., 2007. Detecting population trends in migratory birds of prey. *The Auk*, *124*(3), pp.1047-1062.

Fink, D., T. Auer, A. Johnston, M. Strimas-Mackey, S. Ligocki, O. Robinson, W. Hochachka, L. Jaromczyk, C. Crowley, K. Dunham, A. Stillman, I. Davies, A. Rodewald, V. Ruiz-Gutierrez, C. Wood. 2023. eBird Status and Trends, Data Version: 2022; Released: 2023. *Cornell Lab of Ornithology, Ithaca, New York.* https://doi.org/10.2173/ebirdst.2022

Francis, C.M. and Hussell, D.J.T., 1998. Changes in numbers of land birds counted in migration at Long Point Bird Observatory, 1961-1997. *Bird Populations*, *4*, pp.37-66.

Heesen, R., Bright, L.K. and Zucker, A., 2019. Vindicating methodological triangulation. *Synthese*, *196*, pp. 3067-3081.

Hill, J.M., 2023. The State of the Mountain Birds Report: 2023. *Vermont Center for Ecostudies, White River Junction, VT.* https://mountainbirds.vtecostudies.org/. ‎Accessed 1/15/2024.

Hobson, K.A., Wilson, A.G., Van Wilgenburg, S.L. and Bayne, E.M., 2013. An estimate of nest loss in Canada due to industrial forestry operations. *Avian Conservation & Ecology, 8(2).*

Hobson, K., Van Wilgenburg, S., Dunn, E., Hussell, D., Taylor, P. and Collister, D., 2015. Predicting origins of passerines migrating through Canadian migration monitoring stations using stable-hydrogen isotope analyses of feathers: a new tool for bird conservation. *Avian Conservation and Ecology*, *10(1).*

Holberton, Rebecca L., Steven L. Van Wilgenburg, Adrienne J. Leppold, and Keith A. Hobson, 2015. “Isotopic (Δ2Hf) Evidence of ‘Loop Migration’ and Use of the Gulf of Maine Flyway by Both Western and Eastern Breeding Populations of Blackpoll Warblers.” *Journal of Field Ornithology 86 (3):* 213–28.

Kellner, K., 2021. jagsUI: a wrapper around rjags to streamline JAGS analyses. R package version 1.5.2.

Kirby, J.S., Stattersfield, A.J., Butchart, S.H., Evans, M.I., Grimmett, R.F., Jones, V.R., O'Sullivan, J., Tucker, G.M. and Newton, I., 2008. Key conservation issues for migratory land-and waterbird species on the world's major flyways. *Bird Conservation International*, *18*(S1), pp.S49-S73.

Link, W.A., Sauer, J.R. and Niven, D.K., 2006. A hierarchical model for regional analysis of population change using Christmas Bird Count data, with application to the American Black Duck. *The Condor*, *108*(1), pp.13-24.

Link, W.A., Sauer, J.R. and Niven, D.K., 2017. Model selection for the North American Breeding Bird Survey: A comparison of methods. *The Condor: Ornithological Applications*, *119*(3), pp.546-556.

Machtans, C.S., Kardynal, K.J. and Smith, P.A., 2014. How well do regional or national Breeding Bird Survey data predict songbird population trends at an intact boreal site?. *Avian Conservation & Ecology*, *9*(1).

Mahon, C.L., Bayne, E.M., Sólymos, P., Matsuoka, S.M., Carlson, M., Dzus, E., Schmiegelow, F.K. and Song, S.J., 2014. Does expected future landscape condition support proposed population objectives for boreal birds?. *Forest Ecology and Management*, *312*, p.28-39.

Meehan, T.D., Saunders, S.P., DeLuca, W.V., Michel, N.L., Grand, J., Deppe, J.L., Jimenez, M.F., Knight, E.J., Seavy, N.E., Smith, M.A. and Taylor, L., 2022. Integrating data types to estimate spatial patterns of avian migration across the Western Hemisphere. *Ecological applications*, *32*(7).

Morris, S. R., Covino, K. M., Jacobs, J. D., & Taylor, P. D., 2016. Fall migratory patterns of the Blackpoll Warbler at a continental scale. *The Auk: Ornithological Advances*, *133*(1), 41-51.

Niemi, G., Hanowski, J., Helle, P., Howe, R., Mönkkönen, M., Venier, L. and Welsh, D., 1998. Ecological sustainability of birds in boreal forests. *Conservation Ecology*, *2*(2).

Pavlacky Jr, D.C., Lukacs, P.M., Blakesley, J.A., Skorkowsky, R.C., Klute, D.S., Hahn, B.A., Dreitz, V.J., George, T.L. and Hanni, D.J., 2017. A statistically rigorous sampling design to integrate avian monitoring and management within Bird Conservation Regions. PLoS One, 12(10).

Plummer, M., 2003, March. JAGS: A program for analysis of Bayesian graphical models using Gibbs sampling. In *Proceedings of the 3rd international workshop on distributed statistical computing* (Vol. 124, No. 125.10, pp. 1-10).

R Core Team. 2024. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Rosenberg, K.V., Kennedy, J.A., Dettmers, R., Ford, R.P., Reynolds, D., Alexander, J.D., Beardmore, C.J., Blancher, P.J., Bogart, R.E., Butcher, G.S. and Camfield, A.F., 2016. Partners in Flight landbird conservation plan: 2016 revision for Canada and continental United States. *Partners in Flight Science Committee*, *119*.

Rosenberg, K.V., Dokter, A.M., Blancher, P.J., Sauer, J.R., Smith, A.C., Smith, P.A., Stanton, J.C., Panjabi, A., Helft, L., Parr, M. and Marra, P.P., 2019. Decline of the North American avifauna. *Science*, *366*(6461), pp.120-124.

Sauer, J.R., Link, W.A. and Hines, J.E., 2020. The North American breeding bird survey, analysis results 1966–2019. *US Geological Survey data release.* [*https://doi.org/10.5066/P96A7675*](https://doi.org/10.5066/P96A7675).

Smith, A.C., Hudson, M.A.R., Downes, C. and Francis, C.M., 2014. Estimating breeding bird survey trends and annual indices for Canada: How do the new hierarchical Bayesian estimates differ from previous estimates? *The Canadian Field-Naturalist*, *128*(2), pp.119-134.

Smith, A.C. and Edwards, B.P., 2021. North American Breeding Bird Survey status and trend estimates to inform a wide range of conservation needs, using a flexible Bayesian hierarchical generalized additive model. *The Condor*, *123*(1).

Smith, P.A., Smith, A.C., Andres, B., Francis, C.M., Harrington, B., Friis, C., Morrison, R.G., Paquet, J., Winn, B. and Brown, S., 2023. Accelerating declines of North America’s shorebirds signal the need for urgent conservation action. *Ornithological Applications*, *125*(2).

Stewart, R. L. M. 2015. Blackpoll Warbler, pp. 441 in Stewart, R.L.M., Bredin, K.A., Couturier, A.R., Horn, A.G., Lepage, D., Makepeace, S., Taylor, P., Villard, M.-A., and Whittam, R.M. (eds). 2015. Second Atlas of Breeding Birds of the Maritime Provinces. Bird Studies Canada.

Stralberg, D., Matsuoka, S.M., Hamann, A., Bayne, E.M., Sólymos, P., Schmiegelow, F.K.A., Wang, X., Cumming, S.G. and Song, S.J., 2015. Projecting boreal bird responses to climate change: the signal exceeds the noise. *Ecological Applications*, *25*(1), pp.52-69.

Van Wilgenburg, S.L. and Hobson, K.A., 2011. Combining stable‐isotope (δD) and band recovery data to improve probabilistic assignment of migratory birds to origin. *Ecological Applications*, *21*(4), pp.1340-1351.

Van Wilgenburg, S.L., Beck, E.M., Obermayer, B., Joyce, T. and Weddle, B., 2015. Biased representation of disturbance rates in the roadside sampling frame in boreal forests: implications for monitoring design. *Avian Conservation & Ecology*, *10*(2).

Van Wilgenburg, S.L., Mahon, C.L., Campbell, G., McLeod, L., Campbell, M., Evans, D., Easton, W., Francis, C.M., Haché, S., Machtans, C.S. and Mader, C., 2020. A cost efficient spatially balanced hierarchical sampling design for monitoring boreal birds incorporating access costs and habitat stratification. *PLoS One*, *15*(6).