**Migration monitoring provides a potentially powerful way to monitor boreal birds. BBS and migration monitoring**

**Less precise than BBS – reasons.**

**Repeated sampling of isotopes.**

**More precise estimates of catchments.**

* **Many stations lack isotope information. Model yields testable predictions.**
* **More monitoring stations during fall migration, but less precise estimates**
  + **Loop migration of blackpoll warbler**
  + **Lack of catchment information**
* **Recommendations for future monitoring: repeated isotope sampling at stations where catchment is mixed. Repeated sampling of isotopes provides trend information.**

Using a novel statistical model, we estimated regional population trends migration monitoring data. Applying this model to a boreal breeding songbird revealed more optimistic 10-year national trend estimates than those derived from Breeding Bird Surveys that are largely collected at the periphery of the species range. Estimates derived from the BBS suggest that blackpoll warblers comprise 10% (307 million) of the estimated 3 billion breeding birds across all species that no longer exist in North America relative to 1970 (see Data S1 in Rosenberg et al. 2019). Accordingly, the blackpoll warbler is considered a common bird in steep decline and a priority for ongoing monitoring and conservation (Rosenberg et al. 2016). Our analysis suggests that steep population declines are unlikely to have occurred nationally across the three most recent generations for this species, and that there is a low probability blackpoll warbler currently meets COSEWIC criteria for Threatened status designation.

Our findings are consistent with ecological theorythat predicts population trends are less positive at species range margins, where habitat quality is lower and environmental conditions are further from a species’ optimum (MacArthur 1984; Hargreaves, Samis, and Eckert 2014). Theory also predicts that species will be more sensitive to environmental change at range margins, though empirical evidence for this prediction is mixed (Amburgey et al. 2018; Kleinhesselink and Adler 2018; Iles et al. 2020). The North American Breeding Bird Survey, as a roadside survey, contains large spatial gaps in the core of the roadless boreal forest and therefore primarily samples the periphery of boreal species’ ranges. This spatial bias leads to an unrepresentative sample of boreal habitats and anthropogenic disturbance, which is more severe near inhabited roadside areas (Van Wilgenburg et al. 2015; Dunn et al. 2005). If BBS surveys are restricted to the periphery of a species range, and in disproportionately disturbed habitats, trends derived from the BBS will be more negative than methods that survey the core of the range. Indeed, a long-term study of 50 species at an intact boreal study site found that population trends were on average more positive than regional and national BBS trends (Machtans, Kardynal, and Smith 2014). Our national migration trends were also more positive than BBS trends, which is consistent with this hypothesis; the migration monitoring network likely captures individuals from across the entire boreal range (Hobson et al. 2015; Dunn 2005) rather than disproportionately monitoring populations at range margins.

Climate-driven range shifts could also lead to the discrepancy we identified between trends based on breeding and migration surveys. In the case of the Breeding Bird Survey, a northward shift in population range for boreal-breeding species could masquerade as spurious population declines, given that most BBS survey locations are largely restricted to the southern periphery of the Canadian boreal forest. Thus, individuals shifting northward out of the BBS sampling frame would appear as a population decline, even if abundance were stable nationally. Recent evidence suggests that a 600 km northward shift in blackpoll warbler breeding range has likely occurred over the last 45 years (Gómez et al. 2021), coinciding with the period during which trends derived from BBS have been highly negative. In this case, migration monitoring may be more robust to climate-driven range shifts because populations that have shifted their breeding locations will nevertheless continue to be surveyed during their migration.

Migration analysis yielded short-term national trend estimates that had similar precision to those from the BBS, but a lack of historical migration counts and stable isotope data precluded usefully precise long-term estimates of population performance from migration monitoring (i.e., prior to 2008). We therefore cannot compare migration-based trend analysis to those from breeding surveys during the period in which the steepest population declines appear to have occurred for this species. Nevertheless, application of our method to other boreal breeding species would provide a strong test of the hypothesis that BBS-derived trends are overly pessimistic for species experiencing northward range shifts and/or species with large populations in the roadless core of the boreal forest. Simultaneously, our analytical approach could provide valuable insights for other groups of birds that are more reliably covered on migration or at stopover sites, such as shorebirds and raptors (Farmer, Hussell, and Mizrahi 2007), for which BBS-derived trend estimates are highly uncertain.

Independent estimates of abundance within each analytical stratum are required to properly “weight” regional trajectories and produce a national trajectory (see *Converting Regional Trajectories from Migration Monitoring into Regional Population Sizes* in *Methods* section*)*. For North American landbirds, considerable progress has been made towards understanding the relative strengths and limitations of different datasets used for this purpose (Sólymos et al. 2020; Thogmartin 2010; Confer et al. 2008). Our analysis relied on population abundance estimates produced from boosted regression trees trained on hundreds of thousands of avian point counts collected across the Canadian boreal forest (Stralberg et al. 2015; Boreal Avian Modeling Project 2020), with explicit corrections for variation in survey methodology among observations (Sólymos et al. 2013). New efforts to deploy a rigorously designed national sampling protocol across the entire Canadian boreal forest also hold immense promise for producing improved estimates of landbird densities (Van Wilgenburg et al. 2020), that can be used to both test predictions from our model and generate improved model outputs.

Possibly insert a paragraph about the east/west gradient that appears to occur in both the migration and BBS data?

* Causes of this gradient? Things to discuss?
* Somewhat worried that the discussion is too “blackpollish”, and not general enough. Adding this paragraph would make the paper even more species-specific. Thoughts/advice?

The current formulation of our model assumes that migration pressure is constant through time (i.e., has no temporal component; Table 1) and that directional changes in abundance of migrants are due to changes in regional population sizes, rather than directional shifts in migration routes. Repeated sampling of migrants for stable isotopes at multiple stations could be used to evaluate whether station catchment is changing over time and would allow for temporal components to be added to the terms. Importantly, our model makes explicit predictions about the proportion of migrants from each region in a station’s annual catchment (equations 2, 3, and 7). Iteratively confronting predictions with new data is the strongest test of scientific theory and the fastest way to improve ecological understanding (Dietze et al. 2018), and we therefore consider the collection of new stable isotope data across the migration network a priority for further model testing and refinement.

Moving forward, our model could potentially be extended to incorporate non-standardized migration count data from citizen science networks such as eBird (Sullivan et al. 2014), 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 any single migration monitoring station 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). For migration monitoring, this also requires limiting data to locations outside breeding and/or wintering areas to avoid confounding changes in migrant numbers with signals of change in local numbers of seasonal residents. Simultaneously, the continual improvement of wildlife tracking technologies will undoubtedly yield finer resolution estimates of migration behaviour, and thus, station catchment. Future integrated analysis of these data would allow trends to be estimated in a larger number of higher resolution strata, yielding enhanced information at conservation-relevant scales.

Interpretation of station-level trends is also complicated by the “loop migration” behaviour of blackpoll warblers, wherein populations follow very different migration routes during spring and fall (Holberton et al. 2015; Covino et al. 2020; DeLuca et al. 2019). A single station may therefore be monitoring birds originating from different origins of the breeding range during each migration season. Furthermore, most of the continental population appears to congregate along the northeast coast of the United States during fall migration, prior to undertaking a transoceanic flight to nonbreeding areas in South America (Holberton et al. 2015; DeLuca et al. 2015; Nisbet et al. 1995). Thus, stations in this region are likely to capture a mixture of birds from across the breeding range.