Together, these added data streams produce a model which is much better able to delineate migratory and post-migratory states during certain seasons.

The improved error rates and migratory characteristics for certain seasonal models seems to be due to several added data streams working in aggregate. Individual variables had a minor contribution to overall error rates (range -1.20–0.19%; Fig. 5), although the addition of all six data

Despite differences in error rates between base and full models, removal of individual variables from the full model resulted in only minor differences in error rates (range:-1.20–0.19%; Fig. 5), suggesting that many of the additional data streams function in aggregate to reduce error rates.

better fit the migratory movements of American Woodcock, as measured using error rates. The magnitude of the improved fit differed by error type, with the largest improvements occurring for Type II errors in the spring female model (Type II error ranges: base model 10.0–77.6%, full model 2.0%–11.4%%; Fig. 4). Migr

We found that migratory characteristics also differed between the full and base models, particularly for spring females. The base model was 2.12 times less likely than the full model to identify a post-migratory state for any given spring female track, and the base model produced lower estimates for migratory duration (tk) and distance (tk) and an earlier estimated migratory termination date (tk) than the full model. The improved error rates and migratory characteristics for certain seasonal models seems to be due to several added data streams working in aggregate. Individual variables

Despite differences in error rates between base and full models, removal of individual variables from the full model resulted in only minor differences in error rates (range:-1.20–0.19%; Fig. 5), suggesting that many of the additional data streams function in aggregate to reduce error rates.

Hidden Markov models are well suited to estimation using multiple data streams due to the extensible nature of their likelihoods (Zucchini et al. 2017), which allow state estimation to be informed by as many parameters as are available. By adding additional data streams we were able to effectively increase the amount of data available to estimate the underlying behavioral state, and as such improve our accuracy in state classification.

For some migratory movements such measures might not be necessary; our measurements of comparative migratory characteristics for fall migration and spring males found similar characteristics between the base and full models.

Even in circumstances of sparse and irregular data, the base HMM model might be enough to delineate movement states of birds in certain situations.

However, spring female migration had substantial differences between the base and full models, with the base model being 2.12 times less likely than the full model to identify a post-migratory state for any given track, and the base model producing lower estimates for migratory duration (tk) and distance (tk) and an earlier estimated migratory termination date (tk) than the full model.

The difficulties encountered in fitting the base model to spring female migration is likely due to female woodcocks’ tendency to make nesting attempts during spring migration, frequently with continued migration after the presumed failure of a nesting attempt (Slezak et al. in press). This reproductive system may produce similar step lengths and turn angles between the stopover and post-migratory states for spring females, which causes the base model to encounter difficulties in differentiating between the two. The addition of data streams, especially residence time, ordinal day, and latitude, was able to substantially increase the accuracy of the spring female model (Fig. 5), likely by helping the model to differentiate between early, southerly nesting attempts that are prone to failure and resumption of migration and later nesting attempts in the breeding range which are less likely to have a subsequent migratory movement. While woodcocks’ breeding system is uncommon among bird species (Slezak et al. in press), this technique for refining HMMs may be useful for any species in which stopover and post-migratory states have both spatial overlap and similar movement characteristics. For example, Sora (*Porzana carolina*) use the Chesapeake Bay in Virginia, Maryland, and Delaware, USA, as both a breeding and a staging area during spring migration, and an HMM technique like this one could be used to estimate the likelihood that a GPS-tagged Sora in the Chesapeake was in a breeding or staging state based on its movement characteristics (cite tk). This technique may be widely applicable to shorebirds and waterbirds, for which extended stopover and staging behaviors are common, and facultative migrants (e.g. American Robin, *Turdus migratorius*) which encounter substantial overlap in their migratory, breeding, and wintering ranges.

Modeling migratory bird movements provides several challenges:

* Small size of transmitter (as addressed here)
* Rapid shifts between movement modes (as shown here, can break CRW)

The resourceful modification of pre-existing movement modeling techniques can allow us to apply these tools to a much greater array of species, and allow us to gain more insight into the ecology and habits of migratory birds.

techniques originally developed for

can allow us to

Future directions:

Small transmitters for tracking migratory birds are prevalent, and becoming more common

Advantages in tracking small scale movements and individual differences in movements, survival, and habitat selection

Determining how to use this migratory

Advancements in the field of movement ecology have been driven by innovations in the individual tracking of animals using transmitters, particularly high-frequency transmitters that can collect multiple locations per day, if not per hour (Mills et al. 2006, Joo et al. 2020). Methods that have been designed to accommodate high frequency data, such as approximations of continuous trajectories and step selection functions, have considerable potential for the field (Thurfjell et al. 2014, Calabrese et al. 2016). However, methodological advances have not kept pace with the increasing prevalence of small transmitters that can fit on a much larger portion of the world’s animals but collect more sparse and irregular data. The satellite GPS transmitters used in this manuscript, as well as non-satellite tracking devices such as Lotek NanoTag transmitters (Rakhimberdiev et al. 2015, Taylor et al. 2017), are examples of small transmitters that are useful for tracking small animals but collect sparse and irregular location data. While this study demonstrates that hidden Markov models can be retrofitted for use with imperfect data, new methods will eventually be required for the abundance of new transmitter data collected by migratory bird studies. Recent innovations in point process modeling provide examples of tools that might better allow for the modeling of movement data from small animals. The traditionally used technique for interpolating movement trajectories, correlated random walk models, can encounter difficulties with infrequent locations and data gaps that are common in migratory bird data, as demonstrated in this manuscript. Non-mechanistic movement models are better able to compensate for rapid behavioral shifts and, due to their non-parametric nature, may better deal with irregular time intervals in which step lengths and turn angles are not consistent (Rieber 2023). Beyond advances in modeling techniques, proper modeling of migratory bird movements may require bespoke models which are specifically designed to accommodate rapid alternation between stopover states with short, recursive steps and migratory states with long, directional steps. With further innovation, we can take the myriad successes of the advancement of the field of movement ecology and better apply those tools to the much larger network of animals which can be tracked using small transmitters.