Appendix 1

Table A1. Names and locations of sites where geolocators were deployed.

Site	State	Lat	Lon	Years geolocators deployed
Airlie Gardens	North Carolina	34.22	-77.83	2017
Carolina Beach State Park	North Carolina	34.05	-77.92	2017
Bald Head Island	North Carolina	33.86	-77.98	2019
Kiawah Island	South Carolina	32.61	-80.02	2017, 2018, 2019
Spring Island	South Carolina	32.35	-80.84	2018, 2019
Dewees Island	South Carolina	32.84	-79.72	2018
St. Matthews	South Carolina	33.69	-80.73	2018
Little Saint Simons Island	Georgia	31.26	-81.30	2017, 2018, 2019
Little Talbot Island State Park	Florida	30.46	-81.41	2017, 2018, 2019
Wichita Mountains NWR	Oklahoma	34.7	-98.7	2011, 2012
Holla Bend NWR	Arkansas	35.16	-93.1	2018

Geolocator analysis

The development of miniaturized light-level geolocators has been transformative to the study of migratory birds (Stutchbury et al. 2009, McKinnon et al. 2013, McKinnon and Love 2018). Birds as small as 7 grams (about the weight of three American pennies) can now be tracked throughout their annual migration with a reasonable degree of accuracy. However, the process of analyzing and interpreting geolocator data is complex and should be done thoughtfully and transparently, especially as it concerns latitudinal movement (Lisovski et al. 2018). The following analysis draws heavily from Lisovski et al., 2020 (Lisovski et al. 2020) and the online manual that accompanies it.

Raw geolocator (Eastern population: stalked model P50Z11-7-DIP, Migrate Technology Ltd, Coton, Cambridge, UK; Interior population: See Contina et al. 2013) data consist of light levels recorded at predetermined intervals for the duration of the tag's battery life. Geolocator analysis relies on accurate estimates of twilights (sunrise/sunset). Twilights were identified using the function *preprocessLight*, which is part of the R package TwGeos (Wotherspoon et al. 2016). Twilight editing/filtering was done only by automation, with the following parameters: If an identified twilight was more than 45 minutes different from the 2 twilights on either side, and those 2 twilights were within 25 minutes of each other, the outlier twilight was replaced with the median value of the 2 twilights on either side. If the 2 twilights on either side of the outlier were not within 25 minutes of each other, the outlier twilight was deleted. This method of geolocator analysis requires the user to define light-level thresholds that define transitions between day and night. Light-levels above the threshold indicate daytime, light levels below the threshold indicate nighttime. We kept the light threshold consistent for all birds within each population unless extraordinary shading required threshold adjustment. Adjusting the threshold does not strongly affect location estimates unless zenith (sun angle) estimates are not reevaluated using the new threshold.

Analysis of light-level data requires calibration to account for inaccuracies in twilight estimation. These inaccuracies can be related to the sensor's inability to perfectly detect light-levels or by shading effects caused by vegetation, topography, or even the feathers adjacent to the sensor. The calibration period(s) refers to time periods where the location of the individual is known. In this case, calibration starts when the tag is deployed and ends before the individual has left the breeding ground. For eastern birds, the calibration period terminated on August 1st, as it is extremely unlikely for eastern Buntings to depart the breeding ground prior to this date. For interior birds, the stationary breeding period began when the geolocator was deployed and ended when the bird departed the breeding ground. This flexible time frame was necessary because some interior birds had already reached the molting ground and stopped recording locations before others had even received their geolocator on the breeding ground. For individuals whose geolocators lasted long enough to record the return to the breeding ground the following spring, we used two calibration periods. The second calibration period started as soon as the bird was assured to have returned to the breeding ground and ended when the geolocator stopped recording locations. The *thresholdCalibration* function in R package SGAT creates the threshold model by fitting a gamma distribution to the twilight error (minutes) during the calibration period (Wotherspoon et al. 2013). The parameters from this model help to inform the model that optimizes location estimates later on. The zenith angle that is associated with the median twilight error during the calibration period is taken to be the best zenith estimate for the calibration period, as that is the zenith angle that results in the average amount of error. One of the most difficult steps of geolocator analysis is determining an appropriate zenith angle for time periods when the bird is at an unknown location (away from the breeding ground, in this case). Adjusting zenith angles will drastically change estimates of latitude. There is some precedent for using a constant zenith angle for the duration of the track, but we (and others) found that using a zenith calibrated for the breeding ground did not result in realistic location estimates on the non-breeding ground (Cooper et al. 2017). To determine appropriate zenith angles at times of the year when location is unknown (e.g., the nonbreeding season), we used the Hill-Ekstrom calibration method (HEC) (Lisovski et al. 2012, 2020), which works on the principle that the true zenith angle should result in the smallest variation in estimated latitudes. We attempted to be as methodical as possible in how we implemented this method by using the same window (December 1st- March 15th) for each bird. Even so, this method occasionally returned spurious zenith estimates.

We specified a gamma-distributed movement model with parameters that assume most movements are near-zero distance (stationary periods) but that allow for long-distance movements (migration). We specified a location mask to constrain location estimates to the known range of the Painted Bunting (Hallworth et al. 2015). The built-in MCMC sampler in SGAT uses the initial crude locations generated from recorded light-levels, the land mask, and the prior distributions from the threshold model and the movement model to simulate thousands of tracks (Sumner et al. 2009). For each time point, the mean location estimate from all iterations is taken to be the best location estimate. For visualization of non-breeding locations, we created a location density layer from the posterior distribution from each individual using the *slices* function within SGAT.

Estimates of latitude derived from light-level tags can have considerable uncertainty (>100 km) under certain conditions. During the equinox periods, which can last up to 30 days on either side of the fall and spring equinox, estimates of latitude are unreliable due to the lack of latitudinal variation in day length during this period. Unfortunately, this often coincides with migration, such that only longitudinal movements can be inferred. Naturally, this can make determining dates of arrival/departure using geolocator data difficult. We defined departure as a significant (>2 degrees) longitudinal movement away from a known stationary location. To determine arrival, we looked for longitude to stabilize during a stationary period, and then tracked backwards until longitude moved significantly (>2 degrees) away. We only assigned arrival/ departure dates for individuals whose movements allowed confident determination of arrival/departure. Some individuals had such little longitudinal movement or migrated such short distances that assigning arrival or departure dates was not feasible or appropriate.

Accurate time keeping is critical to geolocator analysis. If the clock onboard the geolocator speeds up or slows down, estimates of longitude will become increasingly biased as the clock drift accumulates. Clock drift is apparent if longitudinal estimates of known locations (breeding ground) are accurate when the geolocator is deployed, but have shifted east or west by the time the bird returns the following spring. Most of our geolocators showed no sign of clock drift. For the < 5 tags that showed evidence of clock drift, we used the following method to correct the bias (assumes rate of drift is constant through time):

1. Determine total amount of clock drift in seconds (ΔT)
    1. ΔT = (Fall Breeding Longitude - Spring Breeding Longitude) * 300 seconds
2. For each recorded date time at time step ***i***, add (or subtract, depending on direction of clock drift) a portion of ΔT proportional to how far along that time step is in the data set
    1. Corrected Time_i = Biased Time_i + **(**ΔT * (***i***/ total number of time steps)**)**
    2. The result of this method is that very little correction is added to date-times early on in the dataset, because very little clock drift has accumulated. By the final time step, 100% of the total clock drift is added.

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