

Appendix S2 – Estimation of shorebird arrival probabilities

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Model specification and goodness-of-fit

We used a multistate formulation of the Jolly-Seber model (Kéry and Schaub 2012) to estimate arrival probabilities for each species across the stopover season in each year. Resightings of flagged individuals occur in 3-day sampling periods to ensure that all study beaches are visited within each sampling period. Using this data we constructed capture histories with two states: detected (1) and not detected (2). In order to estimate entry probability for the first time step, we augmented the data set with a dummy sampling occasion at the beginning of each capture history in which all individuals were assigned the “not detected” state. We used a hierarchical state-space approach to estimate the true underlying state of each individual (not yet entered (1), present (2), or departed (3)). The state transition process can be represented by a row-stochastic matrix in which the rows indicate an individual’s state at period t (not yet entered, present, departed) and columns indicate state at period $t+1$,

$$\begin{bmatrix} 1 - \gamma_t & \gamma_t & 0 \\ 0 & \varphi_t & 1 - \varphi_t \\ 0 & 0 & 1 \end{bmatrix}$$

where γ_t is the period-specific entry probability, i.e. the probability that an individual that is not present at time $t-1$ will enter the study area at time t , and φ_t is the period-specific persistence probability, i.e. the probability that an individual that is present at time t will remain in the study area until time $t+1$. The observation process can be mapped to the true state of each individual using the matrix in which rows indicate an individual’s state at period t and columns indicate observed state (seen, not seen),

$$\begin{bmatrix} 0 & 1 \\ p_t & 1 - p_t \\ 0 & 1 \end{bmatrix}$$

where p_t is the period-specific detection probability, i.e. the probability that an individual that is present at time t will be detected. In stopover systems persistence probability tends to be high early in the

season and decline as the season progresses and individuals depart for the breeding grounds. Therefore we estimated persistence probability as a fixed effect of sampling period. Resighting data for this project is collected by a volunteer-based team, and therefore observer effort varies across the season. To account for this variation, we estimated detection probability as a random effect of sampling period. We used the R2Ucare package in R (R Core Team 2016, Gimenez et al. 2018) to assess goodness-of-fit and determine the appropriate model for each species in each year. Goodness-of-fit tests indicated evidence of transience and trap-dependence in some datasets (Table S2), and so we developed four Jolly-Seber models to account for transience, trap-dependence, or both. Transients are common at stopover sites, as some individuals may stop only briefly and not stay to refuel; not accounting for transients can bias persistence probability estimates low. Trap-dependence could arise in our data if individuals tend to remain at or return to feeding sites that receive high observer effort. In Delaware Bay, a small sheltered harbor has been created at the mouth of the Mispillion River, creating several sandy foraging beaches with low wave activity and high horseshoe crab spawning activity. This site consistently has the largest foraging flocks and receives the most observer effort, which could create a type of trap-dependence in observations.

We defined transients as individuals that were present for only a single three-day sampling period, and therefore we defined residents as individuals detected in at least two sampling periods. We estimated an additional parameter, τ , the probability of remaining at the stopover site for at least two sampling periods. For each individual, residency status w_i was estimated as a Bernoulli random trial, $w_i \sim \text{Bern}(\tau)$, and persistence probability $\varphi_{i,t}$ was estimated as the product of period-specific persistence probability and the residency of each individual, $\varphi_{i,t} = \varphi_t * w_i$. Under this formulation, only residents have the opportunity to remain in the study area after initial entry. We assumed transience probability was constant across the stopover period. To account for trap-dependence, we estimated detection probability as an individual effect of detection at the previous occasion. Including period-

specific random effects, individual detection probability was defined as $\text{logit}(p_{i,t}) = \beta_{d(i)} + \varepsilon_t$, where $d(i) = 1$ if an individual was detected at the previous occasion and $d(i) = 2$ otherwise, $\beta_{d(i)}$ is the average group-specific detection probability and ε_t is the normally-distributed period-specific residual error.

Table S1. Goodness-of-fit test results for Jolly Seber models used to estimate arrival probabilities across the stopover season each year. Tests were implemented using the R2Ucare package for R and described in Gimenez et al (2017).

Species	Year	Significant test(s)	Model
Red knot	2005	Test 3SR, Test 3SM	transience
Red knot	2006	Test 2CT, Test 3SR	trap-dependence and transience
Red knot	2007	Test 2CT, Test 3SR, Test 3SM, Test 2CL	trap-dependence and transience
Red knot	2008	Test 2CT, Test 3SR	trap-dependence and transience
Red knot	2009	Test 2CT, Test 3SR	trap-dependence and transience
Red knot	2010	Test 2CT	trap-dependence
Red knot	2011	Test 2CT, Test 3SR, Test 2CL	trap-dependence and transience
Red knot	2012	Test 3SR	transience
Red knot	2013	Test 2CT, Test 3SR	trap-dependence and transience
Red knot	2014	Test 2CT, Test 3SR	trap-dependence and transience
Red knot	2015	Test 2CT, Test 3SR, Test 3SM, Test 2CL	trap-dependence and transience
Red knot	2016	Test 2CT, Test 3SR, Test 3SM	trap-dependence and transience
Ruddy turnstone	2005	None	standard JS model
Ruddy turnstone	2006	None	standard JS model
Ruddy turnstone	2007	Test 3SR, Test 3SM	transience
Ruddy turnstone	2008	Test 2CT, Test 3SR, Test 2CL	trap-dependence and transience
Ruddy turnstone	2009	Test 3SR	standard JS model
Ruddy turnstone	2010	Test 2CT, Test 3SM	trap-dependence
Ruddy turnstone	2011	None	standard JS model
Ruddy turnstone	2012	Test 2CT, Test 3SR	trap-dependence and transience
Ruddy turnstone	2013	Test 2CT, Test 3SR, Test 3SM	trap-dependence and transience
Ruddy turnstone	2014	Test 2CT, Test 3SR, Test 3SM	trap-dependence and transience
Ruddy turnstone	2015	Test 2CT, Test 3SR	trap-dependence and transience
Ruddy turnstone	2016	Test 2CT, Test 3SR, Test 3SM	trap-dependence and transience

Results

Arrival probability.—Arrival probabilities were consistently low early in the season for both species, increasing in the middle of the season, and declining again. These patterns were relatively consistent although there was some annual variation (Fig S1). In most years, red knot had a more pronounced peak in arrival probabilities than ruddy turnstone.

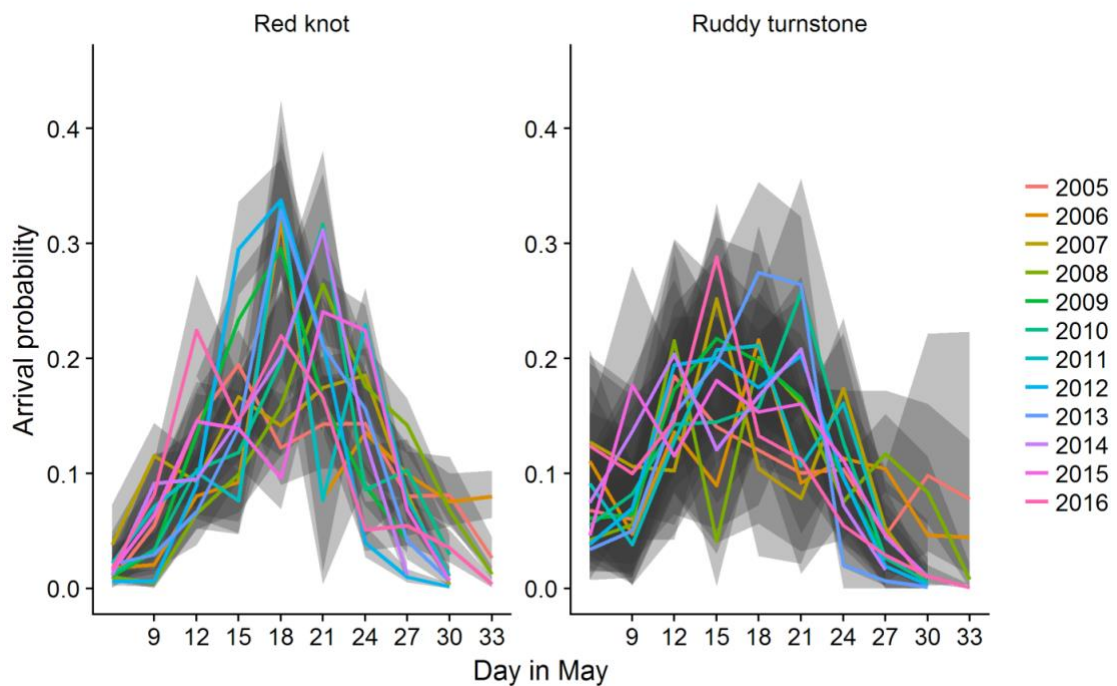


Figure S1. Period-specific arrival probabilities for red knot and ruddy turnstone across the stopover season from 2005-2016. Lines represent posterior means and shaded regions represent 95% credible intervals.

Stopover persistence probability.—Although both species followed a general pattern of higher persistence probability early in the season followed by a sharp decline, there was substantial annual variation in early-season persistence probability for red knot (Fig S2). We assumed no temporary emigration during the stopover period, but a violation of that assumption could result in negative bias in persistence probabilities and is a possible explanation for these estimates.

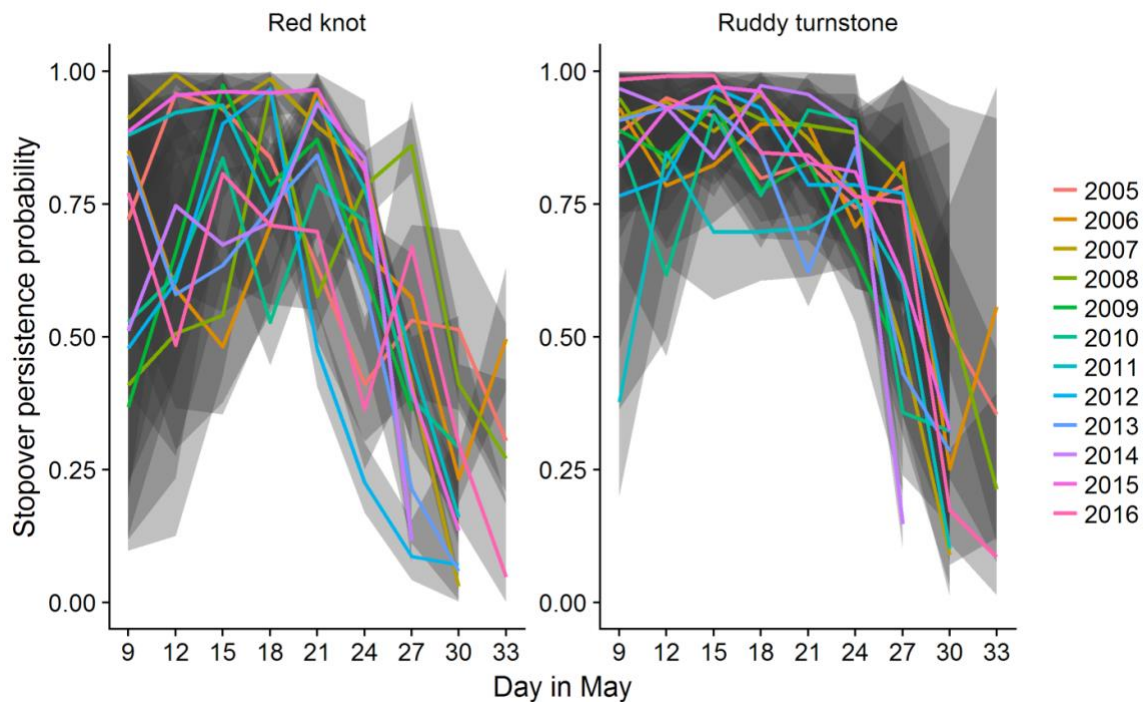


Figure S2. Period-specific persistence probabilities for red knot and ruddy turnstone across the stopover season from 2005-2016. Lines represent posterior means and shaded regions represent 95% credible intervals.

Detection probability.—Average detection probability for both species was relatively consistent across years (Fig S3). Although trap-dependence was indicated for several datasets, estimates of average

detection probability did not differ substantially between birds seen at the previous occasion and those not seen at the previous occasion for either species in any year (i.e. 95% credible intervals overlapped).

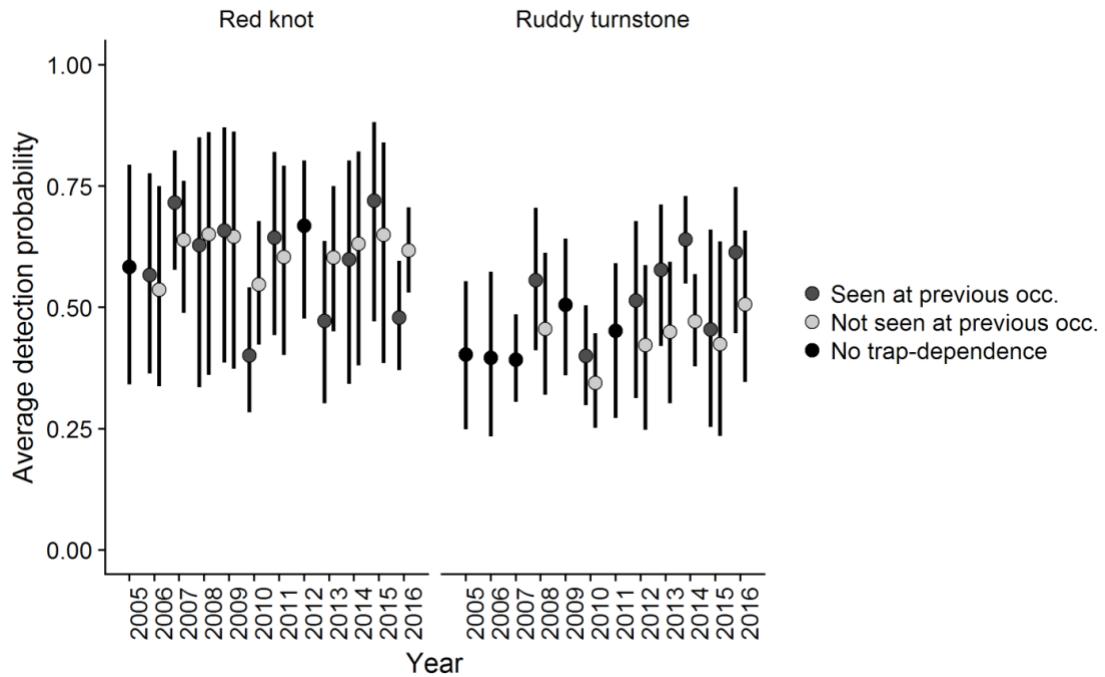


Figure S3. Annual average detection probabilities for red knot and ruddy turnstone from 2005-2016. Points represent posterior means and lines represent 95% credible intervals. For models fit with trap-dependence, dark gray points indicate birds that were seen at the previous occasion and light gray points indicate birds that were not seen at the previous occasion. For models fit without trap-dependence, black points represent the average detection probability.