Combining multistate models and network theory to evaluate movement patterns during migratory stopover

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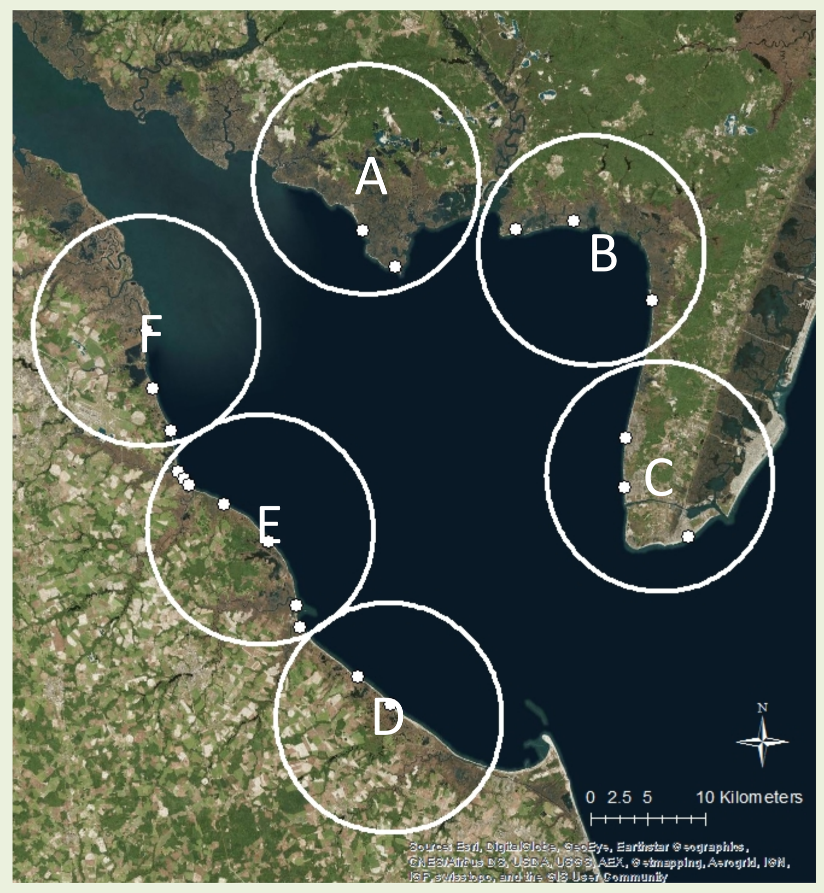
How do regional patterns of stopover site use vary annually? What are the ecological drivers of those patterns?

- Individuals are time- and energy-limited during migration and must use stopover sites efficiently
- Delaware Bay is a globally-important spring stopover site for migratory shorebirds (Fig. 1) where horseshoe crab eggs are a preferred food
- Regional patterns and drivers of site use are of interest for beach management and local conservation efforts
- We evaluate movement patterns using resights of flagged birds, combining multistate models with network theory to compare site-use dynamics across species and years



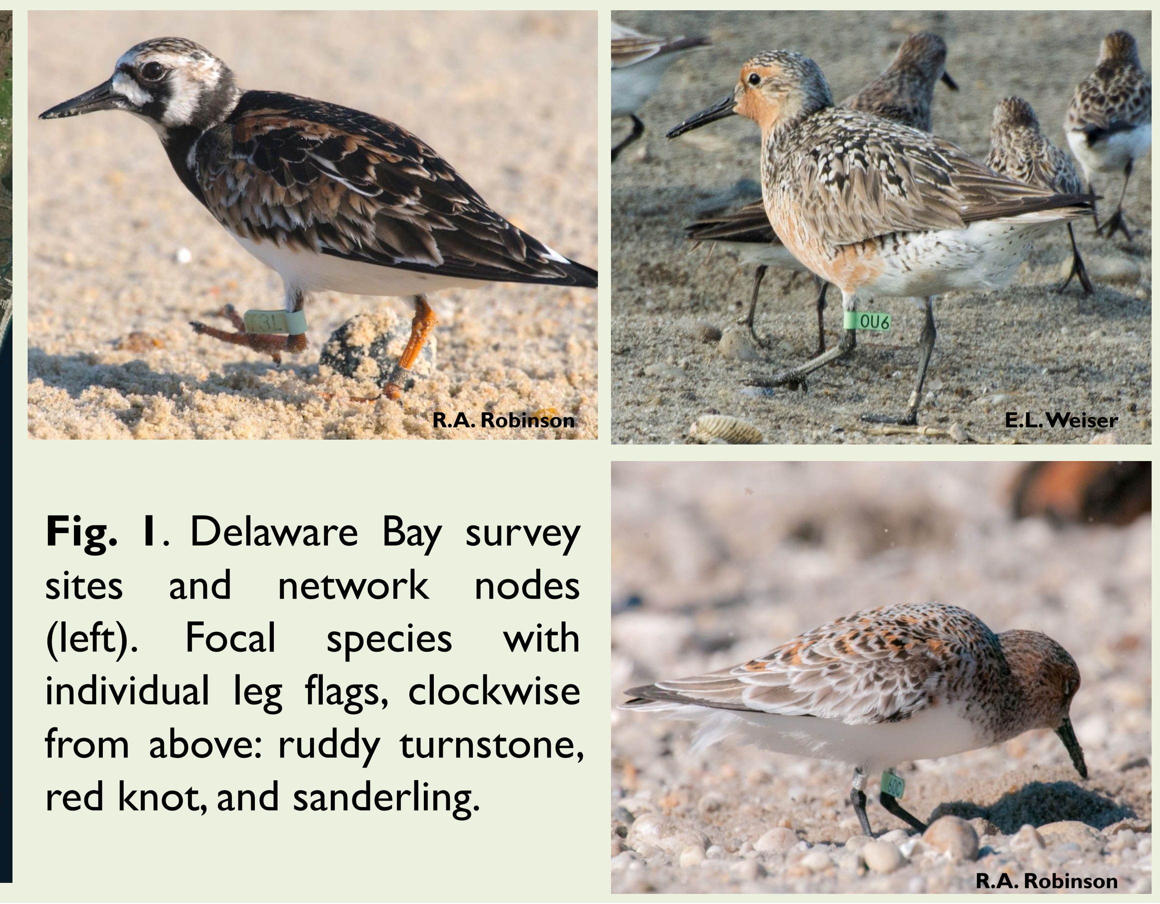
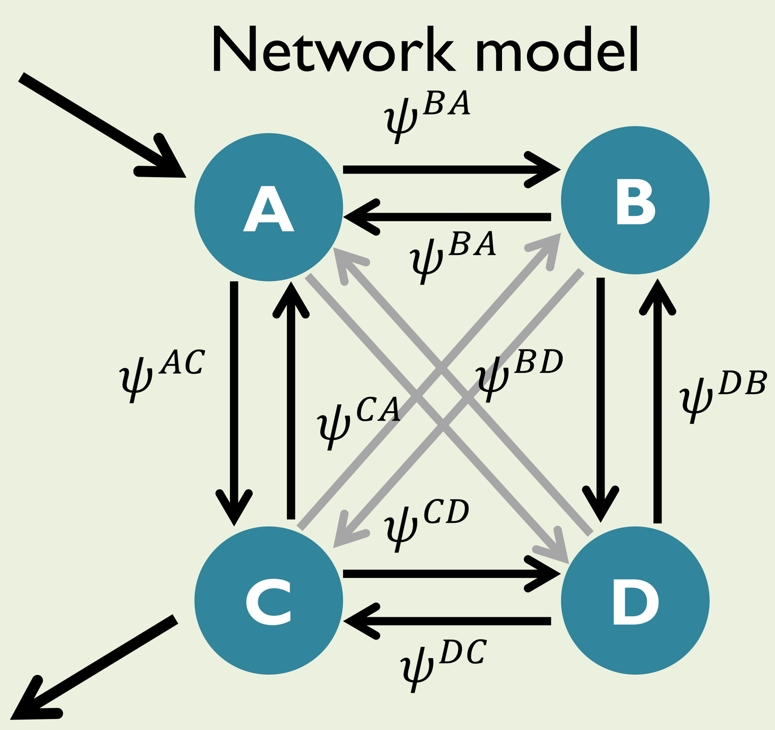


Fig. 1. Delaware Bay survey sites and network nodes (left). Focal species with individual leg flags, clockwise from above: ruddy turnstone, red knot, and sanderling.

Network theory helps visualize multistate model results and facilitates comparisons among species and years

Multistate process model

$$\begin{bmatrix} \phi_t\psi^{AA} & \phi_t\psi^{AB} & \phi_t\psi^{AC} & \phi_t\psi^{AD} & 1-\phi_t \\ \phi_t\psi^{BA} & \phi_t\psi^{BB} & \phi_t\psi^{BC} & \phi_t\psi^{BD} & 1-\phi_t \\ \phi_t\psi^{CA} & \phi_t\psi^{CB} & \phi_t\psi^{CC} & \phi_t\psi^{CD} & 1-\phi_t \\ \phi_t\psi^{DA} & \phi_t\psi^{DB} & \phi_t\psi^{DC} & \phi_t\psi^{DD} & 1-\phi_t \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$



Comparing networks

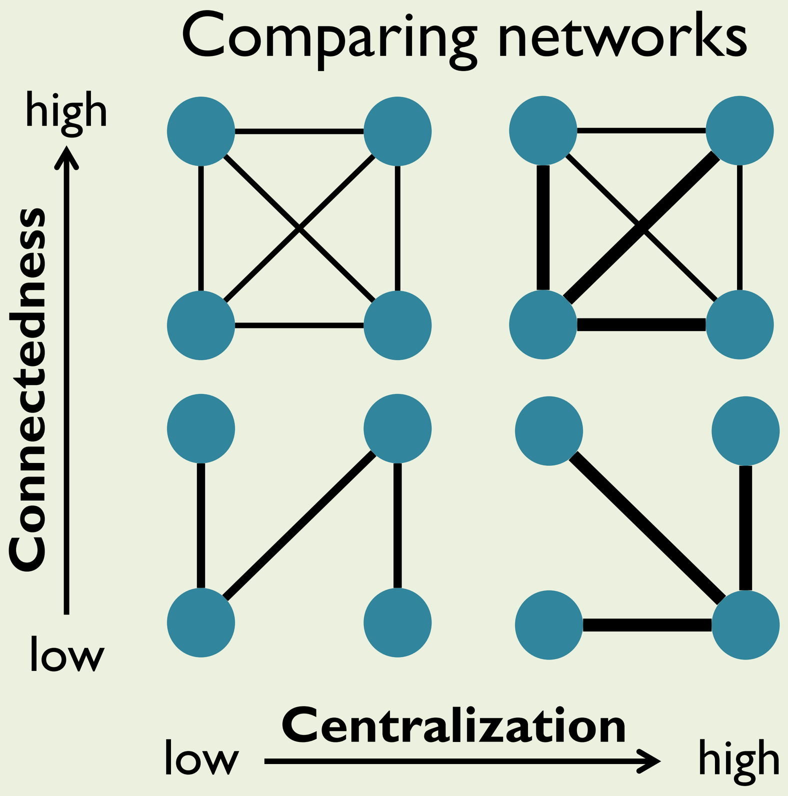


Fig 2. Multistate model used to estimate transition probabilities (ψ) used as edge weights in networks. Emergent network properties, as opposed to individual ψ estimates, are of ecological interest

Quantifying regional movement patterns

- Re-sighting data from 2005-2012 were used in multistate models to estimate transition probabilities among sites (ψ), which are then used as edge weights in year-specific networks (Fig. 2)
- Metrics of network connectedness (number of edges) and centralization (distribution of edges and edge weights) quantify emergent network patterns

Abundance and heterogeneity in preferred food resource

- Index of female horseshoe crab spawning abundance (proxy for food abundance) was analyzed two ways:
  1. Tested for correlation between network metrics (centrality, connectedness) and regional average abundance each year
  2. Pairwise differences in abundance between nodes included as covariates for ψ in within-year process model

Variation in network patterns is associated with both abundance and distribution of preferred food

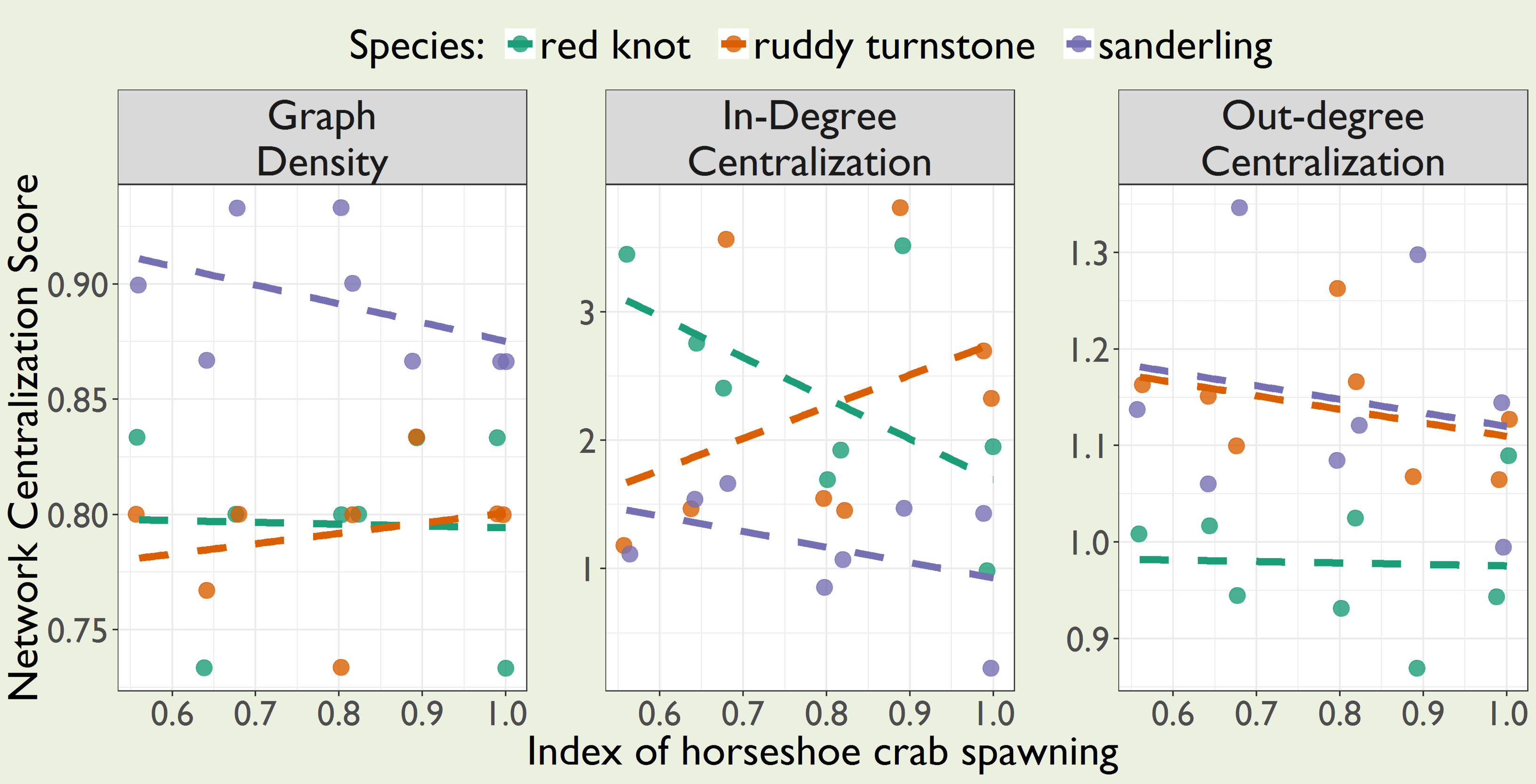
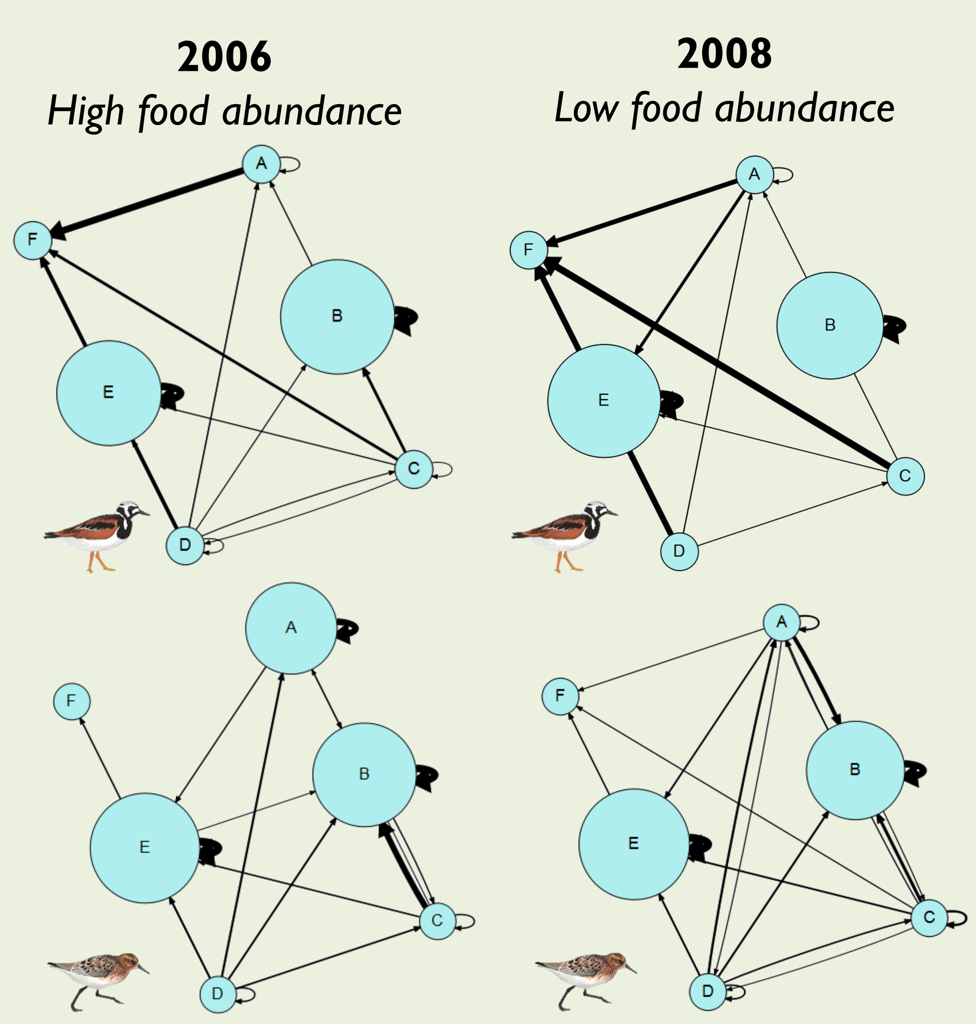


Fig 3. Association between horseshoe crab abundance and network connectedness (graph density) and centralization for each species (above). Representative networks for site use with high (2006) and low (2008) average horseshoe crab abundance (right).



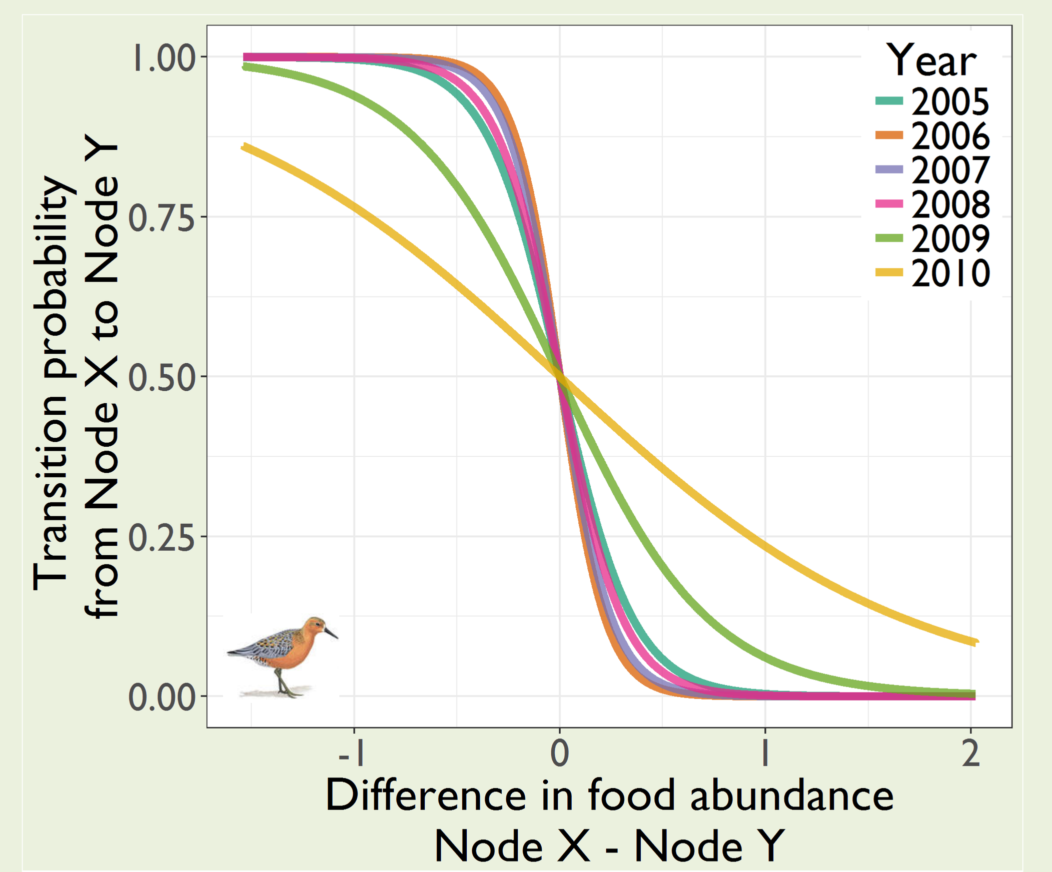


Fig 4. Predicted effect of between-site difference in food abundance on red knot transition probabilities each year.

- All species had relatively high graph density (network connectedness) in all years, regardless of food abundance (Fig. 3)
- High food abundance was related to lower network centralization for ruddy turnstone but higher for red knot and sanderling (Fig. 3)
- Between-site differences in food abundance were a strong predictor of red knot movement probability between sites in most years (Fig. 4)
- Birds use multiple sites in the region and yearly variation in site-use is associated with the abundance and distribution of horseshoe crab eggs
- This highlights the importance of regional-scale beach management and conservation decision-making for these species
- Our approach can be applied to a range of systems when movement patterns are of interest but telemetry or other tracking data are lacking

Acknowledgements—Thanks to DE Division of Fish and Wildlife, NJ Department of Environmental Projection, Conserve Wildlife Foundation of NJ, Amanda Dey, Larry Niles, and volunteers for resight data collection. Horseshoe crab data from DEDFW. Funding from Garden Club of America.

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