Connectivity between flyway populations of waterbirds: assessment of rates of exchange, their causes and consequences

## Appendix S1 – Supporting Information

Basic structure of the model to estimate rate of exchange

E-SURGE is a tool for multi-event (or hidden Markov) models, where individuals at each occasion occur in one of a finite set of states, and observations (events) do not necessarily correspond to the underlying states ([Pradel 2005](#_ENREF_1)). Our model included five states: alive in the western flyway, low observability (state 1), alive in the western flyway, high observability (state 2), alive in the eastern flyway, low observability (state 3), alive in the eastern flyway, high observability (state 4), and dead (state 5). There were three events: not seen, seen alive in the western flyway, and seen alive in the eastern flyway. The state ‘dead’ was thus unobservable (we did not include dead encounter data).

The first stage in a multi-event model is specifying the initial state probabilities, i.e. the probabilities that new individuals belong to each of the four states. We decomposed this into two steps: probabilities of belonging to each flyway, followed by probabilities of belonging to each observability state. Observability was thus modelled separately for the two flyways. In E-SURGE, the pattern matrices for the two steps were:

Step 1:

Step 2:

In these matrices, rows indicate states of origin, columns states of arrival, *y* indicates a parameter to be estimated, \* a parameter estimated by subtraction (the matrices are row-stochastic, i.e. rows sum to one), and – a parameter set to zero by definition. The initial state probabilities for flyways (step 1) were fixed to the observed annual proportion of new birds entering the data set in the western respectively eastern flyway. Step 2 was modelled separately for each flyway. The initial probability of the state ‘dead’ is per definition zero, and does not appear in the matrix for the first stage.

The next stage involves the transition probabilities between states from one year to the next. We decomposed the transition into three steps:

Step 1 (survival):

Survival was always modelled as the same for both observability states within each flyway, i.e. for states 1 and 2, respectively 3 and 4.

Step 2:

Step 2 of the transition was complex and involved two new ‘dummy’ states: newly arrived in respectively the western flyway (column 5) and the eastern flyway (column 6). As an example, birds in state 1 (western flyway, low observability) could either move to the high observability state (state 2), move physically to the eastern flyway (appearing as new arrivals in state 6), or remain in the same state (estimated by subtraction). To enforce the same probability of moving between flyways for birds in the two observability states, probabilities in this matrix were modelled as depending on state of arrival.

Step 3:

In step 3, the newly arrived birds in ‘dummy’ states 5 and 6 were allocated to the high or low observability state in the respective flyway. The split into steps 2 and 3 allowed birds in the two observability states to have the same probability of moving between flyways.

The third stage of the modelling process specifies the observation process, i.e. the link between states and events.

The encounter probability was modelled separately for each flyway, with additive effects of observability state and group (neck-banded vs. leg-ringed). Dead encounters were not included, and dead birds (state 5) therefore appeared as ‘not seen’ (event 1) with probability 1.

Constraints and initial model selection

The number of observed moves between flyways was low, and there was therefore very little information available to estimate the parameters in step 3 of the transition process (observability state probabilities for newly arrived birds). To ensure robust estimation, we therefore constrained these probabilities to be the same as the initial observability state probabilities for new birds (step 2 in the first stage). This constraint seemed biologically reasonable. Furthermore, models with this constraint generally had lower deviance than otherwise identical models without, indicating that models without the constraint did not converge properly.

Survival and encounter probabilities were modelled separately for each flyway. For encounter probabilities, we used an additive structure for group, state and potentially time effects in order to preserve parsimony while retaining biological realism. Because convergence was very difficult to achieve, we started from a simple model with all parameters constant over time and gradually increased complexity. There was strong evidence for variation over time in both encounter and survival probabilities (Table S1). We also attempted to introduce time effects for initial and transition probabilities for the two observability states, but these models did not converge (deviance higher than for the best model in Table S1 despite the greater complexity). The GEMACO definition for best model in Table S1 was:

Initial step 1: t (fixed to known proportions)

Initial step 2: f

Transition step 1: f(1:2,3:4).t

Transition step 2: to

Transition step 3: to (constrained identical to initial step 2)

Encounter: firste+nexte.[f(1:2).[f+g+t]+f(3:4).[f+g+t]] (firste fixed to 1)

Survival, encounter and transition probabilities

Estimated survival was considerably higher in the eastern flyway (mean 0.89, range of annual estimates 0.72-1) than in the western flyway (mean 0.74, range 0.51-1). In the high observability state, encounter probabilities were high for neck-collared birds (west: mean 0.86, east: mean 0.99) and reasonable for leg-ringed birds (west: mean 0.39, east: mean 0.14). Birds in the low observability state had much lower encounter probabilities (neck-collared west: mean 0.41, neck-collared east: mean 0.12, leg-ringed west: mean 0.05, leg-ringed east: mean < 0.01). The initial probability of being in the low observability state was 0.68 in the western flyway and 0 in the eastern flyway. Birds had a higher probability of changing from the high observability state to the low observability state (west: 0.11, east: 0.12) than in the opposite direction (west: 0.07, east: 0.01).

Detailed results will be reported elsewhere.

Fig S1 shows the overview of the ringing data used for the current analysis.

References

Pradel, R. (2005) Multievent: an extension of multistate capture-recapture models to uncertain states. *Biometrics,* **61**, 442-447.

Table S1. Initial model selection. Deviance and QAICc were adjusted for overdispersion according to the goodness-of-fit test (*ĉ* = 1.83).

|  |  |  |  |
| --- | --- | --- | --- |
| Model | Quasi-deviance | # parameters | ΔQAICc |
| All constant | 23662.7 | 16 | 429.2 |
| Time-dependent encounter | 23161.7 | 60 | 16.4 |
| Time-dependent encounter and survival | 23058.6 | 103 | 0 |

Fig. S1. Overview of the ringing data used for the analysis, based on neck-banding and leg-ring marking in Britain, Iceland, Denmark and Svalbard, respectively, during 1987-2010.

