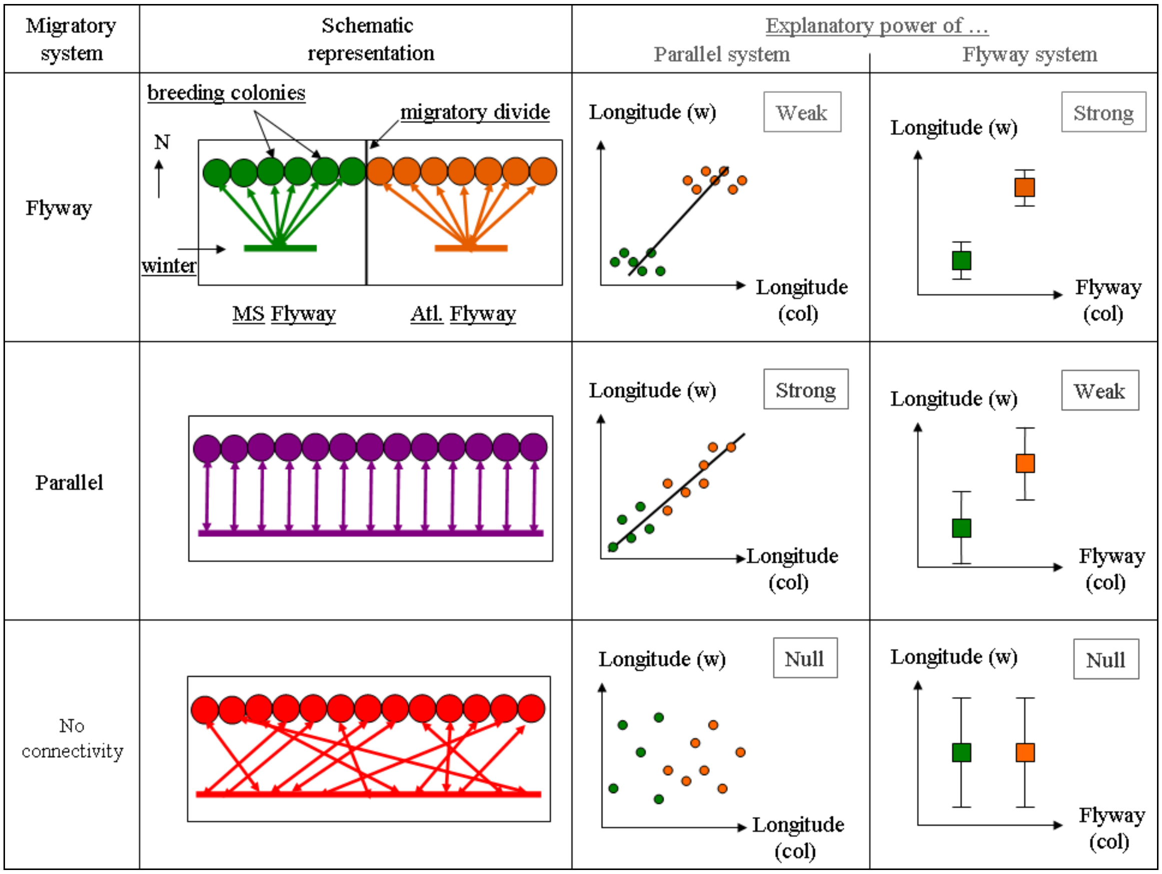
Appendix 2 - Migratory connectivity

1 - Definitions and predictions of the three migration systems investigated

Fig. A2.1



A flyway migration system is a special type of parallel migration system in which cormorants from either side of a migratory divide congregate along two distinct migratory and/or wintering areas. In this case, the Mississippi and Atlantic Flyways, were taken as separate biological corridors rather than contiguous administrative units (e.g. Zimpfer and Conroy (2006)). The Appalachian Mountains which may be an unsuitable intermediate migratory corridor for cormorants are a good candidate for generating such a migratory divide (Brooks, 1952; Fuller et al., 1998). In our analyses the flyway migration system predicts that flyway variables (Flyway (col) = *flyway_col*, and *flyway_stag*) have a better explanatory power on the response variable (longitude (w) = longitude in winter, i.e. *long_11*, *long_12* or *long_1*) than parallel migration variables (Longitude (col) = *long_col*, and *long_stag*).

A parallel migration system in a strict sense (called "parallel migration system" in the paper) is a migration system in which all individuals tend to follow the same migratory orientation, so that no sub-populations with alternative strategies can be identified (also called broad-front migration by Berthold, 2001). Unlike the flyway system, the parallel migration system predicts that parallel migration variables would have a better explanatory power than flyway variables.

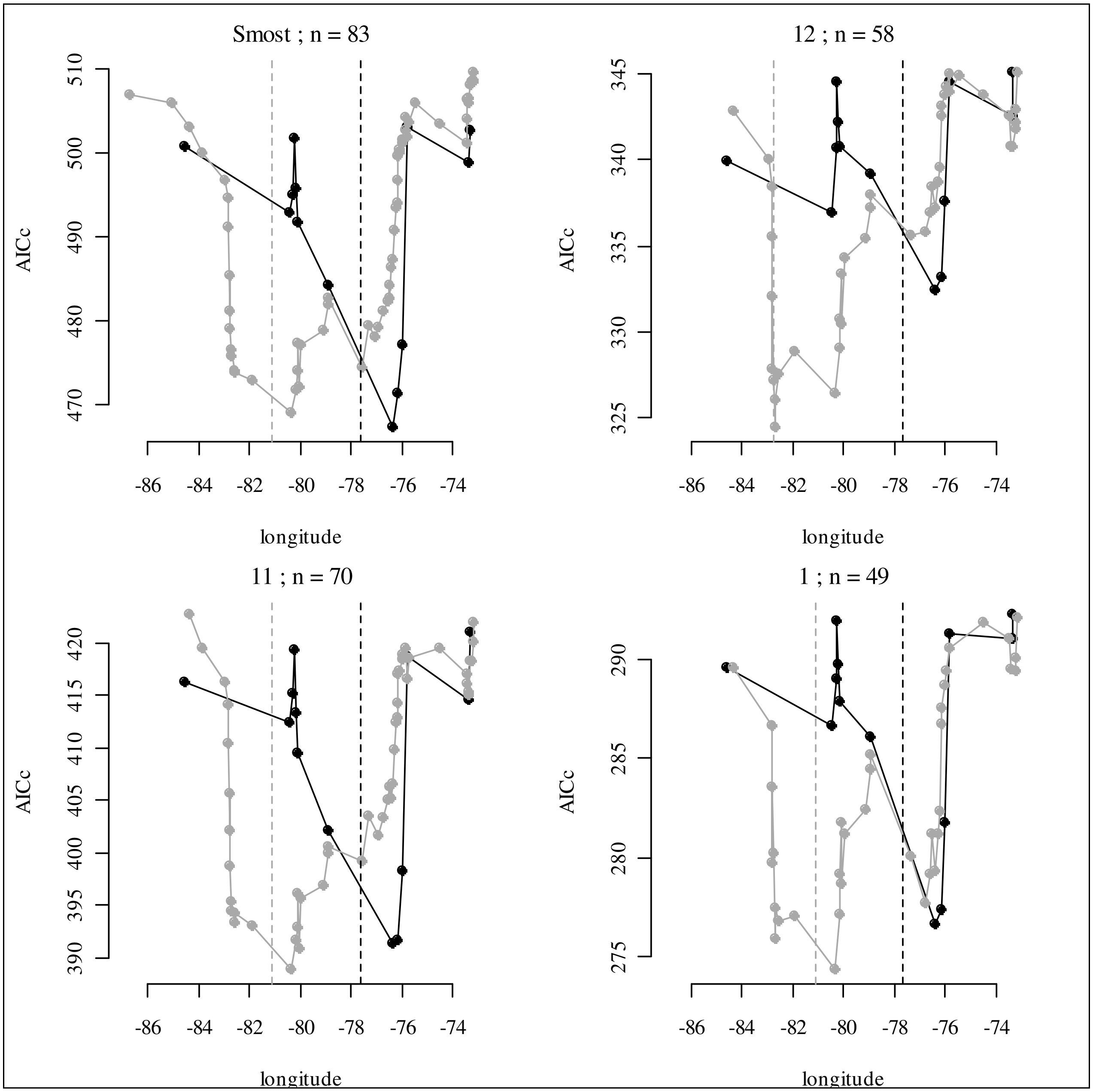
A lack of migratory connectivity, as might been suggested by cormorant banding data (see Dolbeer, 1991), corresponds to random individual decisions. A lack of connectivity predicts that neither the parallel nor the flyway variables would be important to explain the response variable.

2 - Method to calculate the position of the potential migratory divide

The first step of our method is to calculate the position of the potential migratory divide. For each period, we created a binary variable *flyway_col* that grouped the colonies using the Mississippi Flyway (value = 0) and the Atlantic Flyway (1). Initially only the easternmost colony was taken as part of the Atlantic Flyway, the remaining thirteen colonies were treated as part of the Mississippi Flyway. We then calculated the AICc of the linear model where the longitude reached by cormorants during the migratory period (e.g., in December) was explained by the variable *flyway_col*. This yielded the easternmost point (black dot) on Fig. A2.2. We then added the easternmost of the thirteen remaining colonies to the Atlantic Flyway, while the remaining twelve colonies remained as part of the Mississippi Flyway. We re-calculated the AICc of the model where the longitude was explained by the updated variable *flyway_col*. As can be seen, choosing a divide further west improved the explanatory power of *flyway_col*. This procedure was repeated until only the westernmost colony was part of the Mississippi Flyway. The grouping that yielded the lowest AICc was used for subsequent analyses. The position of the divide was calculated as the average between the longitude of the westernmost colony included in the Atlantic Flyway and the longitude of the easternmost colony included in the Mississippi Flyway (dotted black vertical line).

The same procedure was repeated for calculating the migratory divide based on the position of the last Great Lakes staging area (grey dots; the divide is represented by a dotted grey vertical line). In Figure A2.2, we present the results obtained for the southernmost winter position (variable = Smost) and the last available cormorant positions in November (11), December (12) and January (1); n = sample size.

Fig. A2.2



Smost ; n = 83
12 ; n = 58
11 ; n = 70
1 ; n = 49
AICc
longitude
510
500
490
480
470
345
340
335
330
325
420
415
410
405
400
395
390
290
285
280
275
-86
-84
-82
-80
-78
-76
-74

3 - Identification of the relevant migration pattern

Once the position of the putative migratory divide was obtained (Fig. A2.2), the second step of our method consisted of comparing the relative explanatory power of the flyway and migration variables using an information-theoretic approach.

In a "perfect" parallel migration pattern (Fig. A2.1), the flyway variables would still be significant (scenario 1). Conversely, in a "perfect" flyway migration pattern (Fig. A2.1), the parallel migration variables would still be significant (scenario 2). The important point is that the relative explanatory power of these different variables differ allowing us to correctly identify the relevant migration pattern.

In this section, we illustrate our method using data generated with R software. We use a sample of n = 100 birds, each belonging to a different breeding colony. For the sake of simplicity, we will only consider the case of a migratory divide based on the breeding colonies, but the same methods would extend to a divide based on staging areas.

In this example colonies are regularly spaced along the longitudinal axis; the longitude (= long_col) varies from 1 to n. We calculate the position of each bird in winter (longitude = long_w) according to two scenarios:

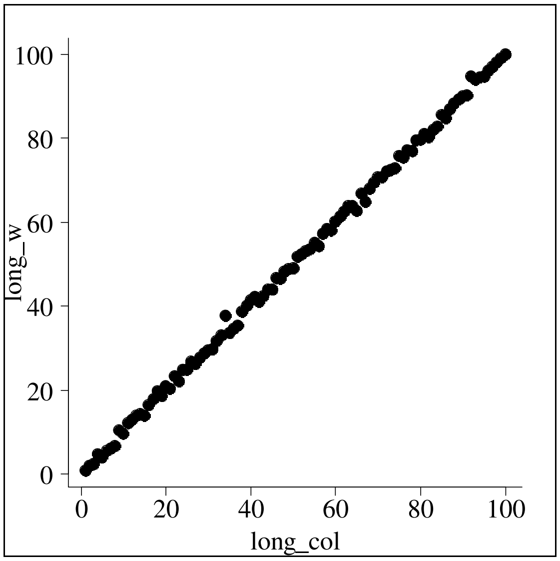
- scenario 1) long_w is calculated as (long_col + ε), where ε is drawn from a standard normal distribution; i.e this corresponds to a perfect parallel system, to which we added some noise (e.g. due to measurement error).
- scenario 2) long_w is calculated as (37.5 + ε) if long_col ≤ 75, (87.5 + ε) otherwise; this corresponds to a perfect flyway migration pattern (+ noise). The migratory divide was selected here at long_col = 75, but the actual position of the divide does not affect the results (not shown).
- We also modified scenario 2 (scenario 3) with the following two differences: i) the noise was increased to make conditions more realistic (ε was drawn from a normal distribution with mean = 0 and SD = 10); ii) we tested our method with unbalanced sample size, where only 1/4 of the birds belonged to the Mississippi flyway, vs. 3/4 for the Atlantic flyway.

For each scenario, the position of the potential migratory divide is inferred using the methodology developed in the paper, and presented above. The inferred (optimal) position is used to ascribe each bird/colony to either the Mississippi flyway (variable flyway_col = "M"), or the Atlantic flyway (flyway_col = "A").

Then we compare for each scenario the explanatory power of two linear models (using AICc values), i.e. i) the parallel migration model, where long_w is explained by long_col; ii) the migratory divide (flyway) model, where long_w is explained by flyway_col.

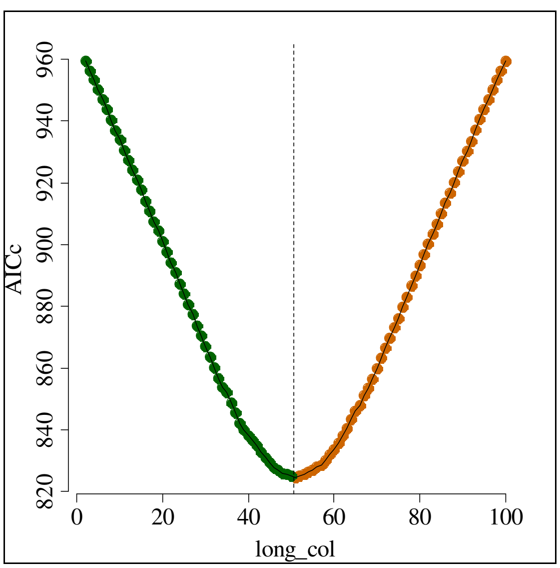
- Scenario 1) "Perfect" parallel system. Raw data are shown in the Fig. A2.3.

Fig. A2.3



Our method identifies the center of the range as the best candidate position for a migratory divide (dotted line in Fig. A2.4 where green is for the colonies ascribed to the Mississippi flyway and orange for the Atlantic flyway). The within-flyway variance is minimized with a central position of the divide.

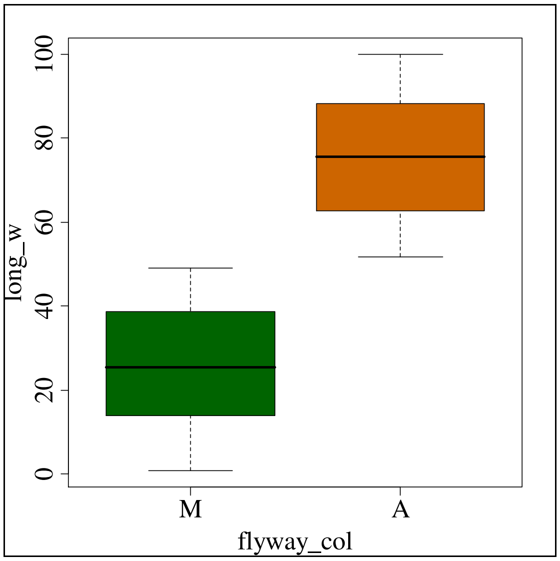
Fig. A2.4



In the parallel migration scenario both the parallel and the flyway models are significant (t = 301, $P < 0.001$, and t = 17.1, $P < 0.001$, respectively). However, the parallel migration model has a much better explanatory power (AICc = 279.24; Fig.

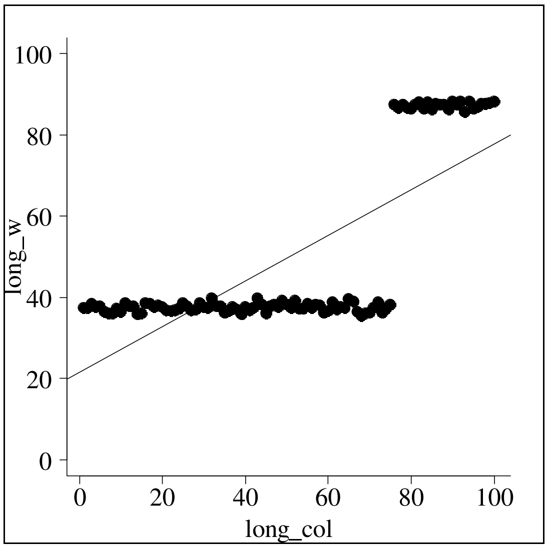
A2.3) than the flyway model (AICc = 824.68; Fig. A2.5). The Akaike weight of the parallel migration model is 1.00, while the Akaike weight of the flyway migration model is ~ 0 (3.62×10^{-119}). Hence for scenario 1, our method correctly identifies a parallel system as the best model.

Fig. A2.5



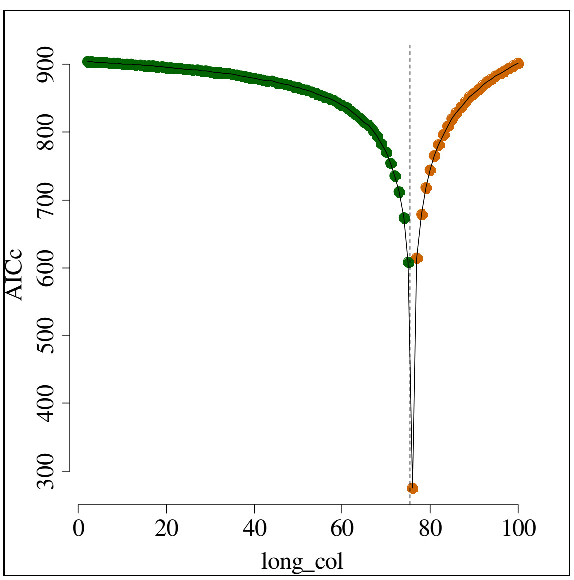
- Scenario 2) "Perfect" flyway system. Raw data are shown in the Fig. A2.6. The simple linear regression corresponding to the parallel migration model is also represented.

Fig. A2.6



As expected, our method correctly identifies the migratory divide in the center of the eastern part of the range (i.e. for long_col = 75; Fig. A2.7)

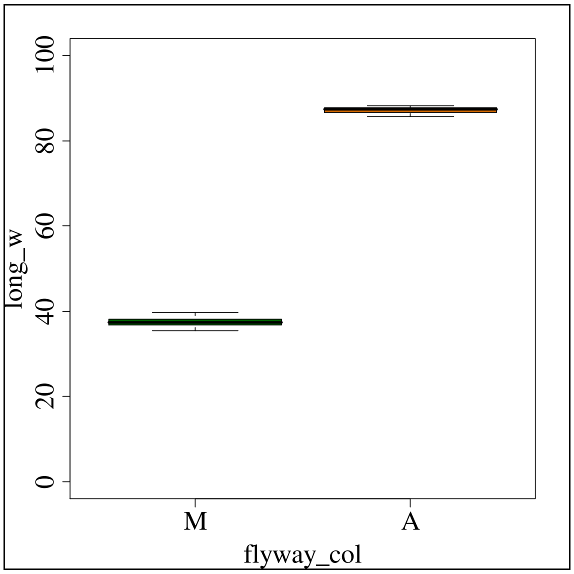
Fig. A2.7



As in the previous example both parallel and flyway models are significant (t = 11.28, $P < 0.001$, and t = 230, $P < 0.001$, respectively). However, the parallel migration model (Fig. A2.6) has a much lower explanatory power than the flyway model (Fig. A2.8;

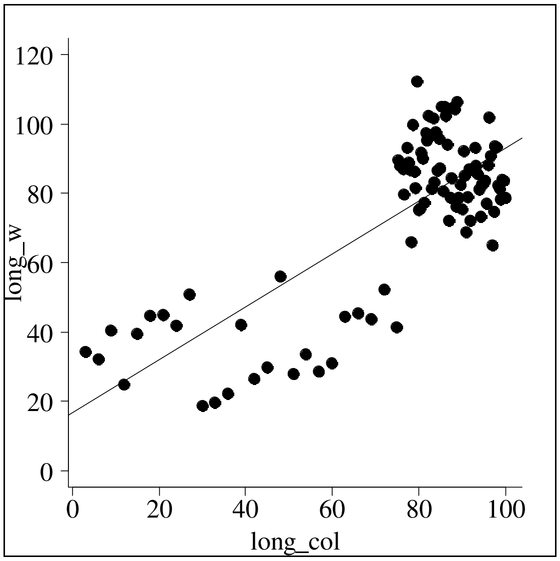
AICc = 821.31, Akaike weight ~ 0, and AICc = 275.03 and Akaike weight = 1.00, respectively). The flyway model is correctly identified as the best model.

Fig. A2.8



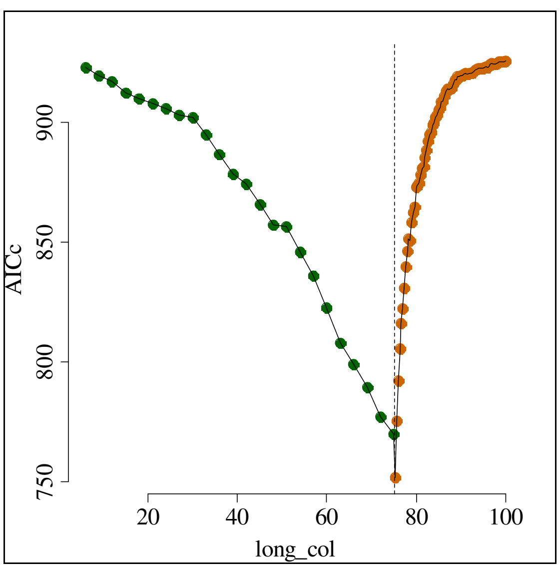
- Scenario 3) "Perfect" flyway system with strong noise and unequal sample size. Figure A2.9 shows the raw data and the simple linear regression corresponding to the parallel migration model.

Fig. A2.9



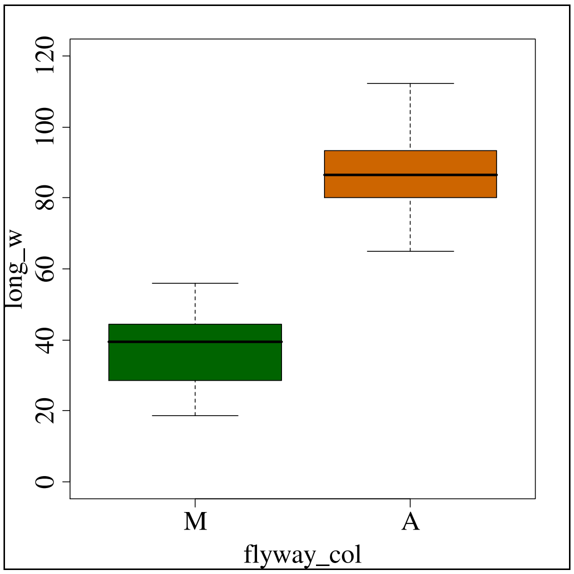
Our method again correctly identified the position of the actual migratory divide (Fig. A2.10).

Fig. A2.10



Again for scenario 3, the information theoretic approach also correctly identified the flyway model as the best model (see Fig. A2.11): t = 12.31, $P < 0.001$, AICc = 832.07, Akaike weight ~ 0 for the parallel model, vs. t = 21.4, $P < 0.001$, AICc = 751.73, Akaike weight = 1.00 for the flyway model.

Fig. A2.11



REFERENCES

Dolbeer RA, 1991. Migration patterns of double-crested cormorants east of the Rocky Mountains. Journal of Field Ornithology 62(1):83-93.