**Electronic Supplementary Material**


# Within and between species competition in a seabird community: statistical exploration and modeling of time-series data

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**Online Resource 1.** Trophic niche segregation among the three seabird species breeding at Kharlov Island.



Mixed colony at Kharlov Island (Common guillemots *Uria aalge* breeding over kittiwakes *Rissa tridactyla*). Photo taken by Y Krasnov.

At Kharlov Island, kittiwakes and guillemots are essentially piscivores targeting capelin and herring. Diet composition was collected on Kharlov Island between 1982-1999 for kittiwakes (lacking data for 1984 and 1985), between 1984-1999 for common guillemots (lacking data for 1985), and between 1992-1999 (lacking data for 1996 and 1997) for Brünnich's guillemots. Using these time series, we have calculated the diet overlap *O* using Schoener's index (Schoener 1968, Mysterud 2000):

$$O_{jk} = 1 - 0.5 * \Sigma | P_{ij} - P_{ik} |$$

where $O_{jk}$ is the overlap between the bird species j and k; $p_{ij}$ is the proportion of species j feeding on prey species/group i; and $p_{ik}$ is the proportion of species k feeding on prey species/group i. Overlap in diet between species j and k is complete when $O_{jk} = 1$ and is absent when $O_{jk} = 0$ (Mysterud 2000).

For Common G. *vs* Kittiwake; $O_{jk} = 0.511 \pm 0.197$ (period 1986-1999)

For Kittiwake *vs* Brünnich's G.; $O_{jk} = 0.449 \pm 0.156$ (period 1992-1999)

For Common G. *vs* Brünnich G.; $O_{jk} = 0.678 \pm 0.141$ (period 1992-1999)

If we consider that when overlap $O > 2*SD$ of the diet overlap is significant, all the diets are significantly overlapping during the studied periods.

Mysterud A (2000) Diet overlap among ruminants in Fennoscandia. Oecologia 124:130-137

Schoener TW (1968) Anolis lizards of Bimini - Resource partitioning in a complex fauna. Ecology 49:704-726

**Online Resource 2.** Times series used as explanatory variables in the analysis.
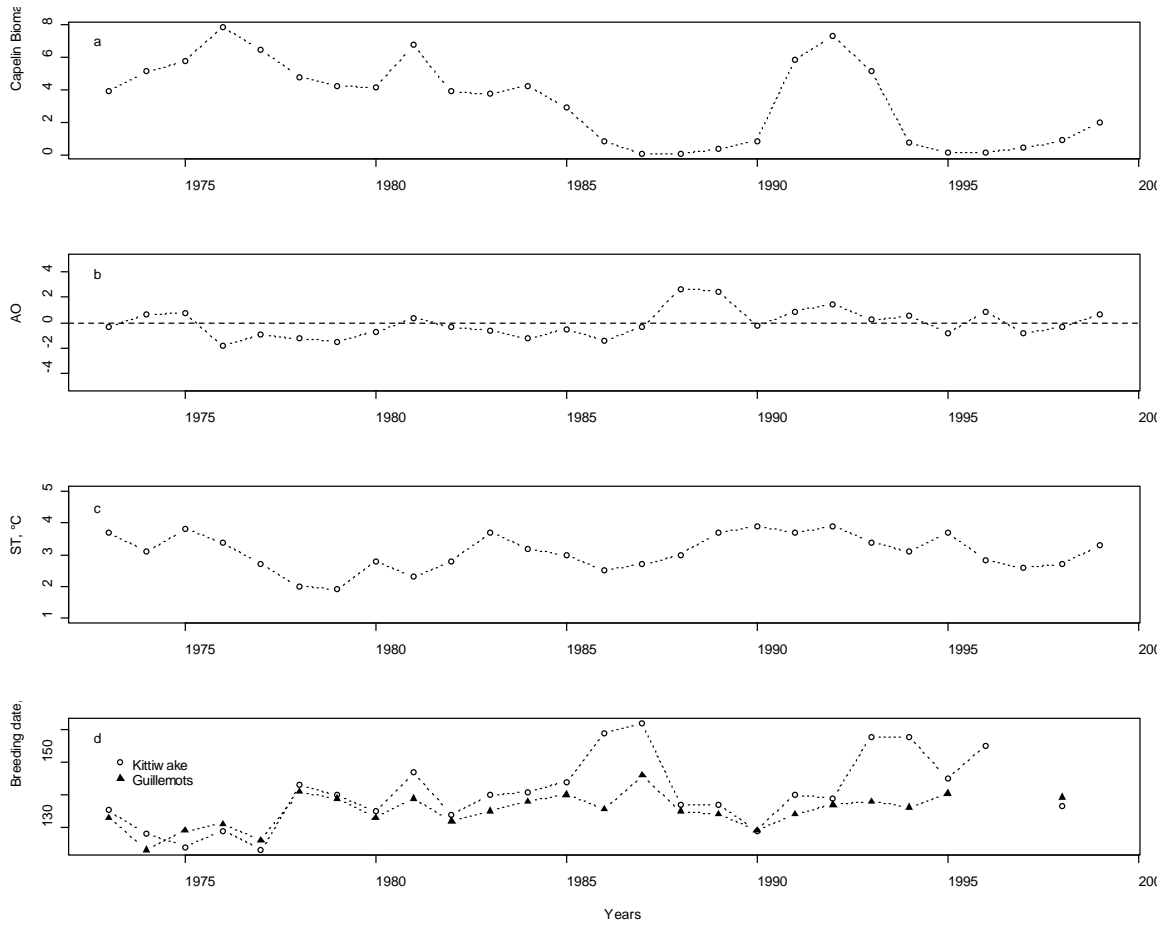


 (**a**) CAPbm is the capelin stock biomass (in million tonnes). Capelin data are coming

from acoustic stock size estimates in September in the Barents Sea (ICES, 2006). (**b**) AO

$_t$ is the Arctic Oscillation index (average of AO from January year $_t$ to March year $_{t+1}$).

(**c**) ST $_t$ is the monthly average sea temperature in °C measured in May $_t$ on the Russian

Kola meridian transect (33° 30' E, 70° 30' N to 72° 30' N). (**d**) Average breeding dates

for Kittiwake and Guillemots (Common and Brünnich's merged) in Julian date.

| | Kittiwake | Common | Brünnich | CAPbm | AO | ST | KittiDate | GuillDate | |
|---|---|---|---|---|---|---|---|---|---|
| **Kittiwake** | | 0.03(24) | 0.08(24) | -0.24(25) | 0.05(25) | 0.33(25) | 0.28(23) | 0.18(22) | |
| **Common** | 0.895 | | **0.65**(24) | **0.47**(24) | **-0.61**(24) | -0.31(24) | -0.19(22) | -0.12(21) | (d.f.) |
| **Brünnich** | 0.692 | <0.001 | | **0.60**(24) | -0.29(24) | -0.11(24) | -0.40(22) | -0.27(21) | |
| **CAPbm** | 0.234 | 0.015 | 0.001 | | -0.18(25) | 0.06(25) | **-0.44**(23) | -0.34(22) | r-values |
| **AO** | 0.801 | 0.001 | 0.151 | 0.371 | | **0.40**(25) | -0.02(23) | -0.14(22) | |
| **ST** | 0.095 | 0.127 | 0.597 | 0.755 | 0.040 | | -0.28(23) | -0.33(22) | |
| **KittiDate** | 0.182 | 0.382 | 0.053 | 0.028 | 0.933 | 0.184 | | **0.75**(22) | |
| **GuillDate** | 0.407 | 0.600 | 0.218 | 0.109 | 0.517 | 0.119 | <0.001 | | |
| | | | | | **p-values** | | | | |

Values for Kittiwake, Common, and Brünnich are $\log_e$ transformed.

Kittiwake (n=27), Common (n=26), Brünnich (n=26), CAPbm (n=27), AO (n=27), ST (n=27), KittiDate (n=25), and GuillDate (n=24). In bold are presented the variables significantly correlated.

Note that the breeding dates for Kittiwake can be modelled (GAM, $R^2$=0.52) using herring abundance (slope: $8.75 \pm 2.21$), the capelin abundance (slope: $-1.82 \pm 0.62$), and the Sea temperature (slope: $-8.05 \pm 2.81$). Likewise, the guillemots the breeding dates can be modelled (GAM, $R^2$=0.38) using the capelin abundance (slope: $-0.72 \pm 0.35$), the herring abundance (edf = 1.53, increase) and the Sea temperature (edf = 1.70, decrease).

**Online Resource 4.** Result from fitting a GAM to the variation in population of three species of seabirds (black-legged kittiwake, common guillemot and Brünnich's guillemot) breeding at Kharlov Island in the Barents Sea. Models are linear when the estimated degree of freedom (edf) by GAM is equal to 1.

| $y_{t+1}$ | $x_t$ | n | edf | GCV | $R^2$ | p-value |
|---|---|---|---|---|---|---|
| | CAPbm | 26 | 1.88 | 0.028 | 0.30 | 0.007 |
| | Common | 25 | 1 | 0.033 | -0.03 | 0.614 |
| | Brünnich | 25 | 1.21 | 0.033 | -0.02 | 0.839 |
| Kittiwake | Kittiwake | 26 | 1.61 | 0.034 | 0.13 | 0.190 |
| | AO | 26 | 1.78 | 0.035 | 0.12 | 0.169 |
| | ST | 26 | 1 | 0.039 | -0.03 | 0.544 |
| | GuillDate | 24 | 1 | 0.039 | -0.02 | 0.442 |
| | Common | 24 | 1.53 | 0.201 | 0.53 | 0.000 |
| | CAPbm | 25 | 1.91 | 0.219 | 0.49 | 0.000 |
| | AO | 25 | 1.66 | 0.336 | 0.21 | 0.022 |
| Common | Brünnich | 24 | 1 | 0.366 | 0.13 | 0.049 |
| | KittiDate | 24 | 1 | 0.373 | 0.14 | 0.040 |
| | Kittiwake | 25 | 1 | 0.382 | 0.08 | 0.093 |
| | ST | 25 | 1 | 0.420 | -0.01 | 0.399 |
| | Brünnich | 24 | 1 | 0.093 | 0.37 | 0.001 |
| | Common | 24 | 1 | 0.111 | 0.25 | 0.008 |
| | KittiDate | 24 | 1 | 0.112 | 0.33 | 0.002 |
| Brünnich | CAPbm | 25 | 1.18 | 0.113 | 0.30 | 0.007 |
| | AO | 25 | 1.32 | 0.154 | 0.05 | 0.204 |
| | Kittiwake | 25 | 1 | 0.159 | 0.01 | 0.293 |
| | ST | 25 | 1 | 0.167 | -0.04 | 0.967 |

Values for Kittiwake, Common guillemot, and Brünnich's guillemot are log transformed.

NAO is the winter North Atlantic Oscillation index (December year $_{t-1}$ to March year $_t$).

KittiDate and GuillDate are the dates of first breeding for kittiwakes and guillemots respectively (in Julian day). AO is the Arctic Oscillation index (January year $_t$ to March year $_t$). ST is the temperature average for May $_t$ measured at Kola. CAPbm is the Capelin stock biomass measured by acoustic survey in the Barents Sea in September year $_{t-1}$.

GCV: Generalized Cross Validation Criterion.

**Online Resource 5.** Community matrix

The community matrix was computed using the ecological parameters found in Table 3.

$$
\begin{bmatrix}
-6.313 & 0 & 0 \\
3.182 & 1.776 & 0 \\
0 & 0 & -2.905
\end{bmatrix}
$$

The eigenvalues of the matrix are -6.313, -2.905, and 1.776. In order to have a stable equilibrium, all eigenvalues need to be negative. The largest eigenvalue of the community matrix being positive the community is not stable (Gillman 2009) .

Gillman, M. (2009) An introduction to mathematical models in ecology and evolution: Time and Space. - Wiley-Blackwell.

**Online Resource 6.** Reflection on the effect of observation error on estimates of intraspecific competition (density dependence) and interspecific competition: results of simulation

Sampling error has been shown to affect the estimation of the direct density dependence effect (Carroll et al. 1995) and can also affect the estimation of the effect of the interspecific term. In their supplementary materials, Hjermann et al. (2010) show that measurement errors can indeed lead to an underestimation of the slope and thereby an overestimation of the density dependence effect. However, they also show that the underestimation is negligible if the variance in the population is strong.

We simulated the effect of observation errors on estimates of density dependence or competition in the following way: Let the abundance at two stages be $X_t$ and $X_{t+1}$ and of competitor species $Y_t$. For density dependence (intra-specific competition), we simulated that $X_{t+1}$ depends on $X_t$ by the following formula: $\log(X_{t+1}) = b*\log(X_t) + \varepsilon$ (where $\varepsilon$ represents random variation in survival; $\varepsilon$ is normally distributed around zero). For interspecific competition, we let $X_{t+1}$ depend on $Y_t$ by the following formula: $\log(X_{t+1}) = b1*\log(X_t) + b2*\log(Y_t) + \varepsilon$. In both cases, we simulated a measurement error in $X_t$ and in $Y_t$, so we observe $X_t' = X_t + \gamma$ ($\gamma$ is measurement error) or $Y_t' = Y_t + \gamma$ respectively, and estimated b using linear regression between $X'_{t+1}$ and $X_t'$ and b2 using linear regression between $X'_{t+1}$ and $X_t'$ and $Y_t'$, simulation 1 and simulation 2 respectively. We let the standard deviation of $\log(X_t)$ and of $\log(Y_t)$, the real value of b, and the degree of measurement (observation) error $\gamma$ vary. The figures show the estimated values of b and

b2 (ordinate axis) compared to the real values (abscissa axis); unbiased estimates should lie on the black line (indicating ordinate=abcissa).

Results for simulation 1 are presented on Panel *a* and the ones for simulation 2 on Panel *b*. We show only results with a large observation error ($\gamma$), given as the coefficient of variation (CV; standard deviation in $\gamma$ as percentage of $X_t$ (or $Y_t$); i.e., a coefficient of variation of 20% means that 95% of the observed $X_t$ values are within +/- 40% of the real $X_t$ values). An observation error of 20% is quite large following the methods used for estimating the seabird population at Kharlov Island (basically a complete count; see Methods). The use of a smaller observation error would have given less deviation of the slope to the real slope (see Hjermann et al. 2010). It is clear that as long as the variation of $X_t$ or $Y_t$ is modest (low system noise), b is strongly underestimated in simulation 1 when there is observation error (and density dependence, given as 1-b, is overestimated). However, if the variation in $X_t$ is large (standard deviation of $\log(X_t) \geq 1$), bias is reduced even for a strong observation error. For the competition term, the underestimation of b2 is less strong and affects the estimation significantly only for a strong competitive effect. We show that the slope of the effect of interspecific competition is not underestimated in the range we are considering (-0.2 to -0.3, see panel *b*).

The slope of the density dependence effect is always underestimated, especially when the system noise is small. For example, the slope of b=0.83 observed for common guillemots corresponds to a real slope b ranging between 1.03-1.10 (thus for a positive density dependence effect) for a system noise ranging from 0.1-2. In a similar way, the slope of b = 0.36 observed for kittiwakes corresponds to a real slope ranging from 0.45 to

0.82 a system noise ranging from 0.1-2. While greatly overestimated in its strength (for

an unrealistic system noise <0.2), the direction of the density dependence effect is

retained.

For info, in our system, kittiwake has a CV= 0.18, Common guillemot a CV = 0.50 (0.19

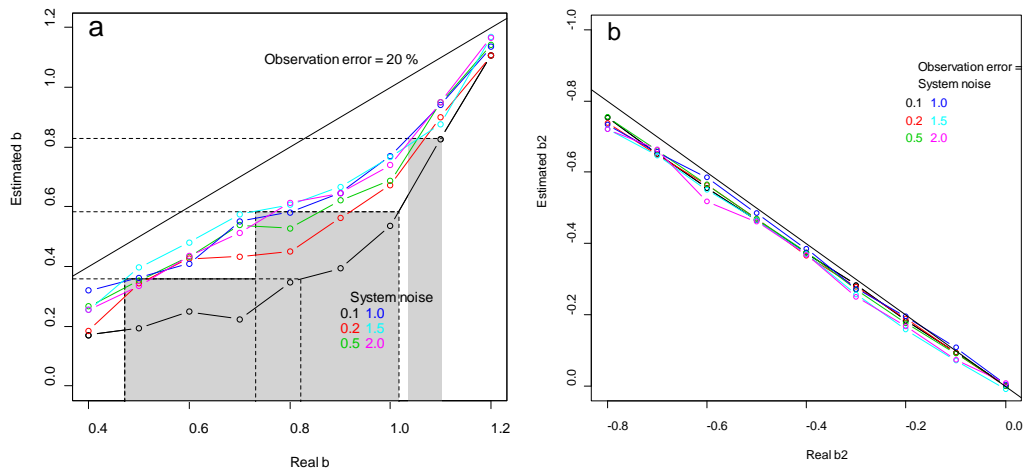and 0.49 if cutting the time series in two at 1986), and Brünnich's guillemot a CV= 0.39.



**Figure S2**. Simulation of the observation error on estimates of intraspecific competition

and interspecific competition effect estimate. (**a**). Difference between the real slope b

(intraspecific effect) and the estimated slope when $\log(X_{t+1}) = b*\log(X_t) + \varepsilon$ (where $\varepsilon$

represents random variation in survival; $\varepsilon$ is normally distributed around zero). Horizontal

lines indicate the slopes estimated for the density dependence for the three species

considered. The grey shaded area corresponds to the real value of $X_t$ depending on the

system noise. (**b**) Difference between the real slope b (interspecific effect) and the

estimated slope when $\log(X_{t+1}) = b1*\log(X_t) + b2*\log(Y_t) + \varepsilon$.

Carroll RJ, Ruppert D, Stefanski LA (1995) Measurement error in non-linear models.

Chapman and Hall, London,UK.

Hjermann DØ, Bogstad B, Dingsør GE, Gjøsæter H, Ottersen G, Eikeset AM, Stenseth NC (2010) Trophic interactions affecting a key ecosystem component: a multi-stage analysis of the recruitment of the Barents Sea capelin. Can J Fish Aquat Sci 67:1363-1375.