The following supplement accompanies the article

Interactions among density, climate, and food web effects determine long-term life cycle dynamics of a key copepod

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SUPPLEMENT. Additional information on sampling design, data handling, variables included in the analyses, and model diagnostics

Table S1. Number of samplings per year in winter (Win), spring (Sum), summer (Sum), and autumn (Aut) (i.e. in each yearly quarter)

Year	Win	Spr	Sum	Aut	Year	Win	Spr	Sum	Aut
1960	2	18	24	12	1985	4	8	8	3
1961	24	10	20	11	1986	2	7	12	2
1962	15	11	21	10	1987	3	7	9	8
1963	8	11	10	13	1988	2	14	11	4
1964	12	12	12	10	1989	6	11	6	6
1965	5	11	11	5	1990	1	11	10	6
1966	0	17	11	10	1991	2	11	8	0
1967	10	9	8	3	1992	1	0	0	0
1968	7	0	0	0	1993	0	11	0	4
1969	2	2	0	3	1994	4	7	3	4
1970	4	8	4	3	1995	2	7	4	6
1971	4	2	4	1	1996	4	8	14	5
1972	7	9	4	6	1997	7	10	11	7
1973	3	6	0	0	1998	0	7	11	7
1974	9	0	0	0	1999	6	8	4	3
1975	5	10	7	6	2000	3	10	12	6
1976	0	14	7	7	2001	6	11	6	7
1977	5	12	8	3	2002	6	12	12	7
1978	3	5	4	6	2003	10	11	12	8
1979	0	0	4	13	2004	8	10	12	10
1980	6	5	9	2	2005	0	26	12	16
1981	4	6	7	4	2006	13	10	17	17
1982	4	10	12	9	2007	13	16	15	13
1983	2	1	6	3	2008	11	8	12	9
1984	4	3	8	4					

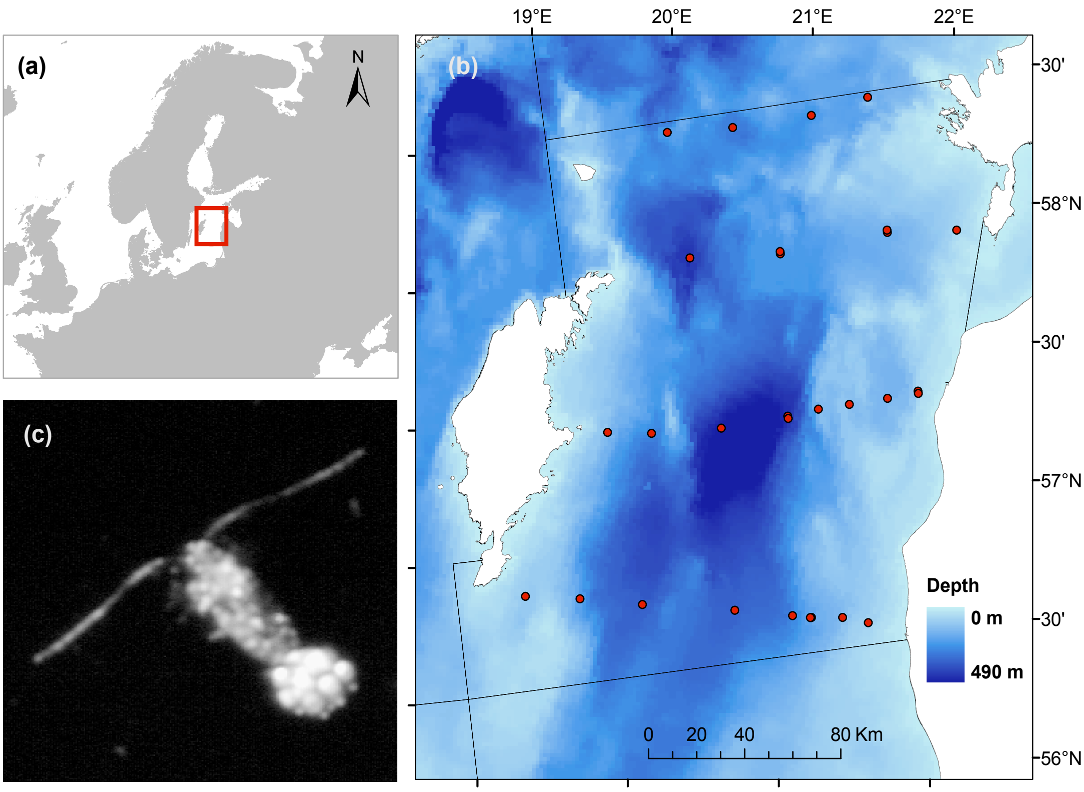
Table S2. List of variables used in the generalized additive modeling (GAM) and threshold generalized additive modeling (TGAM) analyses, with their definition and data source. The seasonal stage abundances were included in the models either as response or explanatory internal variables. The BSI, salinity, temperature, and PI variables represent the external covariates. BIOR = Institute of Food Safety, Animal Health and Environment in Riga, Latvia; ICES = International Council for the Exploration of the Sea; SD 28 = ICES subdivision 28, representing the Eastern Gotland Basin

Variable	**Definition**	**Data source/type**
N_{spr}, N_{sum}, N_{aut}	ln(X+1)-transformed nauplii abundances (n m^{-3}) in spring (Apr-Jun), summer (Jul-Aug), and autumn (Oct-Dec) in SD 28	BIOR zooplankton survey
$C13_{spr}$, $C13_{sum}$, $C13_{aut}$, $C13_{aut(y-1)}$	ln(X+1)-transformed abundances of copepodite stages 1-3 (n m^{-3}) in spring (Apr-Jun), summer (Jul-Aug), and autumn (Oct-Dec; same) in year *y* (not indicated) or the previous year (y – 1) within SD 28	BIOR zooplankton survey
$C45_{win}$, $C45_{spr}$, $C45_{sum}$, $C45_{aut}$, $C45_{aut(y-1)}$	ln(X+1)-transformed abundances of copepodite stages 4-5 (n m^{-3}) in winter (Jan-Mar), spring (Apr-Jun), summer (Jul-Aug), and autumn (Oct-Dec) in year *y* (not indicated) or the previous year (y – 1) within SD 28	BIOR zooplankton survey
F_{win}, F_{spr}, F_{sum}, F_{aut}	ln(X+1)-transformed female abundances (n m^{-3}) in winter (Jan-Mar), spring (Apr-Jun), summer (Jul-Aug), and autumn (Oct-Dec) in year y (not indicated) or the previous year (y – 1) within SD 28	BIOR zooplankton survey
BSI	Baltic Sea Index; mean value of winter months Dec-March. BSI calculations exist either based on sea level pressure values obtained from the NCEP (US National Centers for Environmental Prediction) or the SMHI (Swedish Meteorological and Hydrological Institute) data bank. Both time series differ slightly in their temporal coverage, causing deviations in the overall mean and consequently in the calculated monthly anomalies in overlapping years. In this study, the full time series (1970-2008) of the SMHI based BSI was used, since it is considered to better reflect the local situation (A. Lehmann, IFM-GEOMAR, pers. comm.) For the missing years 1960 – 1969, the index is based on NCEP data. A comparison of the nauplii spring model including this combined BSI time series vs. an alternative approach (i.e. a time series in which the NCEP BSI index is regressed on the SMHI BSI index and this model then used to predict BSI index values for the earliest years based on NCEP BSI) showed no or only slight differences in the partial effects, explained variance, and residual pattern.	GEOMAR Helmholtz Centre for Ocean Research Kiel
S_{win}, S_{spr}, S_{sum}, S_{aut}	mean salinity in the halocline region (70-100 m depth); averaged across the main sampling months in the winter (Feb-Mar), spring (Apr-May), summer (Jul-Aug), and autumn (Oct-Nov) season within SD 28	bottle data from ICES database
T^1_{spr}	mean temperature in 0 – 40 m depth; averaged across the main sampling months in the spring (Apr-May) season within SD 28	bottle data from ICES database
T^2_{spr}, T^2_{sum}, T^2_{aut}	mean temperature in 20 – 60 m depth; averaged across the main sampling months in the spring (Apr-May), summer (Jul-Aug), and autumn (Oct-Nov) season within SD 28	bottle data from ICES database
T^3_{win}, T^3_{spr}, T^3_{sum}, T^3_{aut}	mean temperature in 40 – 80 m depth; averaged across the main sampling months in the winter (Feb-Mar), spring (Apr-May), summer (Jul-Aug), and autumn (Oct-Nov) season within SD 28	bottle data from ICES database
PI	predation index based on Eastern Baltic cod spawning stock biomass (SSB); to mimic the predation pressure by planktivorous sprat we used inversely scaled values between 0 and 1. For this, we calculated the ratio between the difference of the annual SSB to the time series maximum and the overall min./max. range	Estimates from virtual population analysis (VPA)

Table S3. Overview of covariates included in the initial GAM and TGAM. We tested for density effects by including stage abundances from the same or the previous season; these were chosen based on knowledge of their annual life cycle. Hydro-climatological variables were included as abiotic and predation as biotic external variable. **Bold** letters indicate variables that remained in the final model and had a significant effect. *Excluded from analyses due to collinearity (variance inflation factor [VIF] > 3). For abbreviations, see Table S2 in this supplement

Season	Modelled stage	Model	Internal variable	External variable
winter	$C45_{win}$	GAM	$C13_{aut(y-1)}$, $\mathbf{C45_{aut(y-1)}}$	BSI, S_{win}, T^{3}_{win}, **PI**
		TGAM	$C13_{aut(y-1)}$, $\mathbf{C45_{aut(y-1)}}$	BSI, S_{win}, T^{3}_{win}, **PI**
spring	N_{spr}	GAM	$C45_{win}$, F_{win}, $\mathbf{F_{spr}}$	**BSI**, S_{spr}, T^{1}_{spr}
	$C13_{spr}$	GAM	F_{win}, $\mathbf{F_{spr}}$, $\mathbf{N_{spr}}$	BSI*, S_{spr}, $\mathbf{T^{2}_{spr}}$
	F_{spr}	GAM	$\mathbf{C45_{win}}$, F_{win}	BSI, $\mathbf{S_{spr}}$, T^{3}_{spr}, PI
		TGAM	$\mathbf{C45_{win}}$	**BSI**, $\mathbf{S_{spr}}$, T^{3}_{spr}, **PI**
summer	$C13_{sum}$	GAM	$\mathbf{N_{spr}}$, $C13_{spr}$, F_{spr}, N_{sum}, $\mathbf{F_{sum}}$	BSI, S_{sum}, $\mathbf{T^{2}_{sum}}$
	$C45_{sum}$	GAM	N_{spr}, $C13_{spr}$, F_{spr}, $\mathbf{C13_{sum}}$, F_{sum}	BSI*, S_{sum}, T^{3}_{sum}, **PI**
		TGAM	$C13_{spr}$, $\mathbf{C13_{sum}}$	BSI, $\mathbf{S_{sum}}$, T^{3}_{sum}, **PI**
autumn	$C13_{aut}$	GAM	N_{sum}, $\mathbf{C13_{sum}}$, F_{sum}, $\mathbf{F_{aut}}$, $\mathbf{N_{aut}}$	**BSI**, S_{aut}, T^{2}_{aut}
	$C45_{aut}$	GAM	$C13_{sum}$, $C45_{sum}$, F_{sum}, $\mathbf{C13_{aut}}$	BSI, $\mathbf{S_{aut}}$, T^{3}_{aut}, **PI**
		TGAM	$\mathbf{C45_{sum}}$, $\mathbf{C13_{aut}}$	BSI, $\mathbf{S_{aut}}$, T^{3}_{aut}, **PI**

Fig. S1. Baltic Sea and *Pseudocalanus acuspes*. (a) Map showing the location (red rectangular outline) of the Baltic Sea within Europe. (b) Main zooplankton stations (red dots; sampled >20 times during the studied time period) in the Gotland basin (ICES subdivision 28, Central Baltic Sea). (c) Photograph of a *P. acuspes* female carrying an egg sac; taken *in situ* with a video plankton recorder (photo source: Klas O. Möller)



Figs. S2 to S9. Diagnostic plots of the final generalized additive modeling (GAM) or threshold generalized additive modeling (TGAM) formulations. Model fitness is indicated by a comparison of (a) the observed vs. the predicted time series and (d) the fitted vs. each response value. Temporal dependence was evaluated by (b) the auto-correlation function plot (ACF), in which the significance level is indicated by the dashed lines, and (c) by the residual behavior over time. Homogeneity (fitted vs. predicted values) and normality (Q-Q-Plot) are indicated by (e) and (f) respectively. The threshold estimation (generalized cross-validation minimization [GCV]) and the threshold value (blue line) of the predation index defining the low (black) and high (red) regime are given for each TGAM in (g) in Figs. S7 & S9

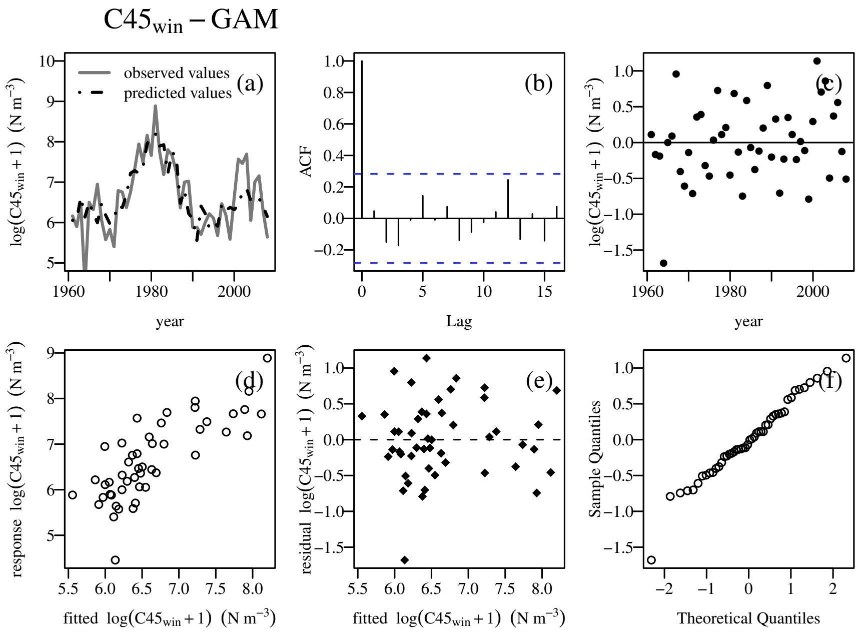


Fig. S2

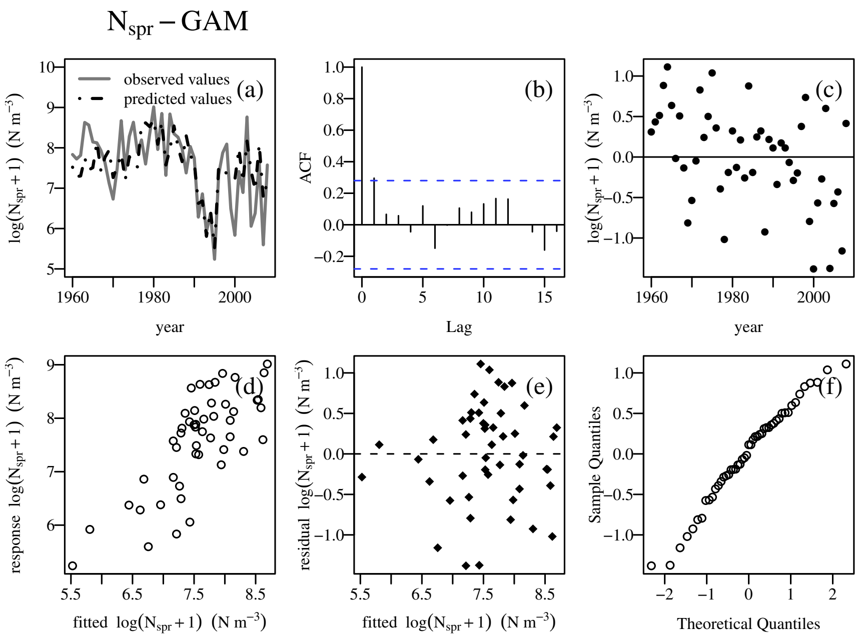


Fig. S3

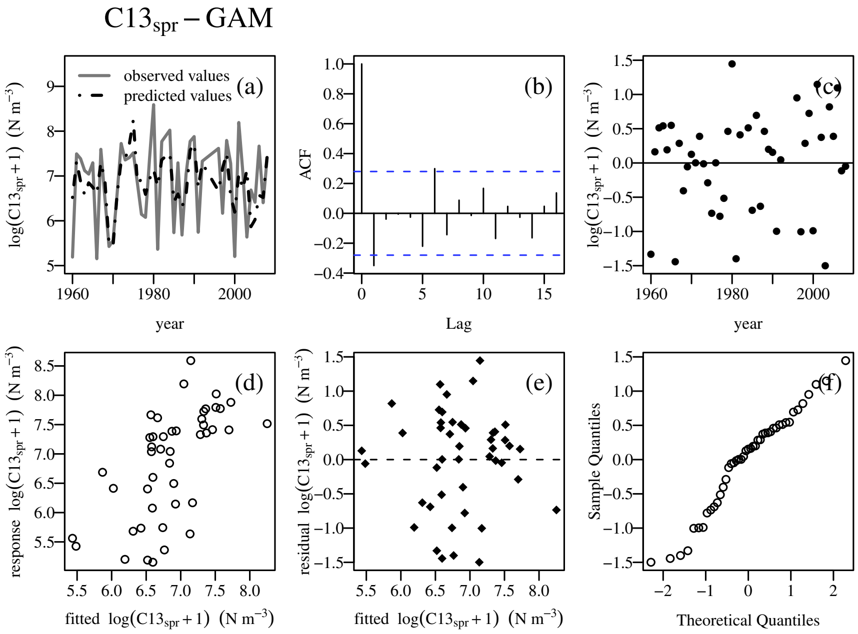

C13spr – GAM
observed values
predicted values
(a)
(b)
(c)
(d)
(e)
(f)
log(C13spr + 1) (N m−3)
year
ACF
Lag
response log(C13spr + 1) (N m−3)
fitted log(C13spr + 1) (N m−3)
residual log(C13spr + 1) (N m−3)
Sample Quantiles
Theoretical Quantiles

Fig. S4

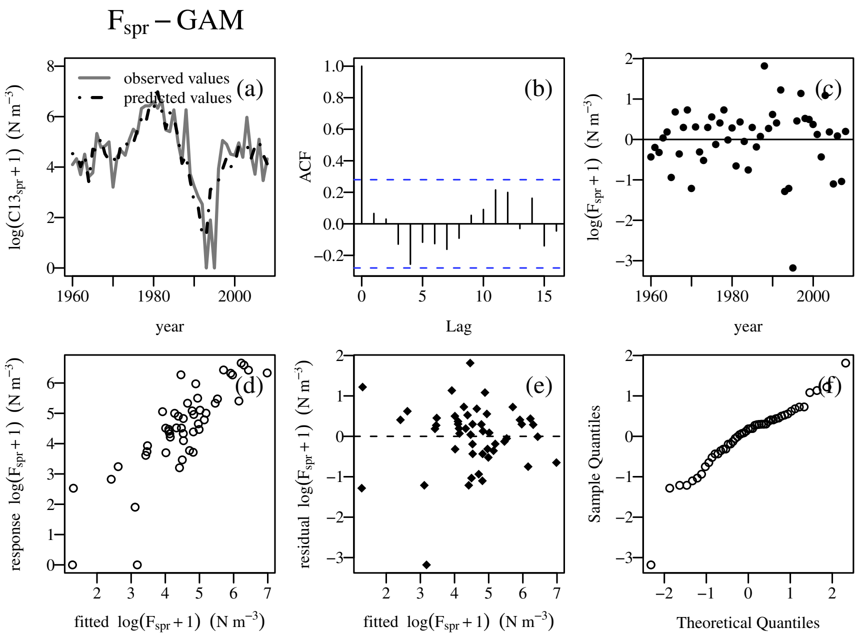

Fspr – GAM
observed values
predicted values
(a)
(b)
(c)
(d)
(e)
(f)
log(C13spr + 1) (N m−3)
year
ACF
Lag
log(Fspr + 1) (N m−3)
response log(Fspr + 1) (N m−3)
fitted log(Fspr + 1) (N m−3)
residual log(Fspr + 1) (N m−3)
Sample Quantiles
Theoretical Quantiles

Fig. S5

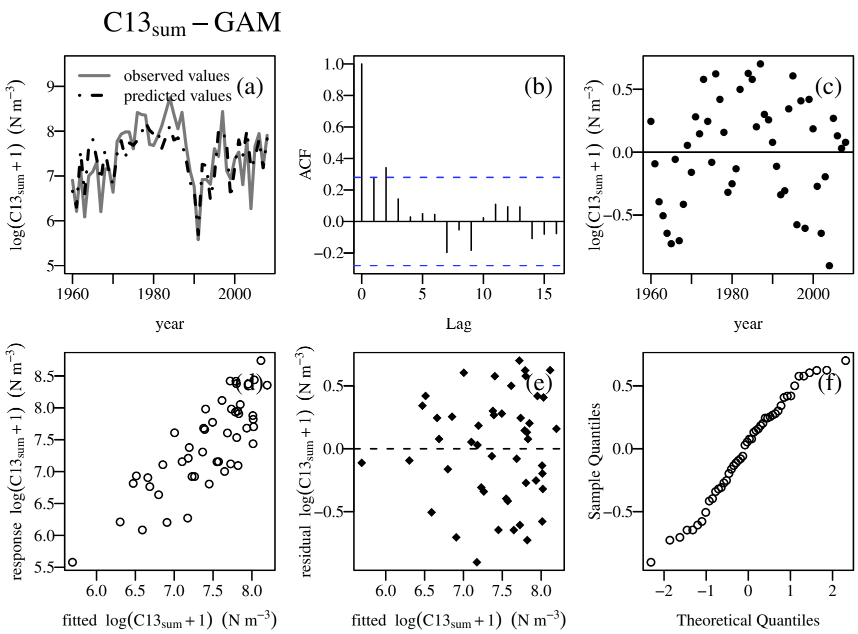

C13sum – GAM
observed values
predicted values
(a)
(b)
(c)
(d)
(e)
(f)
year
Lag
ACF
Theoretical Quantiles
Sample Quantiles
fitted log(C13sum + 1) (N m−3)
response log(C13sum + 1) (N m−3)
residual log(C13sum + 1) (N m−3)

Fig. S6

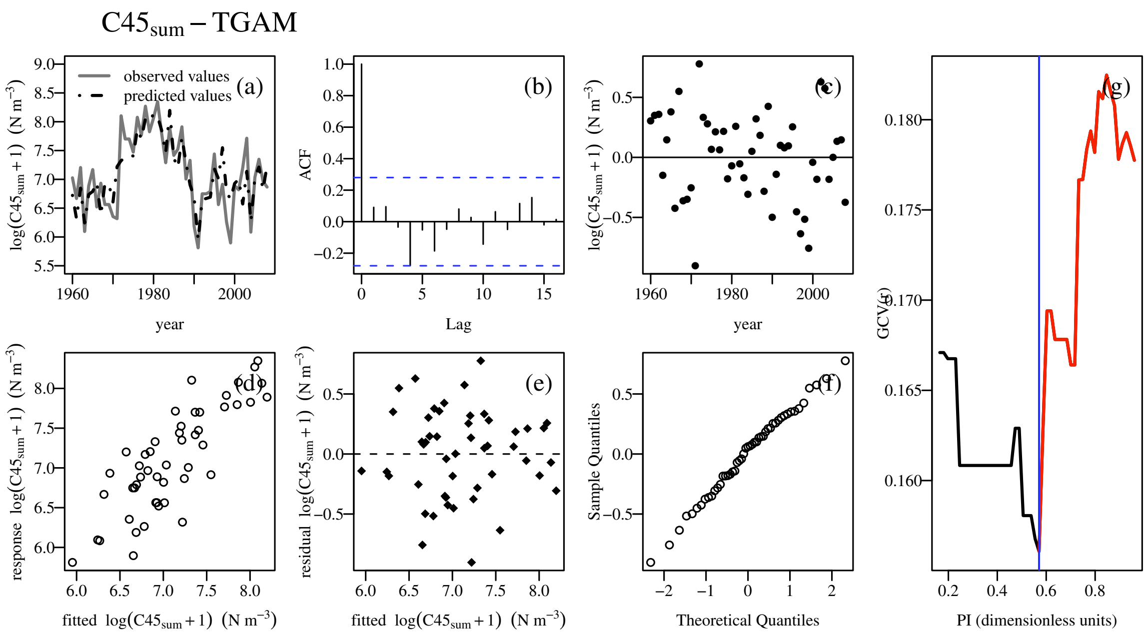
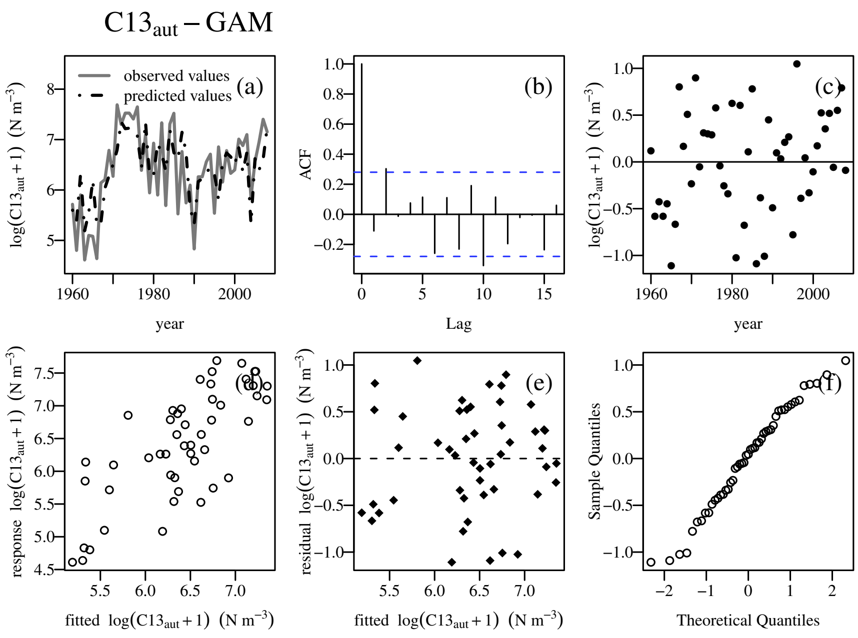
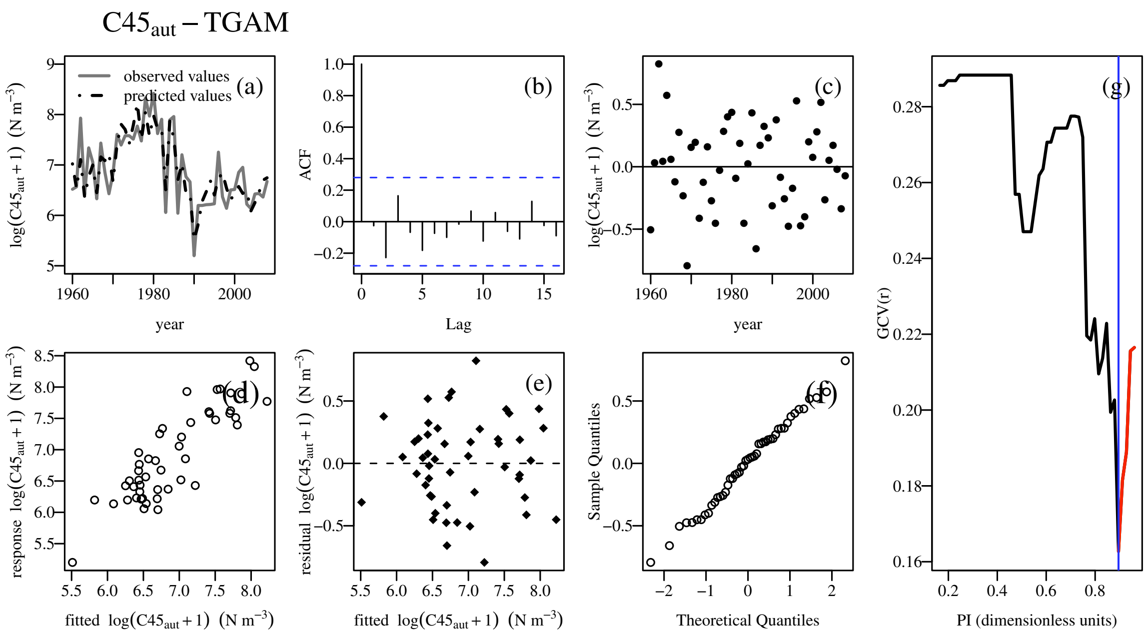

C45sum – TGAM
observed values
predicted values
(a)
(b)
(c)
(d)
(e)
(f)
(g)
year
Lag
ACF
Theoretical Quantiles
Sample Quantiles
fitted log(C45sum + 1) (N m−3)
response log(C45sum + 1) (N m−3)
residual log(C45sum + 1) (N m−3)
GCV(r)
PI (dimensionless units)

Fig. S7



C13aut – GAM
observed values
predicted values
(a)
(b)
(c)
(d)
(e)
(f)
year
Lag
ACF
Theoretical Quantiles
Sample Quantiles

Fig. S8



C45aut – TGAM
observed values
predicted values
(a)
(b)
(c)
(d)
(e)
(f)
(g)
year
Lag
ACF
Theoretical Quantiles
Sample Quantiles
GCV(r)
PI (dimensionless units)

Fig. S9

Data handling and outliers

Data handling

Prior to the analysis, data were visually examined for outliers, and if they were too influential in the model (Cook's distance value > 1 or residual values < –2 or > +2), they were removed (for details, see section 'Outliers' below). As exclusion criteria, we used Cook's distance method (Quinn & Keough 2002) and removed data points with Cook's distance values > 1 as well as data points that had standardized residual values, i.e. residuals divided by their estimated standard errors, < –2 or > +2 (Zuur et al. 2007). We also removed data points that caused smoothing functions to be significant that would not be otherwise and that were ecologically not interpretable. Explanatory variables were tested for collinearity using Pearson's correlation coefficient, and a variance inflation factor (VIF) of 3 was used as an exclusion criterion (Zuur et al. 2007). Missing values in predictor values were estimated by calculating a 4 yr mean, based on the 2 previous and the 2 following years.

Outliers

$C13_{spr}$ model: We removed here the year 1983, since this year represented an outlier in the *y*-space ($C13_{spr}$ abundance of 0 n m^{-3}). Including the year would have led to the same final model in which Cook's distance indicated no strong influence (Cook's distance value = 0.36). Nevertheless, the standardized residual value was at < –6 beyond the acceptable range and caused the residuals in general to be not normally distributed and have a bad model fit.

We further removed the 3 years 1993 to 1995. Although not too influential for the final model in general (Cook's distances < 0.2), these data points caused a weak negative effect of female density, while density effects were in all other final models positive. Excluding these years made this effect insignificant, while the remaining partial effects and the explained variance were kept almost the same. Including the three years and removing the F_{spr} term in the model instead would have reduced the model fit considerably. Beside a low density of females, nauplii were also less abundant during these years. Although $C13_{spr}$ stages showed a positive dependence with nauplii, their abundances were fairly high and did not reflect the modeled value. For simplicity reasons, we decided to remove these exceptional years even though we lost some information.

$C13_{sum}$ model: Year 1983 was removed in this model since this year represented an outlier in the x_1-space ($C13_{spr}$ abundance of 0 n m^{-3}). Although Cook's distance (0.06) as well as the standardized residual value (<0.5) did not indicate a too-strong influence, the outlier caused the otherwise not-significant covariate $C13_{spr}$ to have a significantly negative effect, for which it was difficult to find an ecological interpretation.

LITERATURE CITED

Quinn GP, Keough MJ (2002) Experimental design and data analysis for biologists. Cambridge University Press, Cambridge

Zuur AF, Ieno EN, Smith GM (2007) Analysing ecological data. Springer, New York, NY