Supporting Information

Seasonality in coastal macrobenthic biomass and its implications for estimating secondary production using empirical models

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Limnology & Oceanography

Seasonal pattern in biomass of macrobenthic invertebrates at the community level

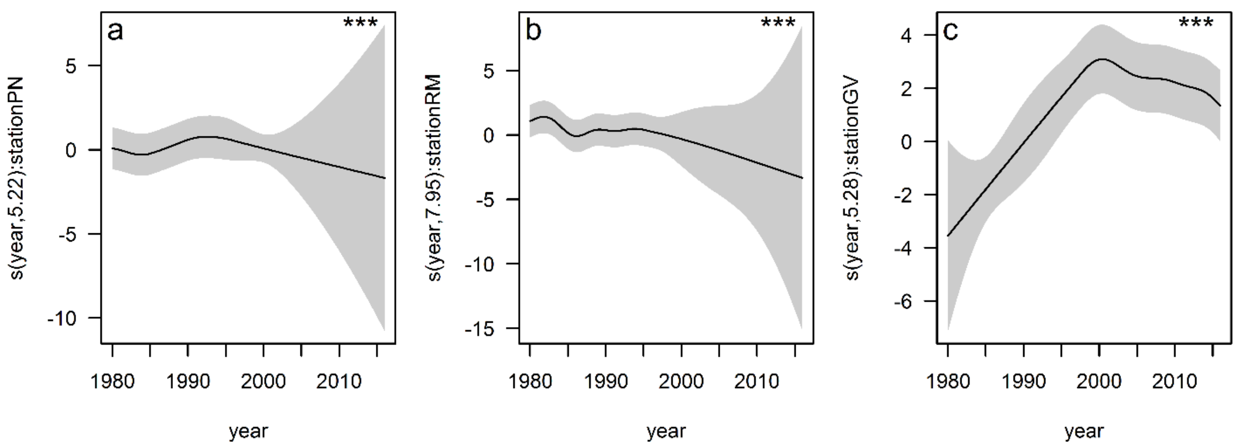

Fig. S1. Long-term trends in biomass on a log-scale at the community level at 'Pierre Noire' (PN) **(a)**, 'Rivière de Morlaix' (RM) **(b)** and 'Gravelines' (GV) **(c)**. Long-term trends were modeled as a smooth function of the years using a generalized additive model (model 1). Significance of the smoothers is indicated by ***$p < 0.001$. Shaded areas represent approximate 95% confidence intervals. The wider part of the 95% confidence intervals is related to the absence of data, e.g. from 1997-2016 at PN **(a)** and at RM **(b)**.

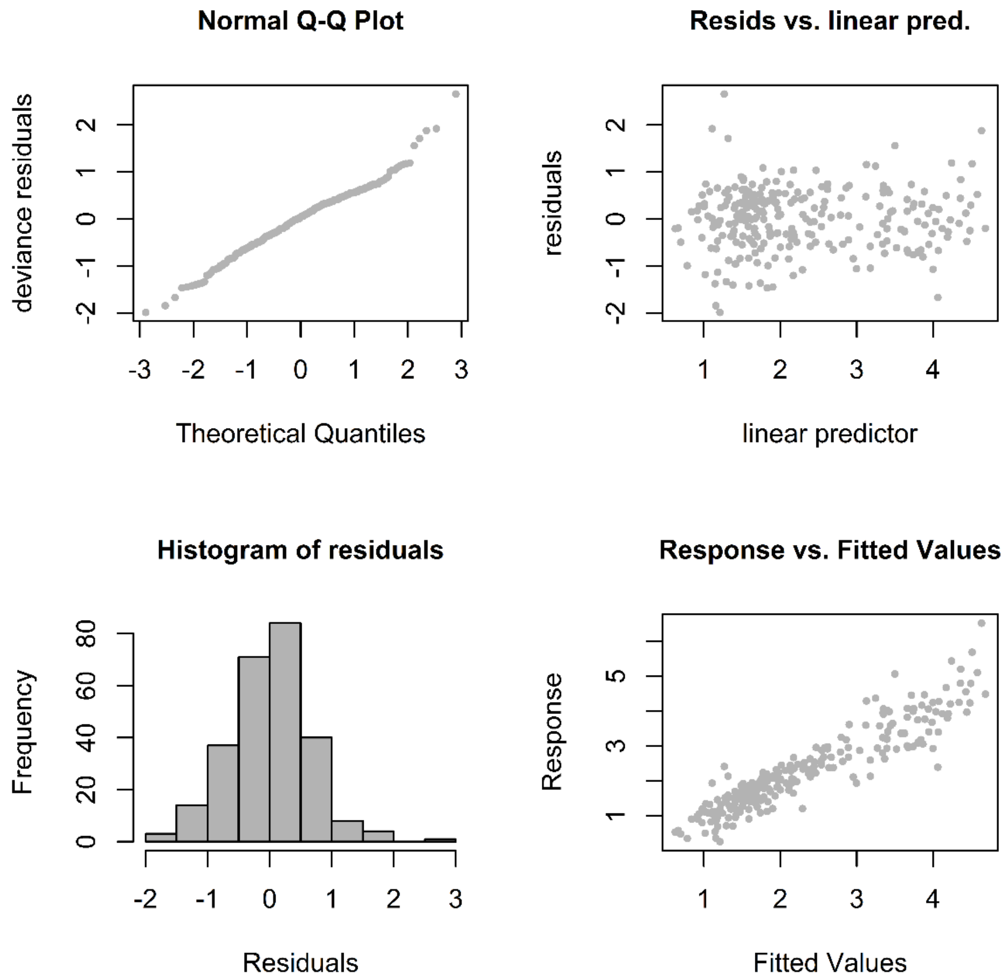

Fig. S2. Model validation graphs for the generalized additive model at the community level (model 1).

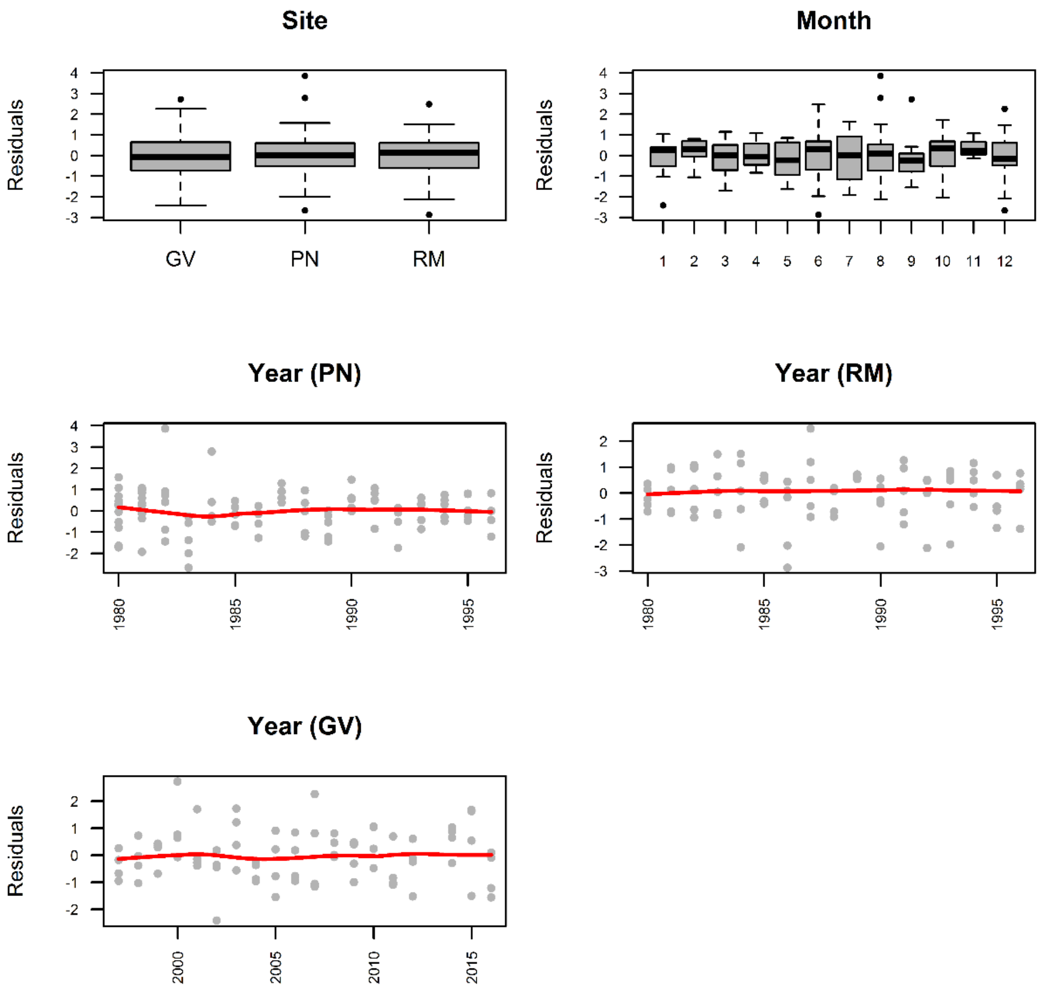

Fig. S3. Residuals vs. the factors ‘site’, ‘month’, and ‘year’ at ‘Pierre Noire’ (PN), ‘Rivière de Morlaix’ (RM) and ‘Gravelines’ (GV) for the generalized additive model at the community level (model 1). A LOESS smoother with a span of 0.5 was fitted and added to plots of residuals vs. year to aid in visual interpretation (red line).

Investigating pairwise differences in seasonal pattern among sites at the community level. To test whether the seasonal pattern differed significantly among sites, we fitted a generalized additive model similar to model 1 but that no longer estimated a different seasonal smoother f_2 for each site. Instead, the first smoother f_2 modeled the seasonal pattern of one site arbitrarily defined as the reference, and the other two seasonal smoothers modeled the non-linear difference between the reference smoother and the smoother of the other two sites. All other components of model 1 remained unchanged. Here, *p*-values of the seasonal smoothers f_2 correspond to the null hypothesis of no difference in seasonal pattern between the reference site and the other two. To calculate pairwise differences between the three sites, we applied the new model twice, after changing the site arbitrarily defined as the reference. The model was built using the package *mgcv* (version 1.8-17: Wood 2006, 2011) of R statistical software (version 3.3.3: R Core Team 2017). Note that the factors must be ordered to perform this test in R. A short description and application of this method can be found in Wieling et al. (2016) and in the reference manual of the *mgcv* package (version 1.8-24, 18 June 2018). The results are presented below (Table S1 and S2)

References

R Core Team. 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available at https://www.R-project.org/.

Wieling, M., F. Tomaschek, D. Arnold, M. Tiede, F. Bröker, S. Thiele, S. N. Wood, and R. H. Baayen. 2016. Investigating dialectal differences using articulography. J. Phon. **59**: 122–143.

Wood, S. N. 2006. Generalized additive models: an introduction with R, Chapman and Hall/CRC.

Wood, S. N. 2011. Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. J. R. Stat. Soc. Ser. B Stat. Methodol. **73**: 3–36.

Table S1. Outputs of the generalized additive model (GAM) fitted to test whether seasonal pattern in biomass differed significantly at the community level between ‘Gravelines’ (GV) and the other two sites (‘Pierre Noire’ (PN), ‘Rivière de Morlaix’ (RM)). The GAM was fitted to the time series on a log-scale (n = 262, adjusted R^2 = 0.794). Significance of the smoothers is indicated by: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$. *DF* = degrees of freedom. The factor ‘site’ {PN, RM, GV} was ordered, with GV used as the reference. The smoother $s(\text{Month})_{GV}$ modeled the seasonal pattern at GV; $s(\text{Month})_{GV-PN}$ modeled the non-linear difference between the seasonal pattern at GV and at PN, and $s(\text{Month})_{GV-RM}$ the non-linear difference between the seasonal pattern at GV and at RM. The smoother $s(\text{Month})_{GV-RM}$ is not significant (p>0.05), indicating that seasonal patterns at GV and RM are not considered two identifiably different patterns under this model. Conversely, the smoother $s(\text{Month})_{GV-PN}$ is significant, indicating that the seasonal pattern at GV differs significantly from the pattern at PN. Model residuals were similar to those of model 1 (Fig. S2, S3).

Explanatory variable	Estimated *DF*	*F*	*p*-value	
s (Year) $_{PN}$	5.223	29.801	< 2.0. 10^{-16}	***
s (Year) $_{RM}$	7.931	19.215	< 2.0. 10^{-16}	***
s (Year) $_{GV}$	5.225	9.335	4.99. 10^{-8}	***
s (Month) $_{GV}$	2.908	3.394	4.33. 10^{-7}	***
s (Month) $_{GV - PN}$	3.170	2.004	2.79. 10^{-4}	***
s (Month) $_{GV - RM}$	2.85. 10^{-7}	0.000	0.506	

Table S2. Outputs of the generalized additive model (GAM) fitted to test whether seasonal pattern in biomass differed significantly at the community level between 'Pierre Noire' (PN) and the other two sites ('Rivière de Morlaix' (RM) and 'Gravelines' (GV)). The GAM was fitted to the time series on a log-scale (n = 262, adjusted R^2 = 0.797). Significance of the smoothers is indicated by: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$. *DF* = degrees of freedom. The factor 'site' {PN, RM, GV} was ordered, with PN used as the reference. The smoother s(Month)$_{PN}$ modeled the seasonal pattern at PN; s(Month)$_{PN-RM}$ modeled the non-linear difference between the seasonal pattern at PN and at RM, and s(Month)$_{PN-GV}$ the non-linear difference between the seasonal pattern at PN and at GV. The smoothers s(Month)$_{PN-RM}$ and s(Month)$_{PN-GV}$ are both significant, indicating that the seasonal pattern at PN differs significantly from the other two. Model residuals were similar to those of model 1 (Fig. S2, S3).

Explanatory variable	Estimated *DF*	*F*	*p*-value	
s (Year) $_{PN}$	5.208	29.479	$< 2.0.\ 10^{-16}$	***
s (Year) $_{RM}$	7.930	19.196	$< 2.0.\ 10^{-16}$	***
s (Year) $_{GV}$	5.194	9.237	$5.83.\ 10^{-8}$	***
s (Month) $_{PN}$	3.866	8.792	$7.62.\ 10^{-16}$	***
s (Month) $_{PN-RM}$	2.625	1.925	0.0080	**
s (Month) $_{PN-GV}$	1.587	0.556	0.0426	*

Table S3. Monthly estimates of the seasonal smooth component on a log-scale for the three study sites: 'Pierre Noire' (PN), 'Rivière de Morlaix' (RM) and 'Gravelines' (GV) (generalized additive model, community level (model 1)). Standard errors are indicated in parentheses.

Month	PN		RM		GV	
1	0.11	(0.05)	-0.09	(0.06)	-0.18	(0.13)
2	-0.19	(0.07)	-0.16	(0.06)	-0.32	(0.12)
3	-0.38	(0.06)	-0.17	(0.06)	-0.36	(0.12)
4	-0.37	(0.08)	-0.15	(0.07)	-0.26	(0.12)
5	-0.22	(0.09)	-0.10	(0.07)	-0.04	(0.13)
6	-0.07	(0.06)	-0.02	(0.06)	0.18	(0.12)
7	0.00	(0.07)	0.09	(0.06)	0.30	(0.13)
8	0.10	(0.06)	0.18	(0.06)	0.30	(0.13)
9	0.25	(0.06)	0.21	(0.06)	0.24	(0.12)
10	0.37	(0.06)	0.15	(0.06)	0.13	(0.12)
11	0.34	(0.07)	0.03	(0.06)	-0.02	(0.14)
12	0.11	(0.05)	-0.09	(0.06)	-0.18	(0.13)

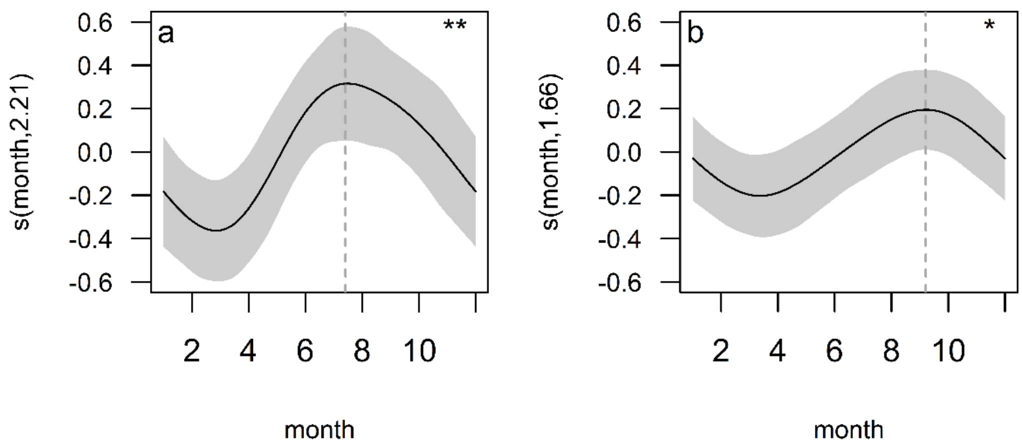

Fig. S4. Seasonal pattern in biomass on a log-scale at the community level at ‘Gravelines’ (GV), modelled **(a)** with and **(b)** without *Lanice conchilega*. Seasonal patterns were modelled as a smooth function of the months using a generalized additive model. Significance of the smoothers is indicated by *$p < 0.05$ and **$p < 0.01$. Estimated degrees of freedom for each smoother are given in parentheses on the y-axis label. Shaded areas represent approximate 95% confidence intervals. Vertical dashed lines help visualize the annual maximum. This illustrates that *L. conchilega* strongly drives the seasonal pattern observed at the community level at GV, in both amplitude and timing.

Seasonal pattern in biomass of macrobenthic invertebrates at the population level

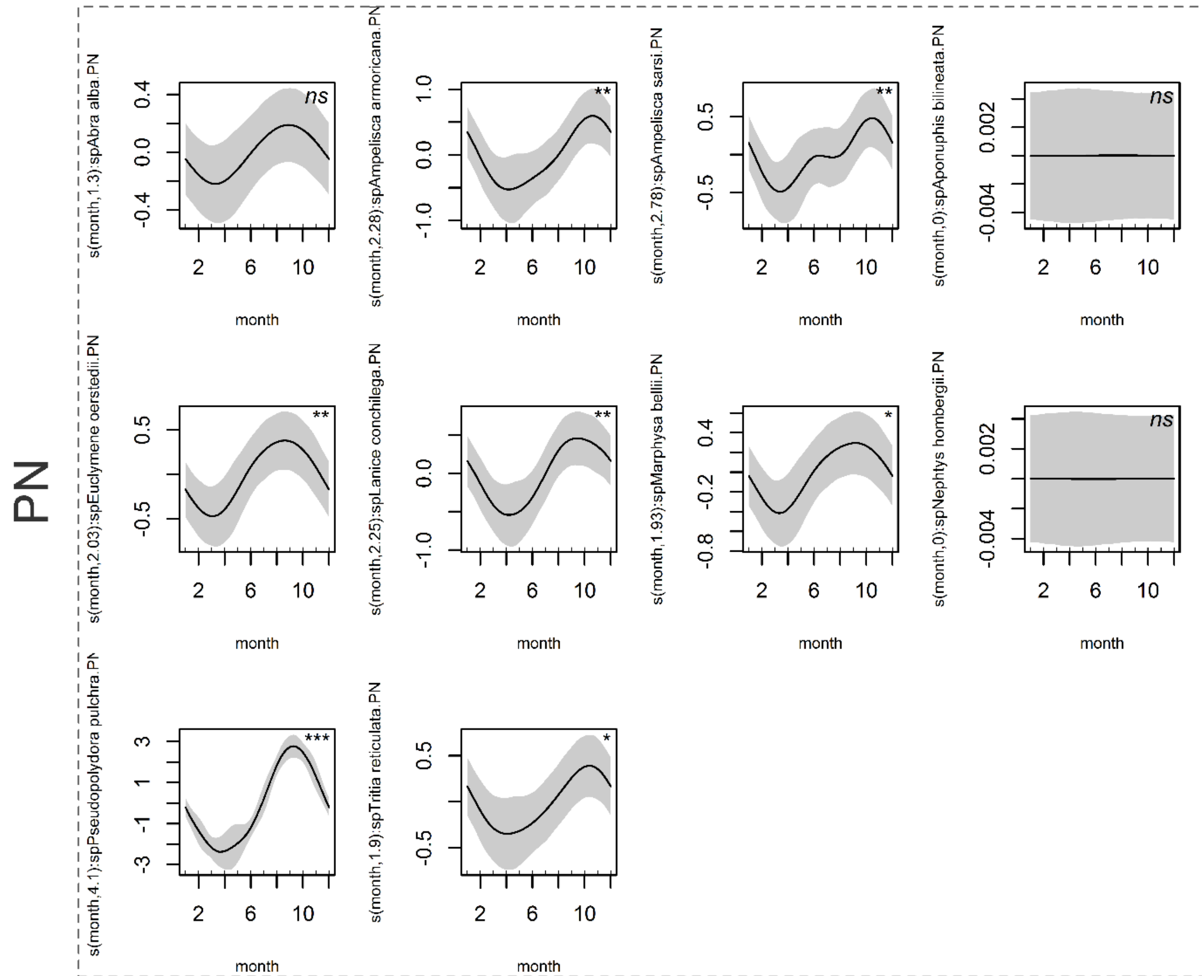

Fig. S5. Seasonal pattern in biomass on a log-scale at the population level for the 10 dominant species (by biomass) at 'Pierre Noire' (PN), 'Rivière de Morlaix' (RM) and 'Gravelines' (GV). Seasonal patterns were modelled as a smooth function of the months using a generalized additive model. Significance of the smoothers is indicated by: *ns*, non-significant; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$. Estimated degrees of freedom for each smoother are given in parentheses on the y-axis label. Shaded areas represent approximate 95% confidence intervals.

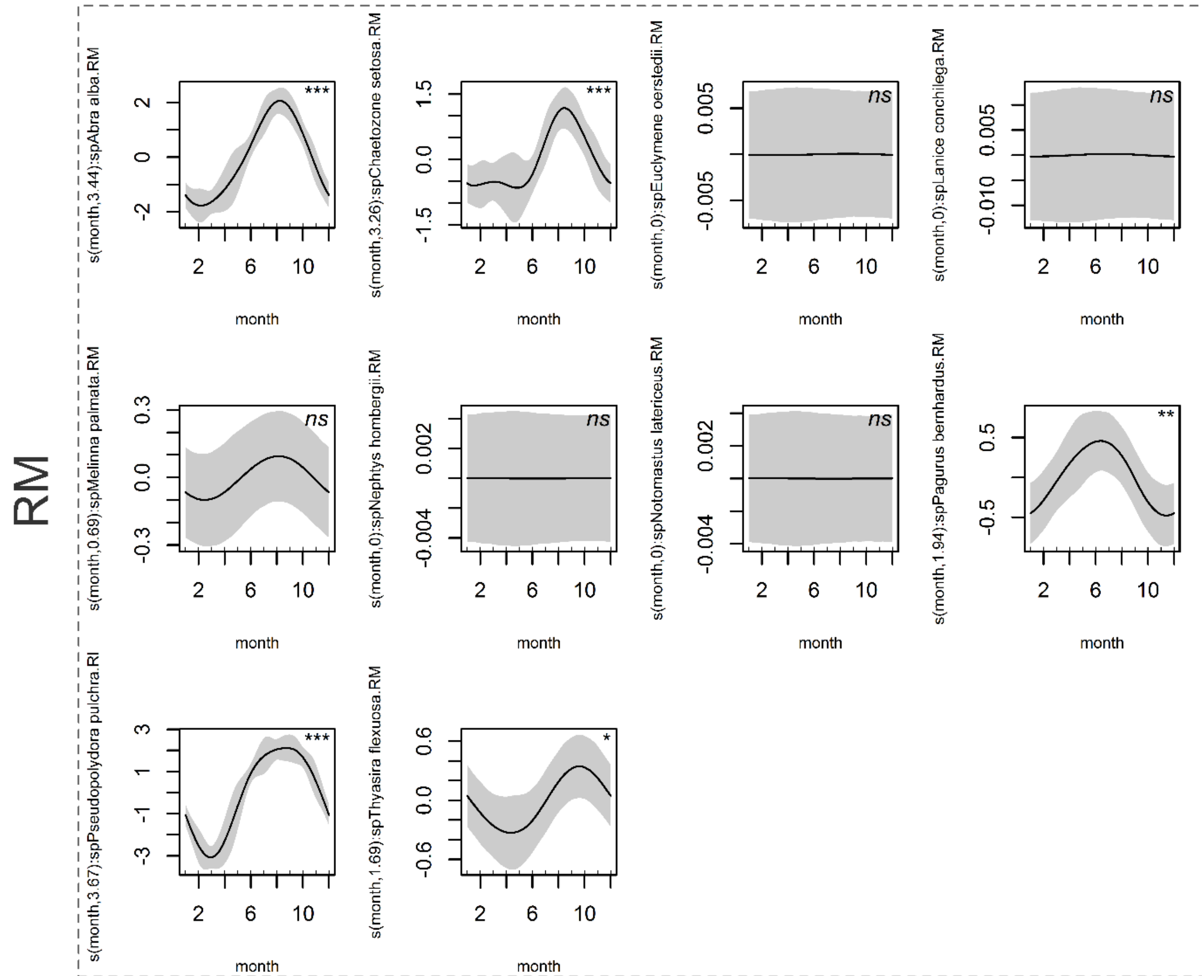

Fig. S5. Continued.

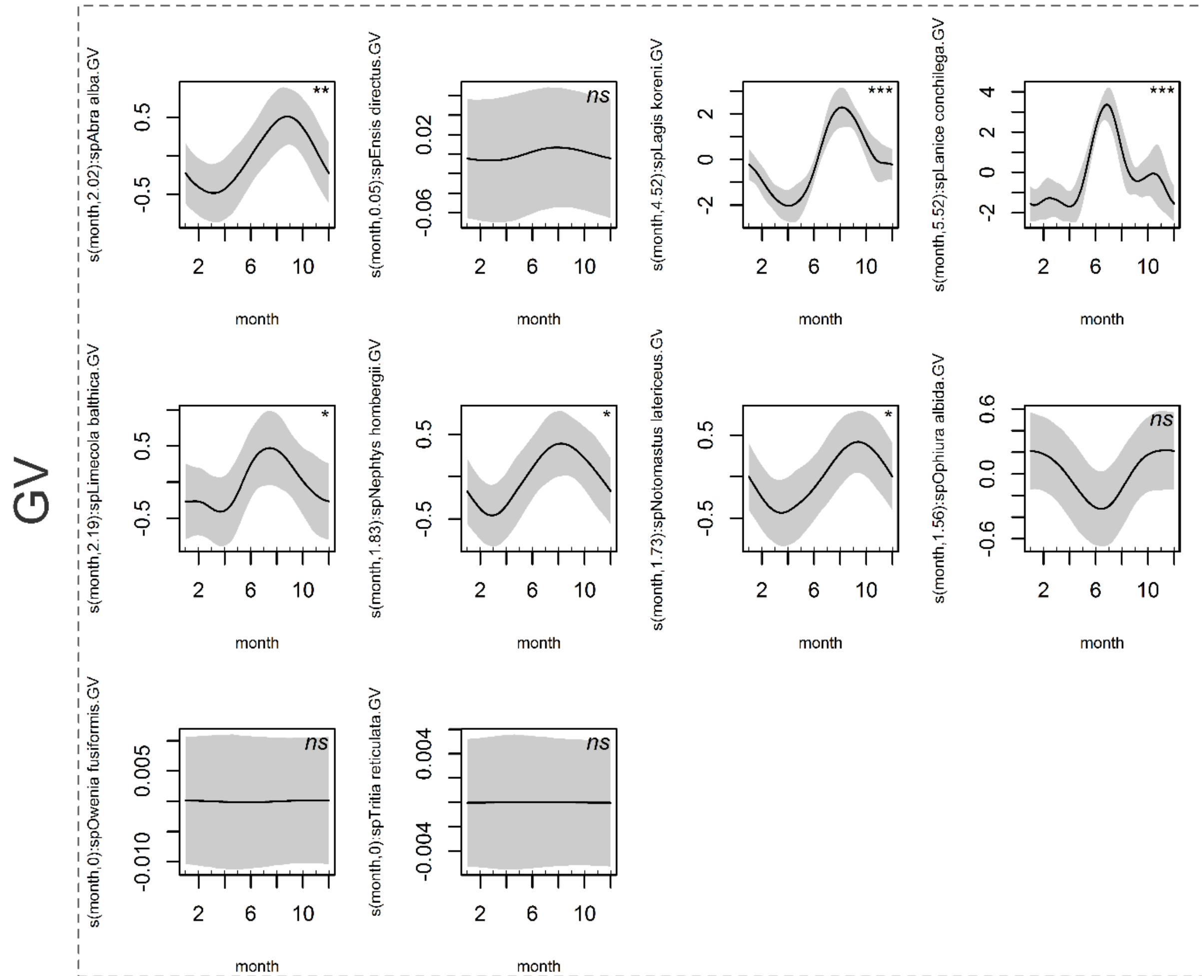

Fig. S5. Continued.

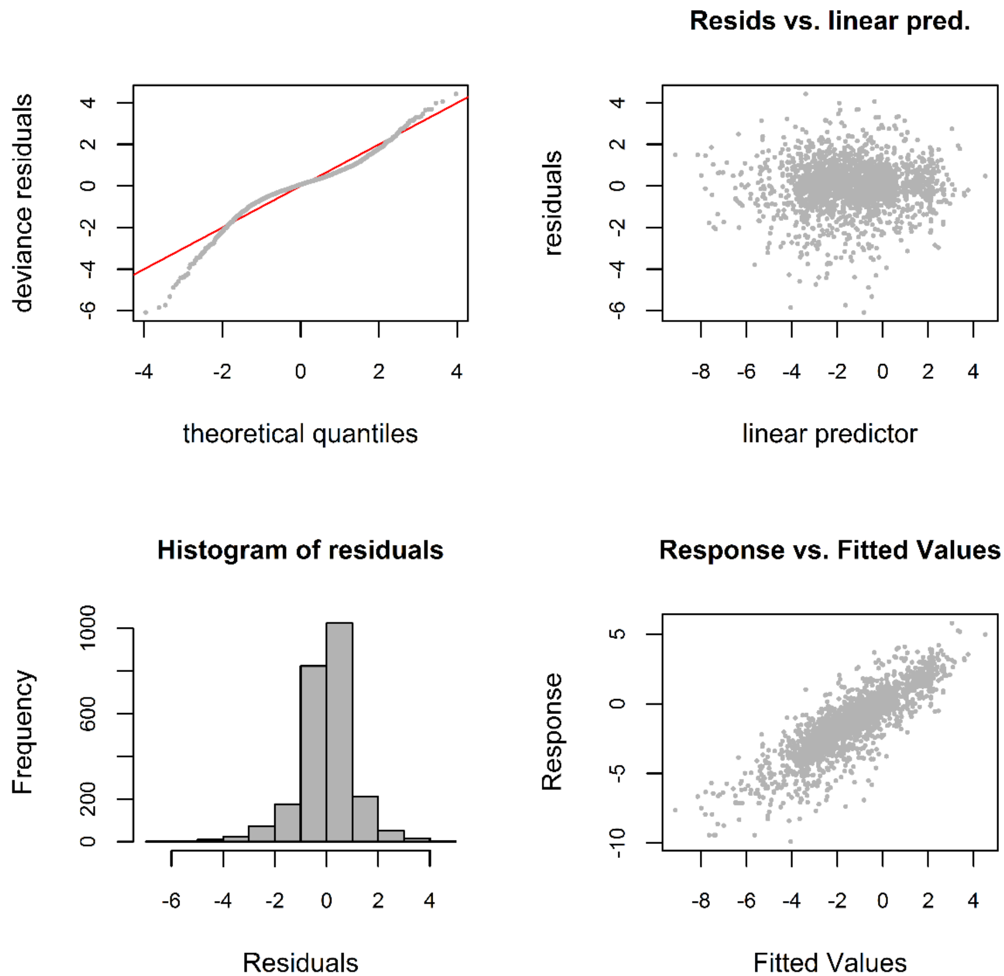

Fig. S6. Model validation graphs for the generalized additive model at the population level (model 2).

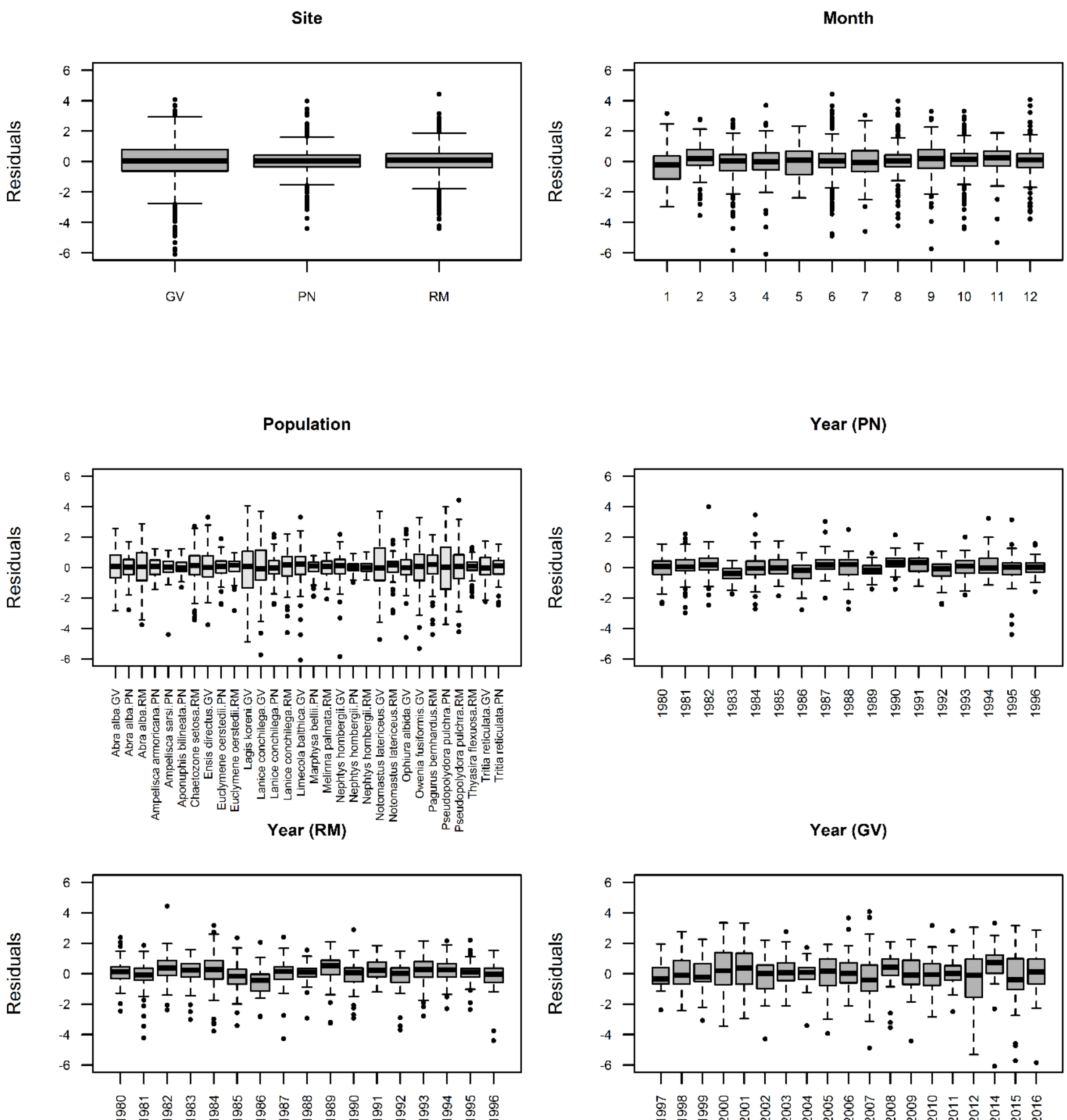

Fig. S7. Residuals vs. the factors ‘site’, ‘month’, population’, and ‘year’ at ‘Pierre Noire’ (PN), ‘Rivière de Morlaix’ (RM) and ‘Gravelines’ (GV) for the generalized additive model at the population level (model 2).

Bias and accuracy in annual production estimates

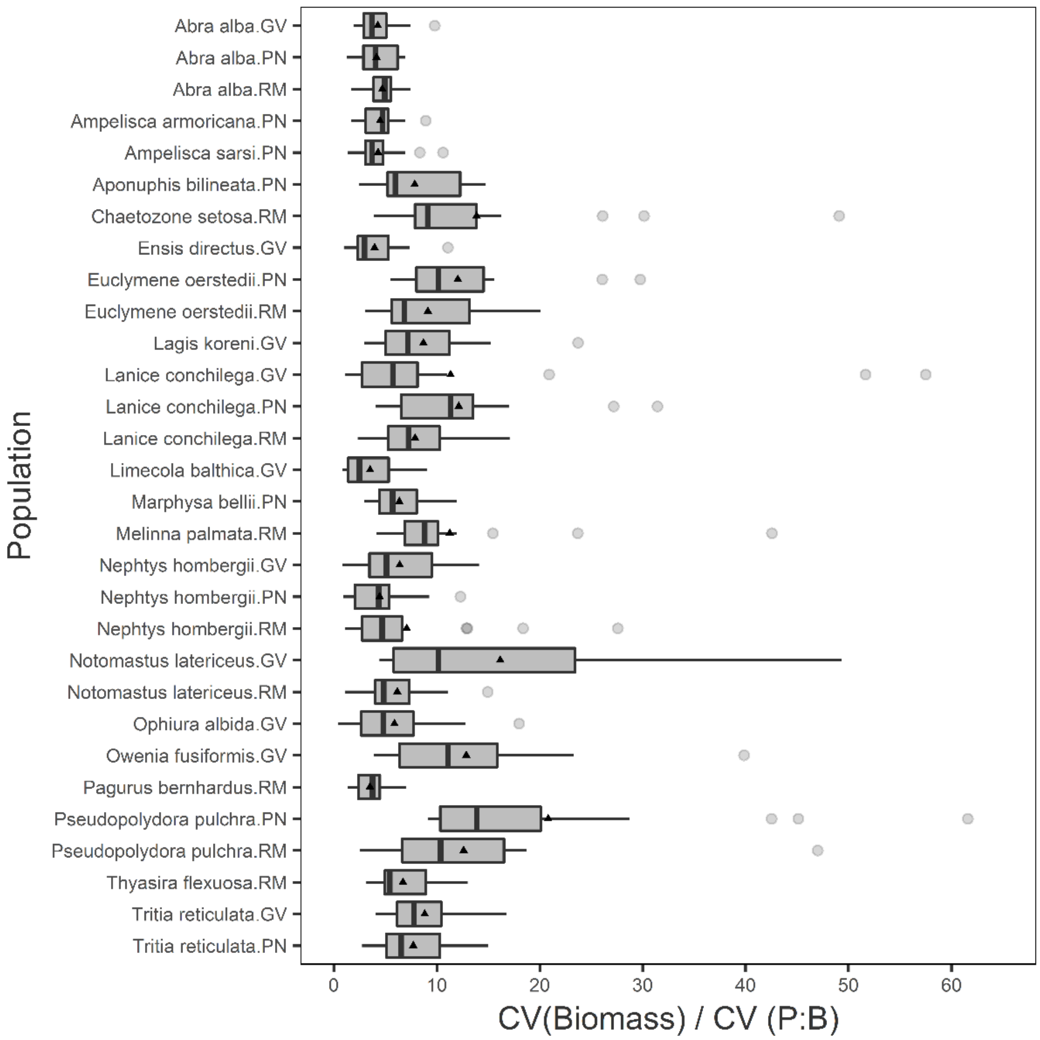

Fig. S8. Ratios of the annual coefficient of variation (CV) of biomass over the annual CV of *P:B* for all 30 dominant macrobenthic populations. The coefficients of variation are used here as a measure of the seasonal amplitude of biomass (and *P:B*). Boxplots show the inter-annual variability of the ratio. Vertical black segments represent the median and black triangles the mean. The seasonal variations in biomass are in average 8 times higher than the seasonal variations in *P:B* (mean ratio ranging from 3.5 to 20.8 according to the population), indicating that seasonal variations in *P* estimates are almost entirely driven by seasonal changes in biomass.

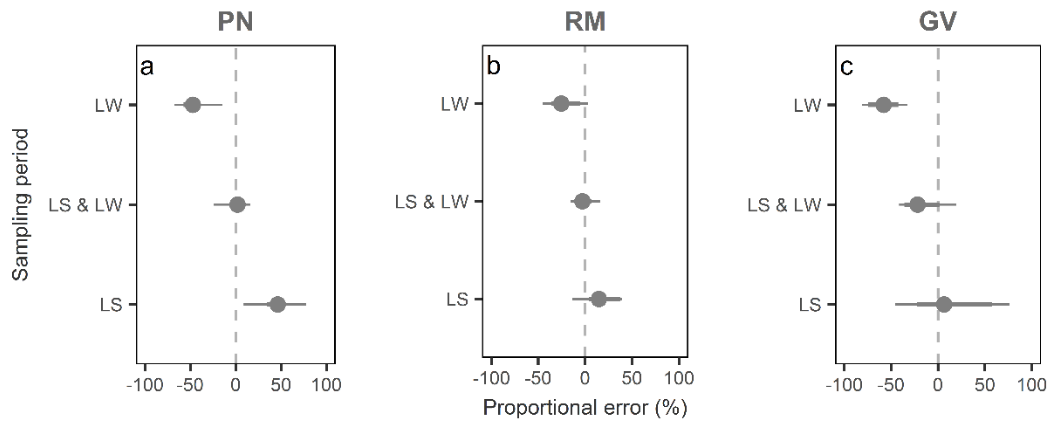

Fig. S9. Proportional error (PE) of production (P) estimates at ‘Pierre Noire’ (PN) **(a)**, ‘Rivière de Morlaix’ (RM) **(b)** and at ‘Gravelines’ (GV) **(c)**, according to the sampling period(s): late winter (LW, March), late summer (LS, September-October), or late summer and late winter (LS & LW). Dots represent median values of PE, used here as a measure of bias. Thick lines represent 25% and 75% quantiles of inter-annual variability in PE, while thin lines represent 10% and 90% quantiles. Sampling in LW and LS increased the accuracy of P estimates at all sites and led to unbiased estimates at two of the three sites (PN and RM).

Table S4. Bias (Median Proportional Error, MPE) and inaccuracy (Median Absolute Proportional Error, MAPE) of annual production estimates for the three study sites (‘Pierre Noire’ (PN), ‘Rivière de Morlaix’ (RM) and ‘Gravelines’ (GV)) based on data from a single sampling period. At GV, sampling months varied slightly among years and were thus grouped by 2-month periods.

Site	Month	Bias (MPE)	Inaccuracy (MAPE)
PN	3	-47%	47%
	6	-22%	22%
	8	-7%	22%
	10	46%	46%
	12	1%	14%
RM	3	-25%	25%
	6	-6%	15%
	8	23%	26%
	10	15%	19%
	12	-17%	18%
GV	1-2	-50%	51%
	3-4	-58%	58%
	6-7	29%	42%
	9-10	8%	51%