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Appendix A1

Model building and analysis

The dynamic model

We used the bioenergetic model of Yodzis and Innes (1992) generalized to food webs of many species by Williams and Martinez (2004), in which the temporal change of the biomass density of population of species i, B_i, is represented by:

$$\frac{dB_i}{d\breve{t}} = B_i r_i \kappa_i \left(1 - \frac{B_i}{K_i}\right) - x_i B_i + \kappa_i \sum_{j=prey} x_i y_{ij} F_{ij} - \sum_{j=cons} \frac{x_j y_{ji} F_{ji}}{\varepsilon_{ji} f_{ji}} \qquad \text{(A1)}$$

Parameter r_i is the maximum mass-specific production rate, set to zero for consumer species. Function κ_i represents the harmful effect of the pollutant on the growth rate of species i (see below). K_i is the carrying capacity of species i, defined as K_{TOT}/number of producers in the food web, where K_{TOT} is the carrying capacity of the system; x_i is the mass-specific metabolic rate of species i, set to zero for producer species; y_{ij} is the maximum consumption rate of species i when consuming prey species j; F_{ij} is the functional response of predator i consuming prey species j; ε_{ji} is the conversion efficiency of consumed resources to biomass of consumer j, and f_{ji} represents ingestion efficiency. K_{TOT} and f_{ji} were set to 5 and 1 respectively; ε_{ji} was set to 0.45 for herbivores and 0.85 for carnivores (Brose et al. 2006). Parameters r_i, x_i and y_{ij} are allometric parameters computed following Brose et al. (2006), as:

$$r_i = 1 \tag{A2}$$

$$x_i = \frac{a_x}{a_r}\left(\frac{M_C}{M_P}\right)^{-0.25} \tag{A3}$$

$$y_{ij} = \frac{a_y}{a_x} \tag{A4}$$

where a_x, a_r and a_y were fixed for invertebrate species at 0.314, 1 and 2.512 respectively. We assume that the body size of consumer species M_C increases as a power of the trophic level TL (Brose et al. 2006)

$$M_C = Z^{TL} \tag{A5}$$

where predator–prey body size ratio Z was fixed at 10^2 and the body size of producers was set to one.

The functional response of predator i consuming prey species j was represented by:

$$F_{ij} = \frac{\alpha_{ij} B_j^h}{B_0^h + \sum_{k=resources} \alpha_{ik} B_k^h} B_i \tag{A6}$$

where α_{ij}, is the preference of predator i for prey species j, that was equal for all prey of a given predator species i, so if n_i is the number of prey of species i, $\alpha_{ij} = 1 / n_i$ for each species j in the diet of species i. B_0 is the half saturation constant fixed at 0.5 (Brose et al. 2006, Martínez et al. 2006). We used a type III functional response ($h = 2$). Type III functional response has a stabilizing effect on ecological systems (Williams and Martinez 2004, Yodzis and Innes 1992), therefore it permits us to evaluate a plausible destabilizing effect of pollutant stress based on stable food webs that are not influenced by an additional destabilizing factor.

The total amount of pollutant accumulated within organisms of species i, A_i, is modeled by:

$$\frac{dA_i}{d\breve{t}} = \omega_i C B_i + \sum_{j=prey} x_i y_{ij} G_{ij} - x_i A_i - \sum_{j=cons} \frac{x_j y_{ji}}{f_{ji} \varepsilon_{ji}} G_{ji} - \Phi_i A_i \tag{A7}$$

where the first two terms correspond to the inputs of pollutant to species i from the environment and food respectively, and where ω_i is the organism's' uptake rate of pollutant from the environment (i.e. by non-dietary routes). G_{ij} is the functional response of predator species i as a function of A_j, the total amount of pollutant accumulated within prey species j. The last three terms describe the losses of pollutant from species i due to: 1) metabolic losses of accumulated pollutant, 2) predation, and 3) excretion and egestion, respectively, with Φ_i defined as the depuration rate of the pollutant (through excretion and egestion) from species i. The output of pollutant due to metabolic losses does not enter in other compartments within our dynamic model because it involves the transformation and therefore the inactivation of pollutants, while the predation and depuration rates are associated with the output of active, non-transformed pollutant. Parameters ω_i and Φ_i (i.e. excretion plus egestion) are allometrically scaled for organic pollutants; their values depend on body size and lipid content, and were calculated from the trophic level following Hendricks et al. (2001), Eq. 5, 8 and 9 respectively.

The dynamics of the pollutant in the environment C was modeled as:

$$\frac{dC}{d\breve{t}} = \Pi(\breve{t}) + \sum_i \Phi_i A_i - \sum_i \omega_i C B_i - \Psi C \qquad \text{(A8)}$$

where the function $\Pi(\breve{t})$ describes the input of the pollutant to the environment (see below) and Ψ is the decay rate of the pollutant in the environment due to biological and physicochemical processes, which was fixed at 10^{-4}.

The pollutant is assumed to enter the environment as a pulse disturbance, as usual for aquatic environments as a consequence of events such as discharges of storm water, overflow from sewage treatment plants, spraying of pesticides and runoff/drainage from fields during rains (Ashauer et al. 2006, McCahon and Pascoe 1990). The pulsed pollutant input was approached by means of the familiar single-peaked Gaussian function

$$\Pi(\breve{t}) = \frac{P}{\sqrt{\sigma\pi}} \exp\left(-\frac{(\breve{t} - M)^2}{\sigma}\right) \qquad \text{(A9)}$$

where $P = 2 \times 10^6$ is the total amount of pollutant to be released in a single pulse, M is the moment of the maximum (i.e. peak) pollutant concentration fixed at 500, and $\sigma = 10^5$ is a shape parameter.

In our model we assume that the pollutant accumulated within the body of organisms (on a per unit biomass basis, i.e. as A_i / B_i), reduces the growth rate of their population through an increase in the energy demand for detoxification and tissue repair. This energy reallocation results in reduced biomass growth. Therefore, the deleterious effect of the pollutant, obtained after rearranging terms, was incorporated into the first and third terms of Eq. A1 by means of the function

$$\kappa_i = 1 - \frac{A_i}{A_i + \gamma_i B_i + \eta} \qquad \text{(A10)}$$

which decreases from unity towards zero as accumulated pollutant on a per unit biomass basis (A_i / B_i) increases. Parameter η avoid the function to be undefined. Parameter γ_i sets the abruptness of the dose-effect curve and therefore represents the sensitivity of the species to pollutant accumulation. Highly sensitive species have small values of γ_i while tolerant species have large values. In this study γ_i was set to 10, 50 and 100 for high, medium and low pollutant stress. For simplicity, we assumed that all species in the food web have the same sensitivity to the pollutant, on a per unit biomass basis. Nevertheless, realized tolerance will depend on population biomass and the amount of accumulated pollutant, which in turn depends on body size and trophic level.

In this model (Eq. A1–A10) the time variable $\breve{t}$ is dimensionless, since it was obtained from the normalization of time t (in units of year) by the growth rate of producer species (in units of 1/year). Note that, following Brose et al. (2006), all producers have identical growth rate values. The normalization of time, results additionally in the nondimensionalization of all the time related parameters of the ODE system. Table A1 shows system variables and parameters with a brief description of them.

Table A1. System variables and parameters description. Note that the time variable denoted by $\breve{t}$ is dimensionless.

Variable/Parameter	Unit	Value	Description
B_i	kg l^{-1}	-	biomass density of population of species *i*
A_i	μg l^{-1}	-	total amount of pollutant accumulated within organisms of species *i*
C	μg l^{-1}	-	pollutant in the environment.
$\breve{t}$	dl	-	time
r_i	dl	1	maximum mass-specific production rate
x_i	dl	allometrically scaled*	mass-specific metabolic rate of species *i*
y_{ij}	dl	allometrically scaled*	maximum consumption rate of species *i* when consuming prey species *j*
f_{ij}	dl	1	ingestion efficiency
K_i	kg l^{-1}	5/number of producers	carrying capacity of species *i*, defined as K_{TOT}/number of producers in the food web, where K_{TOT} (= 5) is the carrying capacity of the system
ε_{ij}	dl	0.85 for carnivores and 0.45 for herbivores	conversion efficiency of consumed resources to biomass of consumer *j*
α_{ij}	dl	1/ number of prey species	preference of predator *i* for prey species *j*
B_0	kg l^{-1}	0.5	half saturation constant
h	dl	2	the exponent of the functional response
ω_i	l kg^{-1}	allometrically scaled**	organism's' uptake rate of pollutant from the environment
Φ_i	dl	allometrically scaled**	depuration rate of the pollutant (through excretion and egestion) from species *i*
Ψ	dl	10^{-4}	decay rate of the pollutant in the environment due to biological and physicochemical processes

M	dl	500	moment of the maximum pollutant concentration
σ	dl	10^5	shape parameter of pulsed pollutant input
P	μg l^{-1}	2×10^6	total amount of pollutant to be released in a single pulse
η	μg l^{-1}	1	parameter that avoid the function to be undefined.
γ_i	μg kg^{-1}	10-50-100	sensitivity of the species to pollutant accumulation

*allometric constants from Yodzis and Innes (1992) and Brose et al. (2006).

** allometric constants from Hendriks et al. (2001).

Back to the general structure of the model

The final version of our model (Eq. A1–A10) was obtained from the original bioenergetic model of Yodzis and Innes (1992) and adding the expressions for pollutant dynamics. The pollutant dynamics was obtained from Kooi et al. (2008). In this section we show how we arrived to the final version of the model, shown in Eq. A1–A10, which exhibits reparameterized terms and normalized time *t*.

The change in time of the biomass density of the population of species *i* is as follows:

$$\frac{dB_i}{dt} = B_i R_i \left(1 - \frac{B_i}{K_i}\right) - T_i B_i + \sum_{j=prey} \varepsilon_{ij} J_{ij} B_i \frac{\alpha_{ij} B_j^h}{B_0^h + \sum_{k=resources} \alpha_{ik} B_k^h} - \sum_{j=cons} \frac{J_{ji}}{f_{ji}} B_j \frac{\alpha_{ji} B_i^h}{B_0^h + \sum_{k=resources} \alpha_{jk} B_k^h} \quad \text{(A11)}$$

where parameters R_i, K_i and T_i, are respectively maximum production rate, carrying capacity and mass specific metabolic rate of population of species *i*. ε_{ij}, J_{ij}, α_{ij}, and f_{ij} are respectively conversion efficiency, maximum ingestion rate, preference and ingestion efficiency of predator species *i* when consuming prey species *j*. Allometrically scaled parameters are defined as:

$$R_i = a_r M_P^{-0.25} \quad \text{(A12)}$$

$$T_i = a_x M_C^{-0.25} \tag{A13}$$

$$\varepsilon_{ij} J_{ij} = a_y M_C^{-0.25} \tag{A14}$$

where a_x, a_r and a_y were fixed for invertebrate species at 0.314, 1 and 2.512 respectively.

Following Kooi et al. (2008) the dynamics of the accumulated pollutant in a per-unit biomass basis is

$$\frac{da_i}{dt} = W_i C - \phi_i a_i + \sum_{j=prey} \varepsilon_{ij} J_{ij} \frac{\alpha_{ij} B_j^h}{B_0^h + \sum_{k=resources} \alpha_{ik} B_k^h} a_j - T_i a_i - \sum_{j=cons} \frac{J_{ji}}{f_{ji}} B_j \frac{\alpha_{ji} B_i^{h-1}}{B_0^h + \sum_{k=resources} \alpha_{jk} B_k^h} a_i - \frac{dB_i}{B_i dt} a_i \tag{A15}$$

The first and second terms correspond, respectively, to the input of pollutant from water and output of pollutant through both excretion and egestion into the water compartment. These parameters, allometrically scaled, were taken from Hendriks et al. (2001) and were properly transformed in order to match the units in the model of Yodzis and Innes (1992). The third term corresponds to input of pollutant due to feeding, and the last three terms describe the losses of pollutant due to 1) metabolic losses, 2) predation, and 3) dilution by growth.

Through the product rule from Eq. A11–A15 we obtained the temporal dynamics of the amount of pollutant accumulated within the population of species i A_i

$$\frac{dA_i}{dt} = W_i C B_i - \phi_i A_i + B_i \sum_{j=prey} \varepsilon_{ij} J_{ij} \frac{\alpha_{ij} B_j^{h-1} A_j}{B_0^h + \sum_{k=resources} \alpha_{ik} B_k^h} - T_i A_i - \sum_{j=cons} \frac{B_j J_{ji}}{f_{ji}} \frac{\alpha_{ji} B_i^{h-1} A_i}{B_0^h + \sum_{k=resources} \alpha_{jk} B_k^h} \tag{A16}$$

The dynamics of the pollutant in the environment C was modeled as:

$$\frac{dC}{dt} = p(t) + \sum_i \phi_i A_i - \sum_i W_i C B_i - \psi C \tag{A17}$$

with $p(t)$ equals to:

$$p(t) = \frac{p}{\sqrt{s\pi}} \exp\left(-\frac{(t-m)^2}{s}\right) \tag{A18}$$

Finally we incorporated the effect of the pollutant through the function κ_i, shown in equation A10, which reduces the conversion efficiency and the maximum production rate within the Eq. A11 of species biomass dynamics.

In Table A2 are shown the units of each state variable and parameters from Eq. A11–A18, the earlier version of the final model described by Eq. A1–A10.

Table A2. System variables and parameters units. Parameters and variables are those from the earlier version of the model, without the normalization of time.

Variable/parameter	Unit
B_i	kg l^{-1}
a_i	μg kg^{-1}
C	μg l^{-1}
A_i	μg l^{-1}
t	y
R_i	y^{-1}
T_i	y^{-1}
J_{ij}	y^{-1}
f_{ij}	dl
K_i	kg l^{-1}
ε_{ij}	dl
α_{ij}	dl
B_0	kg l^{-1}
h	dl
W_i	l $kg^{-1}y^{-1}$
ϕ_i	y^{-1}
ψ	y^{-1}
m	y
s	y^2
p	μg l^{-1}
η	μg l^{-1}
γ_i	μg kg^{-1}

In the final version of the model shown in the previous section 1.1 (Eq. A1–A10) the time $\breve{t}$ is dimensionless due to the normalization of t to the growth rate of producer species i, R_i. The nondimensionalization of time was performed through decomposing t as $t = \breve{t}\hat{t}$ where $\breve{t}$ is the numerical, dimensionless part of the time variable and $\hat{t}$ the dimensional part of time. Through replacing t by the product $\breve{t}\hat{t}$ in the left hand of Eq. A11 and A13–A15 and solving to keep the left hand side of Eq. A11 and A13–A15 with the dimensionless time $\breve{t}$, we get that all the right hand side is multiplied by $\hat{t}$. Next, $\hat{t}$ was defined as $\frac{1}{R_i}$. In this way parameters related to time (R, T, ϕ, m and s) were adimentionalized and the following new parameters were obtained: $r_i = \frac{R_i}{R_i} = 1$, $x_i = \frac{T_i}{R_i}$, $\Phi_i = \frac{\phi_i}{R_i}$, $M = mR_i$ and $\sigma = sR_i$. Additionally, from parameter Wi we get the new parameter $\omega_i = \frac{W_i}{R_i}$ with units of l kg^{-1}. Finally the dimensionless parameter y_{ij} in the rescaled version of the model (Eq. A1–A10) was obtained through the normalization of the maximum ingestion rate to the metabolic rate of consumer species, $y_{ij} = \frac{\varepsilon_{ij} J_{ij}}{T_j}$.

Dimensional analysis

We performed a dimensional analysis of our model (Eq. A11–A18). The dimensional analysis proceeds through the nondimensionalization of the model. This procedure is a powerful tool that allows verifying if the units of the model are consistent between right and left hand side of the ODE system. Below we show, step-by-step, the development of the analysis. The final nondimensionalization of the system, which was obtained stepwise for each state variable, shows that our system is dimensionally homogeneous (Legendre and Legendre 1998).

The change in time of the biomass density of the population of species i is as follows:

$$\frac{dB_i}{dt} = B_i R_i \kappa_i \left(1 - \frac{B_i}{K_i}\right) - T_i B_i + \kappa_i \sum_{j=prey} \varepsilon_{ij} J_{ij} F_{ij} - \sum_{j=cons} \frac{J_{ji}}{f_{ji}} F_{ji} \quad \text{(A19)}$$

The change in time of the pollutant concentration within the population of species i is depicted as:

$$\frac{dA_i}{dt} = W_i C B_i - \phi_i A_i + \sum_{j=prey} \varepsilon_{ij} J_{ij} G_{ij} - T_i A_i - \sum_{j=cons} \frac{J_{ji}}{f_{ji}} G_{ji} \quad \text{(A20)}$$

with the dynamics of pollutant in the environment C modeled as:

$$\frac{dC}{dt} = p(t) + \sum_i \phi_i A_i - \sum_i W_i C B_i - \psi C \quad \text{(A21)}$$

The functions κ_i (Eq. 19), F_{ij} (Eq. 19), G_{ij} (Eq. 20) and p (Eq. 21) in equations are equal to

$$\kappa_i = 1 - \frac{A_i}{A_i + \gamma_i B_i + \eta} \quad \text{(A22)}$$

$$F_{ij} = \frac{\alpha_{ij} B_j^h}{B_0^h + \sum_{k=resources} \alpha_{ik} B_k^h} B_i \quad \text{(A23)}$$

$$F_{ji} = \frac{\alpha_{ji} B_i^h}{B_0^h + \sum_{k=resources} \alpha_{jk} B_k^h} B_j \quad \text{(A24)}$$

$$G_{ij} = \frac{\alpha_{ij} B_j^{h-1} A_j}{B_0^h + \sum_{k=resources} \alpha_{ik} B_k^h} B_i \quad \text{(A25)}$$

$$G_{ji} = \frac{\alpha_{ji} B_i^{h-1} A_i}{B_0^h + \sum_{k=resources} \alpha_{jk} B_k^h} B_j \quad \text{(A26)}$$

$$p(t) = \frac{p}{\sqrt{s\pi}} \exp\left(-\frac{(t-m)^2}{s} \right) \quad \text{(A27)}$$

In Table A2 are shown the units of each state variable and parameters within Eq. A19–A21. Re-writing the differential equations by substituting for each state variable a product of a dimensionless variable and a variable representing 1 unit of that variable, we obtained for equation 1

$$\frac{d\breve{B}_i \widehat{B}_i}{d\breve{t}\widehat{t}} = \breve{B}_i \widehat{B}_i R_i \kappa_i \left(1 - \frac{\breve{B}_i \widehat{B}_i}{K_i} \right) - T_i \breve{B}_i \widehat{B}_i + \kappa_i \sum_{j=prey} \varepsilon_{ij} J_{ij} F_{ij} - \sum_{j=cons} \frac{J_{ji}}{f_{ji}} F_{ji} \quad \text{(A28)}$$

Making the left hand side unit less it follows that:

$$\frac{d\breve{B}_i}{d\breve{t}} = \breve{B}_i \widehat{t} R_i \kappa_i \left(1 - \frac{\breve{B}_i \widehat{B}_i}{K_i} \right) - T_i \breve{B}_i \widehat{t} + \kappa_i \sum_{j=prey} \varepsilon_{ij} J_{ij} \frac{\widehat{t}}{\widehat{B}_i} F_{ij} - \sum_{j=cons} \frac{J_{ji}}{f_{ji}} \frac{\widehat{t}}{\widehat{B}_i} F_{ji} \quad \text{(A29)}$$

Defining $\widehat{t} R_i = 1 \rightarrow \widehat{t} = 1/R_i$ and $\widehat{B}_i / K_i = 1 \rightarrow \widehat{B}_i = K_i$. Replacing in Eq. A29 and rearranging terms within predation terms we have the following expression:

$$\frac{d\breve{B}_i}{d\breve{t}} = \breve{B}_i \kappa_i \left(1 - \breve{B}_i \right) - \frac{T_i}{R_i} \breve{B}_i + \kappa_i \sum_{j=prey} \varepsilon_{ij} J_{ij} \frac{T_i}{T_i} \frac{1}{R_i} F_{ij} - \sum_{j=cons} \frac{\varepsilon_{ji} T_j}{\varepsilon_{ji} T_j} \frac{J_{ji}}{f_{ji}} \frac{1}{R_i} F_{ji} \quad \text{(A30)}$$

Regarding to the functional responses it is obtained that

$$F_{ij} = \breve{B}_i \frac{\alpha_{ij}\breve{B}_j^h K_j^h}{B_0^h\left(1+\sum_{k=resources}\alpha_{ik}\breve{B}_k^h\left(\frac{K_k}{B_0}\right)^h\right)} \tag{A31}$$

$$F_{ji} = \breve{B}_j K_j \frac{\alpha_{ij}\breve{B}_i^h K_i^{h-1}}{B_0^h\left(1+\sum_{k=resources}\alpha_{ik}\breve{B}_k^h\left(\frac{K_k}{B_0}\right)^h\right)} \tag{A32}$$

and as to the function κ_i after some algebraic manipulation we get

$$\kappa_i = 1 - \frac{\breve{A}_i}{\breve{A}_i + \frac{\gamma_i \breve{B}_i K_i}{\widehat{A}_i} + \frac{\eta}{\widehat{A}_i}} \tag{A33}$$

After simplification in Eq. A30–A32 new dimensionless parameters arise, those are $x_i = \frac{T_i}{R_i}$, $y_{ij} = \frac{\varepsilon_{ij} J_{ij}}{T_i}$ and $u_i = \frac{K_i}{B_0}$. Regarding the Eq. A33 we define $\widehat{A}_i/\eta = 1 \rightarrow \widehat{A}_i = \eta$. From this equality it is obtained the dimensionless parameter $\Gamma_i = \frac{\gamma_i K_i}{\eta}$. Replacing those parameters in Eq. A30–A33 we obtained the non-dimensional form of Eq. 19 as follows:

$$\frac{d\breve{B}_i}{d\breve{t}} = \breve{B}_i \kappa_i \left(1-\breve{B}_i\right) - x_i \breve{B}_i + \kappa_i \sum_{j=prey} x_i y_{ij} F_{ij} - \sum_{j=cons} \frac{x_j y_{ji}}{f_{ji}\varepsilon_{ji}} F_{ji} \tag{A34}$$

with functions:

$$F_{ij} = \breve{B}_i u_j^h \frac{\alpha_{ij}\breve{B}_j^h}{1+\sum_{k=resources}\alpha_{ik}\breve{B}_k^h u_k^h} \tag{A35}$$

$$F_{ji} = \breve{B}_j u_j u_i^{h-1} \frac{\alpha_{ij}\breve{B}_i^h}{1+\sum_{k=resources}\alpha_{ik}\breve{B}_k^h u_k^h} \tag{A36}$$

$$\kappa_i = 1 - \frac{\breve{A}_i}{\breve{A}_i + \Gamma_i \breve{B}_i + 1} \tag{A37}$$

Repeating the same procedure for Eq. A20 we get:

$$\frac{d\breve{A}_i\widehat{A}_i}{d\breve{t}\widehat{t}} = W_i \breve{C}\widehat{C}\breve{B}_i\widehat{B}_i - \phi_i \breve{A}_i\widehat{A}_i + \sum_{j=prey}\varepsilon_{ij} J_{ij} G_{ij} - T_i \breve{A}_i\widehat{A}_i - \sum_{j=cons}\frac{J_{ji}}{f_{ji}} G_{ji} \tag{A38}$$

Making the left hand side unit less and replacing the parameters and equalities obtained for Eq. A19 we get

$$\frac{d\breve{A}_i}{d\breve{t}} = \frac{W_i K_i}{R_i}\frac{\hat{C}}{\eta}\breve{C}\breve{B}_i - \frac{\phi_i}{R_i}\breve{A}_i + \sum_{j=prey} x_i y_{ij}\frac{1}{\eta}G_{ij} - x_i\breve{A}_i - \sum_{j=cons}\frac{x_j y_{ji}}{f_{ji}\varepsilon_{ji}}\frac{1}{\eta}G_{ji} \quad \text{(A39)}$$

with functions

$$G_{ij} = \breve{B}_i u_i u_j^{h-1}\frac{\alpha_{ij}\breve{B}_j^{h-1}\breve{A}_j\eta}{1+\sum_{k=resources}\alpha_{ik}\breve{B}_k^h u_k^h} \quad \text{(A40)}$$

$$G_{ji} = \breve{B}_j u_j u_i^{h-1}\frac{\alpha_{ji}\breve{B}_i^{h-1}\breve{A}_i\eta}{1+\sum_{k=resources}\alpha_{jk}\breve{B}_k^h u_k^h} \quad \text{(A41)}$$

New dimensionless parameters from Eq. A39 are $\Omega_i = \frac{W_i K_i}{R_i}$ and $\Phi_i = \frac{\phi_i}{R_i}$. Defining $\hat{C}/\eta = 1 \rightarrow \hat{C} = \eta$. Replacing new parameters and simplifying, the dimensionless version of Eq. A20 is:

$$\frac{d\breve{A}_i}{d\breve{t}} = \Omega_i\breve{C}\breve{B}_i - \Phi_i\breve{A}_i + \sum_{j=prey} x_i y_{ij} G_{ij} - x_i\breve{A}_i - \sum_{j=cons}\frac{x_j y_{ji}}{f_{ji}\varepsilon_{ji}}G_{ji} \quad \text{(A42)}$$

with functions

$$G_{ij} = u_i u_j^{h-1}\frac{\alpha_{ij}\breve{B}_j^{h-1}\breve{A}_i}{1+\sum_{k=resources}\alpha_{ik}\breve{B}_k^h u_k^h} \quad \text{(A43)}$$

$$G_{ji} = u_j u_i^{h-1}\frac{\alpha_{ji}\breve{B}_i^{h-1}\breve{A}_i}{1+\sum_{k=resources}\alpha_{jk}\breve{B}_k^h u_k^h}\breve{B}_j \quad \text{(A44)}$$

Finally, after replacing the new parameters and following new definitions of the non-dimensional part of state variables, we express dimensionless form of Eq. A21 as:

$$\frac{d\breve{C}}{d\breve{t}} = p(t) + \sum_i \Phi_i\breve{A}_i - \sum_i \Omega_i\breve{C}\breve{B}_i - \Psi C \quad \text{(A45)}$$

with the new dimensionless parameter $\Psi = \frac{\psi}{R_i}$ and function p equals to:

$$\Pi(t) = \frac{P}{\sqrt{\sigma\pi}}\exp\left(-\frac{(\breve{t}-M)^2}{\sigma}\right) \quad \text{(A46)}$$

whose new dimensionless parameters are $P = \frac{p}{\eta}$, $\sigma = sR_i^2$ and $M = mR_i^2$.

Data analysis

In the case of the generic perturbation we set the pollutant to zero and introduced in the biomass dynamics an additional mortality rate proportional to species biomass. The increase in per unit biomass mortality rate through time was equal for all species and followed the shape of Eq. A9, using the same parameter values used for pollutant stress, except parameter P, which was varied systematically to generate a gradient of stress (low, medium and high). In this way we introduced a pulsed perturbation that shares most features with the pollutant perturbation but lacks a key property: its ability to propagate itself (not its effects) via trophic interactions. All codes were implemented and executed in MATLAB (R2011b).

Appendix A2

Effect of food web structure

We assessed if the effect of modularity remained the same when we moved away from a realistic food web structure. For addressing this point, we repeated all analyses using food webs with 1) realistic topology (using the generalized niche model) with controlled diet contiguity = 0.2 and random body size distribution, and 2) random topology (Erdös–Renyi model) and random body size distribution. The body size of a species was randomly chosen from the interval $1–10^6$. Random topology was generated through the Erdös–Renyi model with compartements. This model has as parameter inputs the species richness, the number of modules, the overall probability of attachment, and the proportion of links within modules. The proportion of liks within models were fixed at 0.3, and the number of modules was 3, 4 and 5 for food webs with 20, 30 and 40 species respectively.

Figure A1. Modularity–persistence relationship in systems with increasing levels of pollutant stress and controlled diet contiguity. (A) is a plot for unperturbed food webs. (B), (C) and (D) are plots for food webs with low, medium and high levels of pollutant stress, respectively. (E), (F) and (G) are plots for food webs with low, medium and high levels of a generic stress respectively. Continuous, dashed and dotted lines correspond to food webs of 20, 30 and 40 species respectively. Error bars represent 95 per cent confidence intervals arround the mean value of species persistence. γ_j = 200 for low pollutant stress, γ_j = 100 for medium pollutant stress, γ_j = 10 for high pollutant stress.

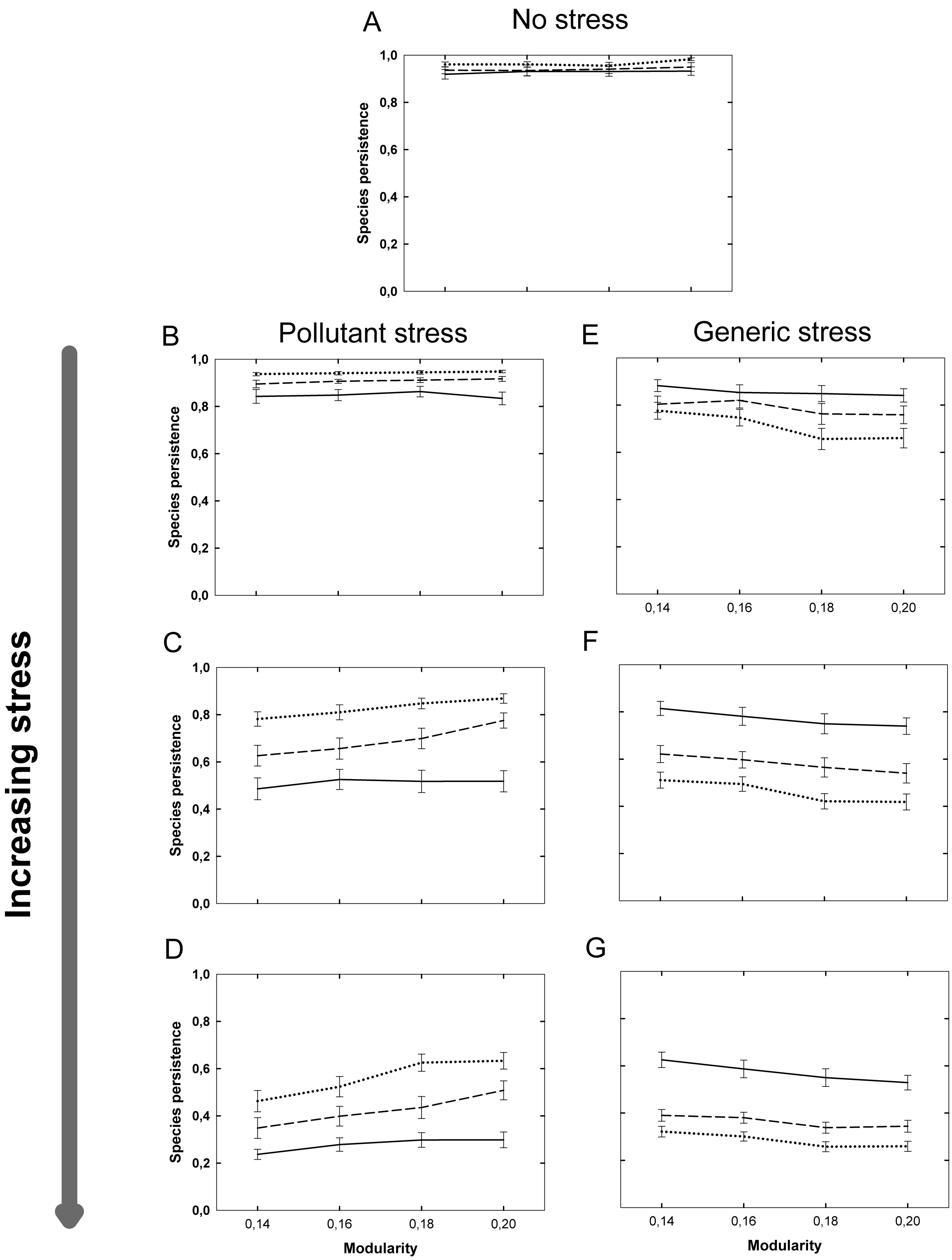


Figure A2. Modularity–persistence relationship in systems with increasing levels of pollutant stress, controlled diet contiguity and random body sizes. (A) is a plot for unperturbed food webs. (B), (C) and (D) are plots for food webs with low, medium and high levels of pollutant stress, respectively. (E), (F) and (G) are plots for food webs with low, medium and high levels of a generic stress respectively. Continuous, dashed and dotted lines correspond to food webs of 20, 30 and 40 species respectively. Error bars represent 95 per cent confidence intervals arround the mean value of species persistence. $\gamma_j = 200$ for low pollutant stress, $\gamma_j = 100$ for medium pollutant stress, $\gamma_j = 10$ for high pollutant stress.

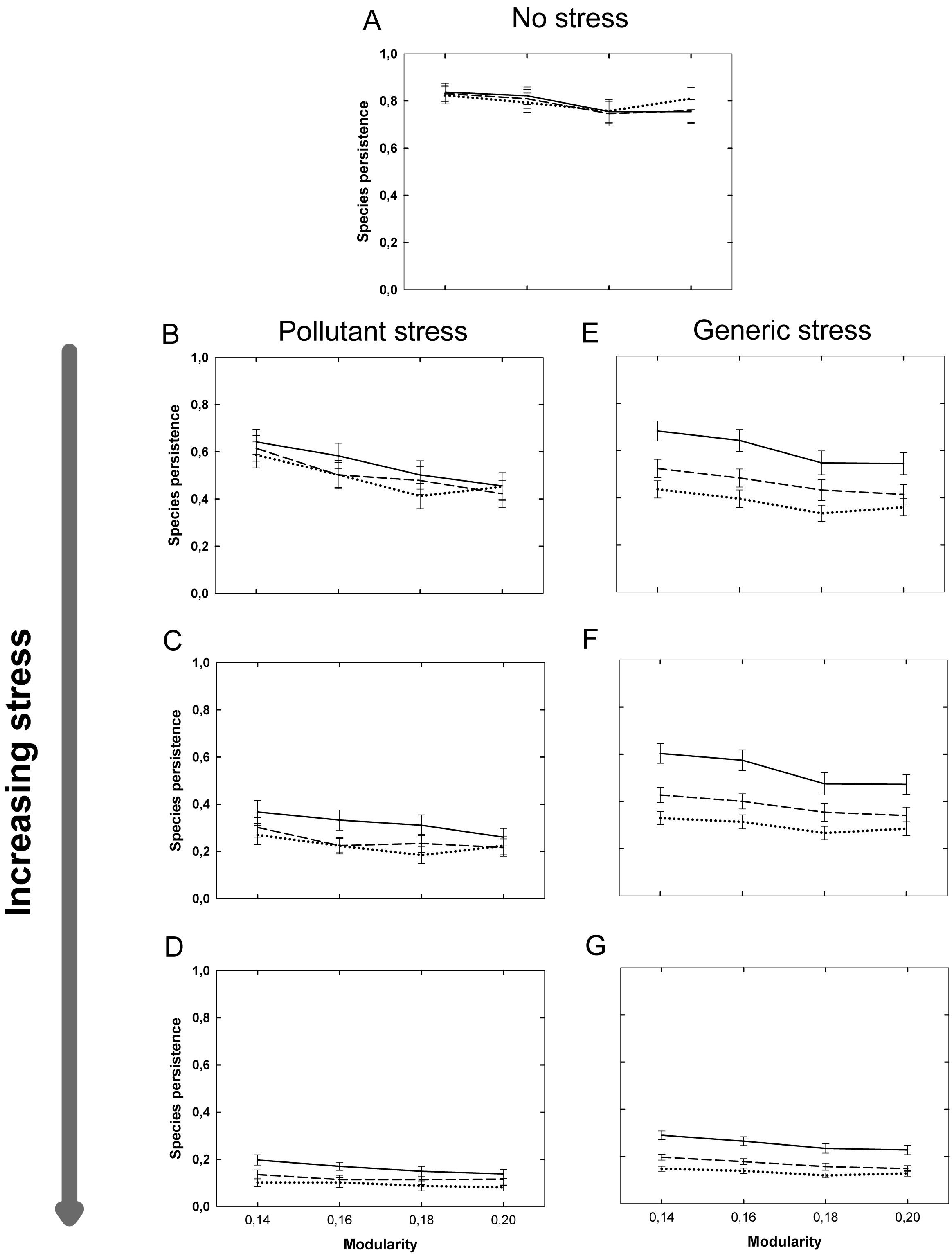
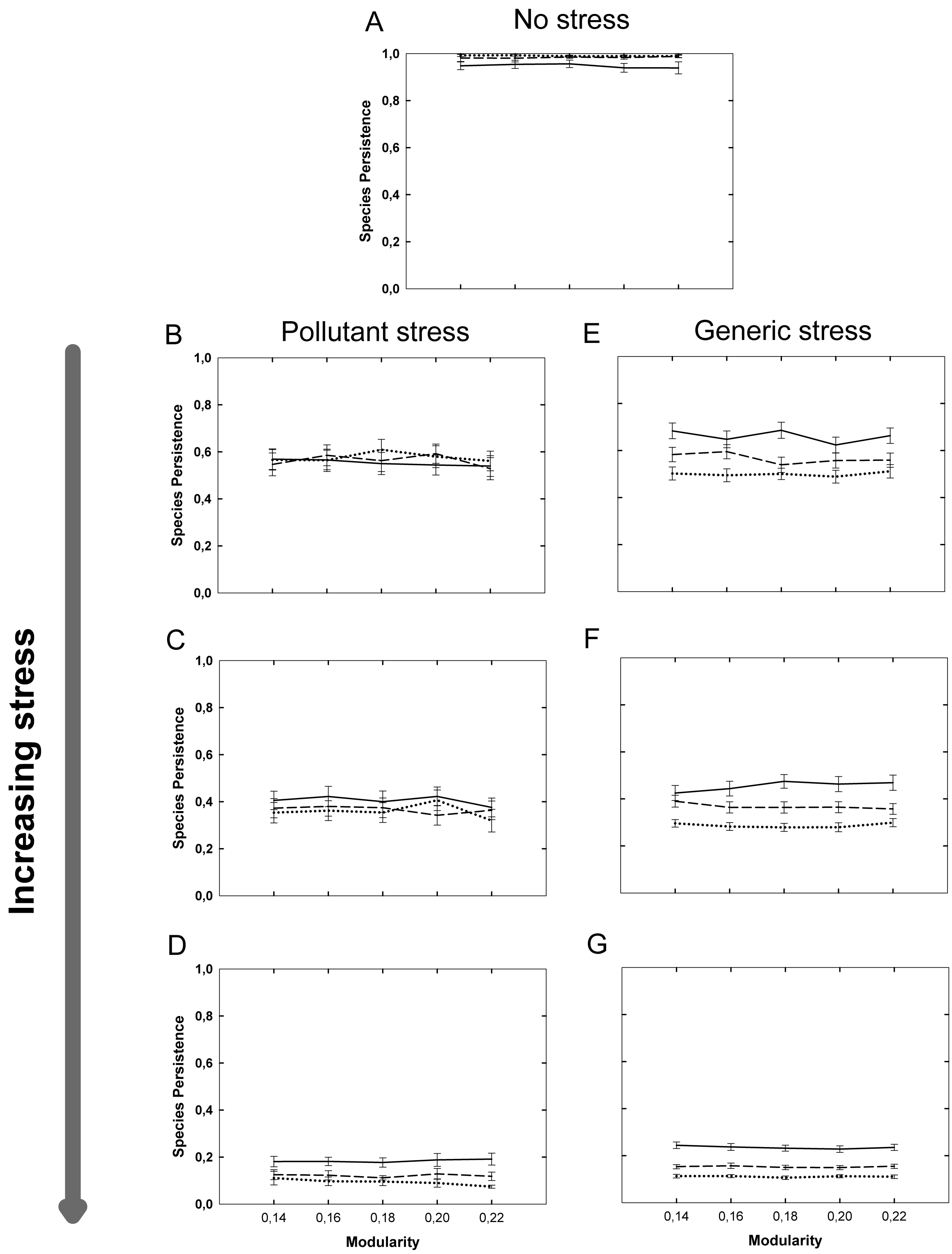


Figure A3. Modularity–persistence relationship in systems with increasing levels of pollutant stress, and random topology and body sizes. (A) is a plot for unperturbed food webs. (B), (C) and (D) are plots for food webs with low, medium and high levels of pollutant stress, respectively. (E), (F) and (G) are plots for food webs with low, medium and high levels of a generic stress respectively. Continuous, dashed and dotted lines correspond to food webs of 20, 30 and 40 species respectively. Error bars represent 95 per cent confidence intervals arround the mean value of species persistence. γ_j = 200 for low pollutant stress, γ_j = 100 for medium pollutant stress, γ_j = 10 for high pollutant stress.



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