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## RESEARCH ARTICLE

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# Interplay between the paradox of enrichment and nutrient cycling in food webs

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## ABSTRACT

Nutrient cycling is fundamental to ecosystem functioning. Despite recent major advances in the understanding of complex food web dynamics, food web models have so far generally ignored nutrient cycling. However, nutrient cycling is expected to strongly impact food web stability and functioning. To make up for this gap, we built an allometric and size structured food web model including nutrient cycling. By releasing mineral nutrients, recycling increases the availability of limiting resources for primary producers and links each trophic level to the bottom of food webs. We found that nutrient cycling can provide a significant part of the total nutrient supply of the food web, leading to a strong enrichment effect that promotes species persistence in nutrient poor ecosystems but leads to a paradox of enrichment at high nutrient inputs. The presence of recycling loops linking each trophic level to the basal resources weakly affects species biomass temporal variability in the food web. Recycling loops tend to slightly dampen the destabilising effect of nutrient enrichment on consumer temporal variability while they have opposite effects for primary producers. By considering nutrient cycling, this new model improves our understanding of the response of food webs to nutrient availability and opens perspectives to better link studies on food web dynamics and ecosystem functioning.

**Keywords:** detritus; diversity; enrichment; mineral nutrients; paradox of enrichment; size structured

## Introduction

Food web dynamics and functioning have been studied thoroughly through empirical and modelling approaches because food webs are essential to ecosystem functioning. A central issue is to determine the characteristics of food webs that affect their key properties, e.g. the number of species composing them, primary production or secondary production. Food chains (*i.e.* linear chains of species or trophic groups interacting through trophic interactions) and food webs (*i.e.* networks of species interacting through trophic interactions) models have been extensively used to tackle these issues. In particular, dynamical models of complex food webs (*i.e.* food webs including numerous interacting species) reveal that size structured food webs (Brose et al., 2006b; Heckmann et al., 2012), allometric scaling of biological rates (Brose et al., 2006b) and adaptive foraging (Kondoh, 2003; Heckmann et al., 2012) promote species coexistence and population stability. However, these models focus on population dynamics and carbon fluxes, forgetting non-living compartments (mineral nutrients and dead organic matter) and nutrient cycling (cyclic fluxes of nutrients through living and non-living compartments). Some studies include mineral nutrients as basal resources for primary producers (Schneider et al., 2016; Wang and Brose, 2017) or detritus as basal resources for bacteria (Boit et al., 2012) or for omnivorous consumers as well (Legagneux et al., 2012), but they never include a complete nutrient cycling.

Nevertheless, the cycling of mineral nutrients such as nitrogen and phosphorus likely tightly interacts with food web stability. Stability can be measured in different ways: resilience (calculated by the leading eigenvalue of the jacobian matrix of the system at equilibrium) represents the ability of the system to return to its equilibrium after a perturbation, resistance measures the degree to which a variable changes after a perturbation and temporal variability (measured for example by the coefficient of variation) represents the variance of population densities over time (McCann, 2000). Several studies highlighted the importance of nutrient cycling processes for ecosystem stability, but with contrasting results (O'Neill, 1976; DeAngelis, 1980; DeAngelis et al., 1989; DeAngelis, 1992; Loreau, 1994; McCann, 2011; Neutel and Thorne, 2014). DeAngelis (1980, 1992) showed that nutrient cycling affects food chain resilience, systems with tighter nutrient cycling (*i.e.* a lower proportion of mineral nutrients is lost from the ecosystem each time they cycle) being less resilient. On the other hand, Loreau (1994) suggested that tighter cycling was associated with greater food chain resistance to perturbations, and McCann (2011) found that food chains with nutrient cycling were less destabilised (*i.e.* more resilient) by nutrient enrichment than food chains without nutrient cycling. Meanwhile, Neutel and Thorne (2014) did not find clear effects of the presence of recycling loops on the resilience of complex soil food webs, some food webs being unaffected by nutrient cycling and others being either destabilised or stabilised. While the study of consequences of nutrient cycling on stability has largely been restricted to resilience of small food web motifs or food chains (but see Neutel and Thorne (2014)), understanding the consequences of nutrient cycling on species dynamics in complex food webs becomes crucial to predict ecosystem response to perturbations. Observed contradictory results on the effects of nutrient cycling might arise from the fact that nutrient cycling can affect food web through different mechanisms, whose importance could also differ between food chain and food web models.

First, the recycled nutrients (*i.e.* excreted nutrients that return to the mineral pool available for primary producers) are added to the external inputs of mineral nutrients and could lead to an enrichment effect (Loreau, 2010). Nutrient availability has contrasting effects on food webs. On one hand, it fuels primary production and increases the energy transfer to consumers, leading to a higher species persistence and sustaining higher trophic levels as supported by models (Abrams, 1993; Binzer et al., 2011) and empirical observations (Yodzis, 1984; Doi, 2012). On the other hand, nutrient overabundance tends to increase the amplitude of population oscillations, which increases the risk of extinction. This characterises the paradox of enrichment (Rosenzweig, 1971; Rip and McCann, 2011) predicted by several food chain and food web models (Roy and Chattopadhyay, 2007; Rall et al., 2008; Hauzy et al., 2013; Gounand et al., 2014; Binzer et al., 2016) and some experiments (Fussmann et al., 2000; Persson et al., 2001). Taken together, this leads to the hypothesis that in nutrient poor ecosystems, nutrient cycling would have a positive effect on food webs, *i.e.* on species persistence and the persistence of higher trophic levels while, in nutrient rich ecosystems, nutrient cycling would destabilise food webs. Thus, the enrichment effect of nutrient cycling may be a major component of its impact on food webs (McCann, 2011). This is particularly meaningful in a context of global nutrient enrichment due to human activities (Vitousek and Reiners, 1975; Smith et al., 1999).

Second, nutrient cycling adds direct feedback loops from all trophic levels to the bottom of food webs. Besides the consequent enrichment effect, these feedback loops may affect biomass dynamics (McCann, 2011; Neutel and Thorne, 2014). Because these feedback loops are positive (Fath and Haines, 2007; Haines et al., 2007) they may have a destabilising effect causing an increase in the oscillation amplitude of biomass densities. However, they could have the opposite effect if nutrient cycling leads to asynchronous dynamics of mineral nutrients and primary producers, as found in a food chain model (McCann, 2011). In such case, a decrease in primary producers could be dampened by a simultaneous increase in mineral nutrients availability, thus reducing population oscillations in the food chain (Brown et al., 2004a). Such effects of recycling feedback loops on stability might however be weaker in complex food webs. In complex food webs, recycled nutrient inputs to detritus and mineral nutrient pools result from many feedback loops, which might attenuate the fluctuations of mineral nutrient dynamics and thus limit the stabilising (resp. destabilising) effect of asynchronous (resp. synchronous) fluctuations of mineral nutrients and primary producers.

Third, the effects of nutrient cycling on stability might be modulated by the ways nutrient are recycled. Consumers in food webs directly affect nutrient cycling both through immobilisation of nutrients in their biomass and through egestion and excretion of non-assimilated food (Vanni, 2002). Furthermore, nutrients are excreted as mineral nutrients (direct recycling) or as detritus releasing mineral nutrients during decomposition (indirect recycling) (Vanni, 2002; Zou et al., 2016). Direct recycling is faster than indirect recycling because decomposition is required before the return of nutrients to the mineral pool, leading to increased primary production (Zou et al., 2016). Increasing the fraction of direct recycling should amplify the enrichment effect by accelerating the recycling. Increasing the decomposition rate of detritus should have a similar effect, especially if direct recycling does not prevail.

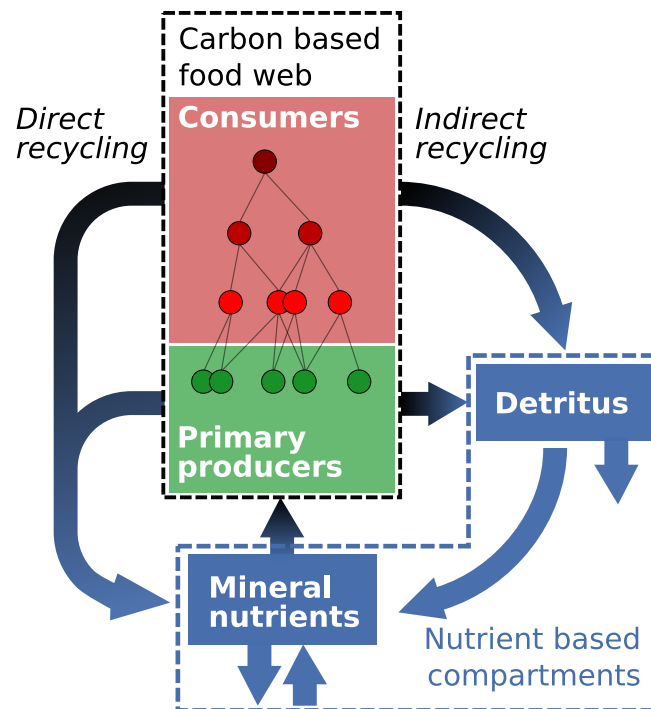
To study the consequences of nutrient cycling on food web response to nutrient enrichment and explore the mechanisms involved, we extended the recent food web modelling approach based on allometric relations with species body mass (e.g. Brose et al. (2006b); Heckmann et al. (2012); Schneider et al. (2016); Wang and Brose (2017)) by integrating basic aspects of nutrient cycling in this framework. Species body mass is linked to fundamental species traits such as metabolic or growth rates (Yodzis and Innes, 1992; McCann et al., 1998; Brown et al., 2004b) and it is also a good predictor of trophic interactions in ecosystems (Williams and Martinez, 2000; Petchey et al., 2008). Models parametrised with such allometric relations have been increasingly used to study food web dynamics and stability, especially because they tend to reproduce well, even though still simplified, observed patterns and dynamics of complex food webs (Boit et al., 2012; Hudson and Reuman, 2013). This framework thus offers a good opportunity to include nutrient cycling to food web models. To disentangle the mechanisms by which nutrient cycling affects food web stability (defined by species persistence and time variability of biomass dynamics), we assessed and compared the respective impact of nutrient cycling through the addition of mineral resources and the addition of feedback loops in both a complex food web and a food chain. These aspects were critical to answer the following questions: How nutrient cycling affect the overall nutrient availability in ecosystems and thus interact with the paradox of enrichment? Can the addition of feedback loops by nutrient cycling change the effects of the paradox of enrichment on species dynamics? Do the relative importance of direct and indirect nutrient cycling and the decomposition rate modulate these effects?

## Material and methods

### General description of the model

We developed a food web model including basic aspects of nutrient cycling by combining food web, allometry and stoichiometric theories (Fig. 1). Following classical allometric food web models (Brose, 2008; Heckmann et al., 2012), that are based on carbon flows, species biological parameters and trophic interactions scale with species body mass. Our model adds two major abiotic compartments, mineral nutrients (e.g. mineral nitrogen pool) and detritus (dead organic matter), to food web dynamics. Since detritus and mineral nutrient compartments are expressed in mass of nutrient whereas species compartments are expressed in mass of carbon, stoichiometry rules ensure the conversion between carbon flows and nutrient flows between the biotic and abiotic compartments and account for species

stoichiometric homeostasis in the food web. Nutrients are either directly recycled (species excretion of mineral nutrients directly available for primary producers) or indirectly recycled (species excretion of detritus releasing mineral nutrients through decomposition). All stocks are expressed for an arbitrary unit of habitat either a surface or a volume. The model is parametrised for nitrogen, but could be applied to other limiting nutrients such as phosphorus.



**Figure 1.** Schematic diagram of the modelled food web. The food web contains several primary producers and consumers forming a complex interaction network. It also includes two non-living compartments: mineral nutrients and detritus. Each organism excretes nutrients either directly as mineral nutrients (arrows on the left), or indirectly through the production of degradable detritus (arrows on the right). Stoichiometric rules ensure the conversions between the carbon based food web and the nutrient based compartments.

### Predator-prey interactions in the allometric food web model

For modelling food web dynamics, one needs to model both the structure of the food web (*i.e.* who eats whom) and the population dynamics within the food web. To define trophic interactions between species (*i.e.* food web structure), we took inspiration from the approach of the allometric diet breath model (ADBM, Petchey et al. (2008); Thierry et al. (2011)) because it predicts well trophic interactions in real food webs from species body mass and does not require additional assumptions on food web connectance (Petchey et al., 2008). To each of the 50 initial species is attributed a value  $c$  drawn uniformly in the interval  $[-5; 1]$ . Then, their body mass  $M$  is calculated as follow:

$$M = 10^c \tag{1}$$

The five smallest species are defined as primary producers, the other as consumers. The diet of consumers depends on the profitability of each prey based on prey handling (*i.e.* the lower is the handling time, the more profitable is the prey). We derive the expression of the mass specific handling time  $h_{ij}$  of species  $j$  by the consumer  $i$  from Petchey et al. (2008) and Thierry et al. (2011) and (see Appendix S1 in the supporting information):

$$h_{ij} = \begin{cases} \frac{b^2}{6y_i(b - \frac{M_j}{M_i})} \frac{M_i}{M_j} & \text{if } \frac{M_j}{M_i} < b \\ \infty & \text{if } \frac{M_j}{M_i} > b \end{cases} \tag{2}$$

With  $y_i$  the maximum ingestion rate (see equation (4e)),  $M_j$  the body mass of the prey,  $M_i$  the body mass of the consumer and  $b$  the maximum prey-predator body mass ratio above which the prey cannot be eaten. The handling time function against prey body mass is U-shaped (see Fig. S1-1 in the supporting information), handling time being minimal when prey body mass is equal to  $b/2 \times M_j$ . We consider that predators can only interact with preys within the body-mass interval  $[0.1bM_i, bM_i]$  with  $b < 1$  (i.e. predators are always larger than their prey) as the handling time increases exponentially out of this interval. Thus, the structure of the food web (e.g. number of trophic levels, see Fig. S2-2C and D in supporting information) is shaped by species biomass distribution and body mass ratios between species.

The predator-prey dynamics follow previous allometric food web models (Brose, 2008; Heckmann et al., 2012). The respective equations for primary producers (equation 3a) and consumers (equation 3b) are:

$$\frac{dB_i}{dt} = r_i G_i B_i - x_i B_i - \beta_i B_i^2 - \sum_{\substack{\text{predators } j \\ \text{of } i}} B_j F_{ji} \quad (3a)$$

$$\frac{dB_i}{dt} = -x_i B_i - \beta_i B_i^2 + \sum_{\substack{\text{prey } j \\ \text{of } i}} e_{ij} B_i F_{ij} - \sum_{\substack{\text{predators } j \\ \text{of } i}} B_j F_{ji} \quad (3b)$$

In these equations,  $B_i$  is the biomass of population  $i$ ,  $G_i$  is the nutrient-dependent growth rate of primary producers,  $r_i$  is the mass-specific maximum growth rate of primary producers,  $x_i$  is the mass-specific metabolic rate,  $\beta_i$  is the density dependent mortality rate (ensuring a reasonable species persistence, see Fig. S3-4 and S3-5A in the supporting information) and  $e_{ij}$  the assimilation efficiency of species  $j$  by species  $i$ . Primary producer growth rates  $r_i$ , species metabolic rates  $x_i$ , density dependent mortality rates  $\beta_i$ , consumer attack rate  $a_i$  and maximum ingestion rates  $y_i$  (involved in handling time parametrisation, see equation (2)) are defined as functions of species body masses, according to the allometric quarter-power laws as described by Yodzis and Innes (1992) and Brown et al. (2004b):

$$r_i = r M_i^{-1/4} \quad (4a)$$

$$x_i = x M_i^{-1/4} \quad (4b)$$

$$\beta_i = \beta M_i^{-1/4} \quad (4c)$$

$$a_i = a M_i^{-1/4} \quad (4d)$$

$$y_i = y x_i \quad (4e)$$

With  $M_i$  the body mass of species  $i$  and  $r, x, \beta, a$  and  $y$  being allometric constants (Table 1, see also Appendix S1 in supporting information).

$F_{ij}$  represents the contribution of species  $j$  in the eaten biomass per unit species  $i$  biomass and follows a Holling functional response:

$$F_{ij} = \frac{\omega_{ij} a_i B_j^q}{1 + \sum_{\substack{\text{prey } k \\ \text{of } i}} \omega_{ik} a_i h_{ik} B_k^q} \quad (5)$$

$B_j$  represents the biomass of the prey  $j$ ,  $q$  is the Hill exponent (the functional response is of type II if  $q = 1$  or type III if  $q > 1$ ),  $a_i$  is the attack rate of consumer  $i$  and  $h_{ik}$  is the handling time of  $k$  by consumer  $i$ .  $\omega_{ij}$  is the preference of  $i$  for the prey  $j$ . We chose here to model preferences as time variables and not as fixed parameters according to the adaptive foraging theoretical framework (results with preferences as fixed parameters are available in Fig. S3-6 in the supporting information). Adaptive foraging is indeed an important aspect of predator-prey interactions (e.g. predator foraging efforts depend on prey availability) and it strongly affects food web dynamics (Kondoh, 2003; Uchida and

Drossel, 2007; Heckmann et al., 2012). The dynamics of foraging efforts were modelled through changes over time of the consumer preferences  $\omega_{ij}$  according to the following equation:

$$\frac{d\omega_{ij}}{dt} = A\omega_{ij} \left( \frac{\partial g_i}{\partial \omega_{ij}} - \sum_{\substack{\text{prey } k \\ \text{of } i}} \omega_{ik} \frac{\partial g_i}{\partial \omega_{ik}} \right) \quad (6)$$

Here,  $A$  represents the adaptive rate of the diet preference and  $g_i$  the total growth rate of species  $i$  defined such as  $\frac{dB_i}{dt} = g_i B_i$ . The initial value of  $\omega_{ij}$  is set assuming a uniform distribution among preys and during the simulation, the  $\omega_{ij}$  are rescaled after the resolution of equation 6 to keep the relation  $\sum_{\substack{\text{prey } k \\ \text{of } i}} \omega_{ik} = 1$  true at each time step.

## From a carbon-based food web model to an ecosystem model including nutrient cycling

To expand the classical food web model to take fundamental aspect of nutrient cycling into account, we model the dynamics of two abiotic compartments, mineral nutrients  $N$  and detritus  $D$ . These compartments are described as masses of nutrient while species biomasses are based on carbon in the food web model. We use species carbon to nutrient ratios (C:N)  $\alpha_i$  to convert carbon flows into nutrient flows (and vice versa). For simplicity, we assume the  $\alpha_i$  to be constant over time. Please note that we could have expressed directly the species biomasses in nutrient instead (as in Zou et al. (2016)), without changing the model behaviour. However, we chose to keep species biomasses based on carbon to relate more clearly our equations with classical allometric food web models. The dynamics of nutrients in the mineral and detritus compartments are described by:

$$\frac{dN}{dt} = I - \ell N + dD + \underbrace{\delta \sum_{\text{species } i} \frac{x_i B_i + \beta_i B_i^2}{\alpha_i}}_{\text{direct recycling}} - \underbrace{\sum_{\text{primary producers } i} \frac{r_i G_i B_i}{\alpha_i}}_{\text{primary producers uptake}} \quad (7a)$$

$$\frac{dD}{dt} = -\ell D - dD + \underbrace{\sum_{\text{consumers } i} \left( \sum_{\substack{\text{prey } j \\ \text{of } i}} \frac{(1 - e_{ij}) B_i F_{ij}}{\alpha_{Dij}} \right)}_{\text{non assimilated biomass}} + (1 - \delta) \underbrace{\sum_{\text{species } i} \frac{x_i B_i + \beta_i B_i^2}{\alpha_i}}_{\text{indirect recycling}} \quad (7b)$$

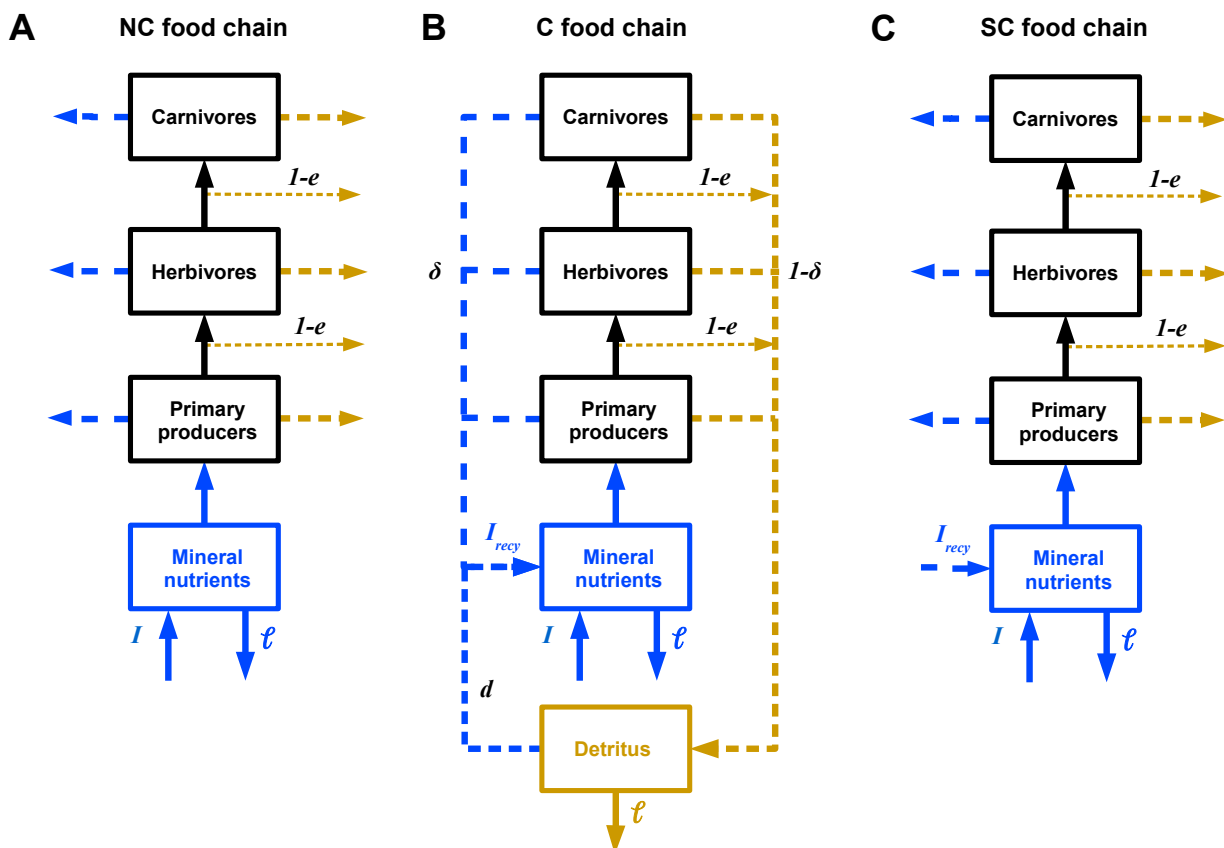
We consider an open ecosystem where  $I$  is the constant external input of nutrients (e.g. through erosion or atmospheric deposition) and  $\ell$  is the rate of loss of mineral nutrients and detritus (e.g. through leaching, sedimentation). The nutrient dependent growth rate of primary producers is expressed as (DeAngelis, 1980; DeAngelis et al., 1989):

$$G_i = \frac{N}{K_i + N} \quad (8)$$

$K_i$  is the half saturation constant of nutrient uptake of primary producer  $i$ . The nutrient uptake by primary producers (expressed as a nutrient flow) is calculated by dividing the growth rate of primary producers (expressed as a carbon flow) by their C:N ratio  $\alpha_i$ . Detritus are decomposed at a constant rate  $d$ . Organisms release nutrients through excretion and mortality to the detritus and mineral nutrient pools (Fig. 2B). A fraction  $\delta$  of these nutrients is released in their mineral form (urine for instance) while the remaining fraction is released as dead organic matter (detritus like feces, dead bodies, litter fall...) as in Zou et al. (2016). We assume that the nutrients contained in the non-assimilated biomass  $(1 - e_{ij})$  go in the detritus compartment. The amount of nutrients released by species in the food web depends on their C:N ratio  $\alpha_i$ . The carbon to nutrient ratio of non-assimilated biomass  $\alpha_{Dij}$  depends on both the C:N ratio of the prey  $j$  and of the consumer  $i$  (calculation detailed in Appendix S1 of supporting information):

$$\alpha_{Dij} = \frac{\alpha_j \alpha_i (1 - e_{ij})}{\alpha_i - \alpha_j e_{ij}} \quad (9)$$

## Assessing nutrient cycling effects on stability



**Figure 2.** Diagram of the general structure of our models with and without nutrient recycling feedback loops. Food chains are represented for more simplicity but these three models are valid for food webs as well. The dotted arrows represent nutrient cycling (nutrient flux in blue, detritus in brown). **A)** NC model. Food chain without nutrient cycling. **B)** C model. Food chain with nutrient cycling. A fraction  $\delta$  of nutrients is excreted as mineral nutrients (direct recycling on the left) and a fraction  $1 - \delta$  plus a fraction  $1 - e$  of non ingested biomass are excreted as detritus (indirect recycling on the right). The total nutrient input  $I_{tot}$  in the pool of mineral nutrients is the sum of the external nutrient input  $I$  and the recycled nutrient  $I_{recy}$ . **C)** SC model. Food chain without nutrient cycling but with a nutrient input corrected by  $I_{recy}$ . The resulting food chain does not have the feedback loop induced by nutrient recycling but has an equivalent nutrient availability as in the food web with nutrient cycling. Note that the first version of our model (NC) is based on the C model where  $I_{recy}$  is set to 0.

Stability was assessed by two measures: species persistence and the average coefficient of variation of species biomass (CV) weighted by the relative biomass of each species. To investigate the effects of nutrient cycling on food web dynamics and disentangle effects due to enrichment from effects due to presence of additional loops, each food web was studied for three configurations of nutrient cycling (Fig. 2). (1) No nutrient cycling with the fraction of direct recycling  $\delta$  and the decomposition rate  $d$  set to zero. This corresponded to the dynamics obtained with classic allometric food web models and will be referred as the NC model (No Cycling) (Fig. 2A). (2) With nutrient cycling with the fraction of direct recycling  $\delta$  and the decomposition rate  $d$  strictly positive (Fig. 2B). This food web was referred as the C model (Cycling). (3) No nutrient cycling but the enrichment effect of nutrient cycling was simulated (Fig. 2C). This food web was referred as the SC model (Simulated Cycling). In this last case, we removed the potential effect of the temporal coupling between higher trophic levels and the basal resource due to the presence of recycling loops while keeping the additional inputs of nutrients associated with nutrient cycling. To simulate the enrichment effect of nutrient cycling, we replaced the basal nutrient input by the total nutrient input  $I_{tot}$ :

$$I_{tot} = I + I_{recy} \quad (10)$$

Where  $I$  is the external nutrient input and  $I_{recy}$  is the average quantity of recycled nutrients (directly and indirectly)



calculated over the last 1000 years of the simulation in the C model. Thus, in the SC model,  $I_{recy}$  was constant over time because recycling (both direct and indirect recycling) was not explicitly modelled. In the C model, these nutrient subsidies varied over time as they directly originated from the direct and indirect recycling loops and thus depended on temporal variations of species biomasses and detritus in the ecosystem.

	Value and units	Description	Reference
$B_i$	$kg.v^{-1}$	Species biomass (carbon) of species $i$	Variable (equation 3a, 3b)
$N$	$kg.v^{-1}$	Mineral nutrient stock (nitrogen)	Variable (equation 7a)
$D$	$kg.v^{-1}$	Detritus stock (nitrogen)	Variable (equation 7b)
$\omega_{ij}$	Dimensionless	Preference of predator $j$ for prey $i$	Variable (equation 6)
$r$	$0.87 kg^{1/4}.year^{-1}$	Growth rate allometric constant	Binzer et al. (2012)
$x$	$0.12 kg^{1/4}.year^{-1}$ $0.27 kg^{1/4}.year^{-1}$	(primary prod.) Metabolic rate (consumer) allometric constant	Brose (2008)
$y$	8	Maximum ingestion rate factor	Brose (2008)
$\beta$	$0.001 v.kg^{-3/4}.year^{-1}$	Density dependent mortality rate allometric constant	Arbitrary (Fig. S3-4 and S3-5)
$a$	$0.1 v.kg^{-3/4}.year^{-1}$	Attack rate allometric constant	Arbitrary (Fig. S3-5)
$h_{ij}$	year	Handling time	Equation (2), Appendix S1
$e_{ij}$	0.45 (herbivore) 0.85 (carnivore)	Assimilation efficiency of species $j$ eaten by species $i$	Yodzis and Innes (1992)
$q$	1	Hill exponent	Brose et al. (2006b)
$A$	0.01	Adaptive rate	Arbitrary (Fig. S3-6)
$b$	0.05	Max prey-predator body mass ratio	Brose et al. (2006a)
$\alpha_i$	6.6 (primary prod.) 5 (consumer)	Constant carbon to nutrient ratio	Anderson (1992)
$K_i$	$10 kg.v^{-1}$	Half saturation of nitrogen uptake	Arbitrary (Fig. S3-3)
$\ell$	$0.2 year^{-1}$	Leaching rate	Arbitrary (Fig. S3-3)
$M_i$	kg	Body mass of species $i$	Log uniform in $[10^{-5}, 10]$
$I$	$kg.v^{-1}.year^{-1}$	External mineral nutrient input	$[0, 400]$
$d$	Dimensionless	Decomposition rate of detritus	$[0, 1]$
$\delta$	Dimensionless	Fraction of direct recycling	$[0, 1]$

**Table 1.** Table of variables and parameters (below the horizontal separation).  $v$  represents a generic metric of space (e.g. that could represent litres or square meters). Indeed all the parameters depending on space are set arbitrarily and thus we do not need to specify a particular unit of space. The values of  $\beta$  and  $a$  are set arbitrary to ensure a reasonable species persistence and and time variability of species biomasses (See Fig. S3-5 in the supporting information).  $K$  and  $\ell$  are set to ensure a maximal persistence at  $I \sim 50$ .

## Simulations

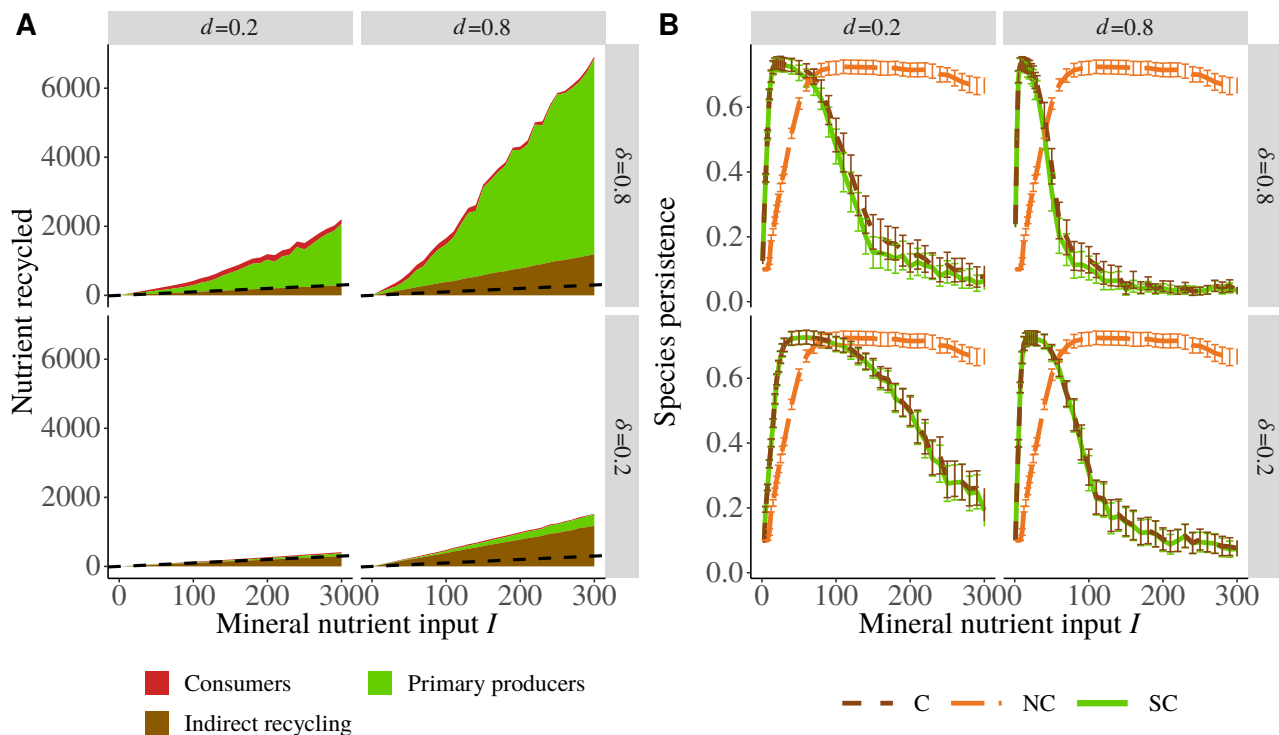
All the parameters, their units and their values as used in the simulations are given in table 1. The sensitivity of the results to arbitrarily set parameters is given in Appendix S3 in supporting information. The simulations were performed with C++ and the GSL ode solver using the Runge-Kutta-Fehlberg (4, 5) method with an adaptive time step and an absolute accuracy of  $10^{-6}$ . Simulations were run as follow: first, 50 species are attributed a body mass (the five smallest being primary producers) and trophic links were set depending on predator-prey body mass ratios (see equation 2). We did not seek for food webs with our 50 species linked by trophic interaction, thus consumer without prey got extinct during simulations. Then, simulations were run a for 9000 years to let the ecosystem reach a steady state. We kept in our results all resulting food webs even when some of the initial 50 species got extinct (see Fig. S3-1C in the supporting information). Species were considered as extinct if their biomass fell below  $10^{-30} kg.v^{-1}$  and consumers without prey got extinct. After this preliminary phase, outputs were recorded for 1000 years. Species persistence was measured as the ratio of the final number of species at  $t = 10,000$  to the initial number of species at  $t = 0$ . The CV was the ratio of the standard deviation to the mean of species biomass or recycled quantity of nutrients over time, calculated for the 1000 last years of each simulation. Each combination of parameters was tested for 100 different food webs (i.e. different randomly drawn sets of species body mass), each of these food webs being simulated in the three configurations of nutrient cycling (i.e. for the NC, C and SC models). To implement the SC model, we recorded the density of each compartment in the simulation of the C model at  $t = 9000$  as well as the averaged quantity of recycled nutrient  $I_{recy}$  for the last 1000 years. We then ran corresponding food web simulations for the SC

model (*i.e.* with  $\delta = d = 0$  and  $D = 0$ ) for 1000 years with initial densities and a nutrient input  $I$  respectively set equal to the densities and  $I_{tot}$  recorded in the C model.

In each simulation for complex food webs, there were initially 50 species and their initial biomasses were set at 10  $\text{kg.v}^{-1}$  for primary producers and at 5  $\text{kg.v}^{-1}$  for consumers ( $v$  is an arbitrary metric of space, see table 1). Initial quantities of nutrients in the mineral nutrients and detritus pools were set at 10  $\text{kg.v}^{-1}$ .

## Results

### Overall effects of nutrient cycling on food web dynamics

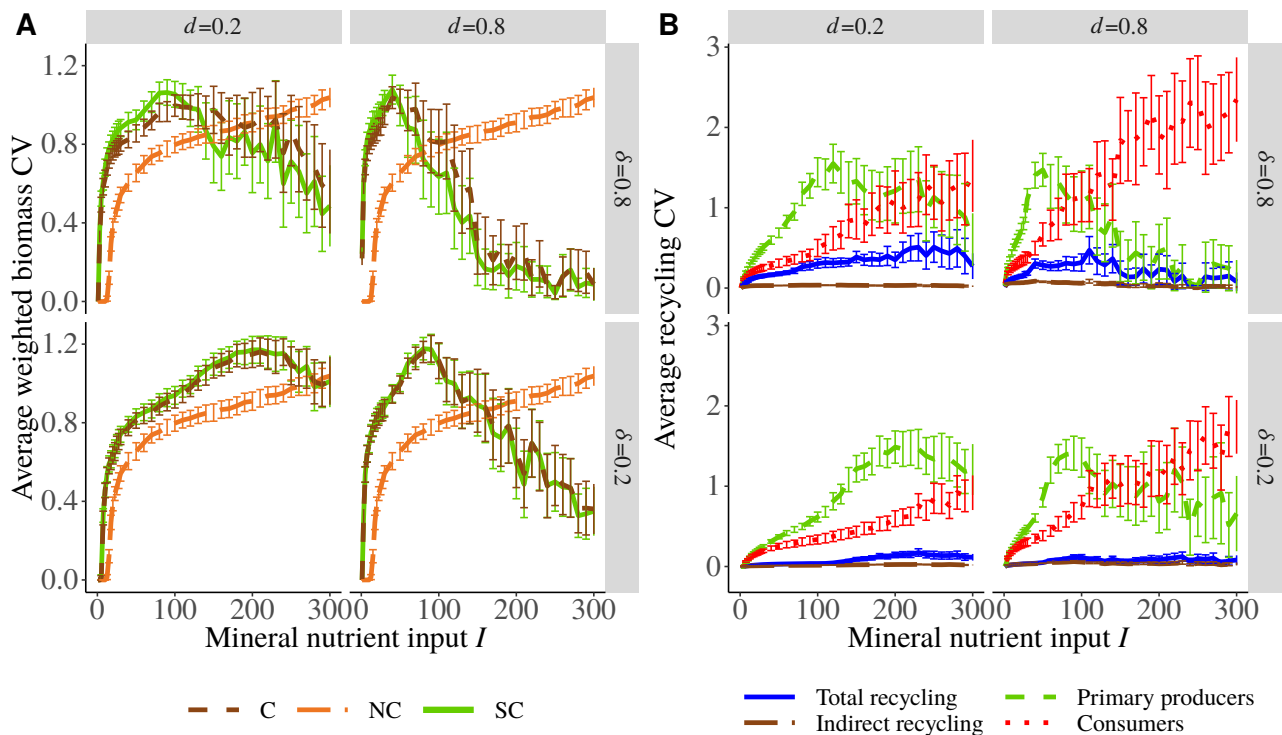


**Figure 3.** Food web responses to a nutrient enrichment gradient (increasing  $I$ ) as a function of recycling parameters  $d$  (decomposition rate) and  $\delta$  (proportion of direct recycling). **A)** Average quantity of nutrients recycled directly by consumers (red), primary producers (green) and indirectly recycled (brown) in C food webs. The dashed line (with a slope equal to 1) represents cases where the average quantity of recycled nutrients is equivalent to the external nutrient input  $I$ . Only food webs where at least one species persists are kept. **B)** Effects of nutrient cycling on species persistence (proportion of surviving species at the end of simulations). The brown dashed curve represents the C food webs with nutrient cycling ( $\delta > 0$ ,  $d > 0$ ), the orange long-dashed curve represents the NC food webs without nutrient cycling and the green solid curve represents the SC food webs without nutrient cycling but with a mineral nutrient input simulating the enrichment effect of nutrient cycling in the C food web. 100 different food webs randomly generated are tested for each combination of parameters. Outputs are then averaged and the error bars represent the confidence intervals of the mean.

Nutrient cycling contributes to an important part of the total mineral inputs of nutrients in the food web, and its contribution increases with the levels of external inputs of nutrients (Fig. 3A), in parallel with variations of primary and secondary productions (see Fig. S2-4B in supporting information). In this study case, nutrient cycling always represents larger inputs of nutrients to the food web than external inputs (Fig. 3A). At low nutrient enrichment levels, consumers are responsible for a significant part of direct recycling (see Fig. S2-3A in supporting information) and indirect recycling as they release more than 50% of detritus (see Fig. S2-3B in supporting information). However, at high nutrient enrichment levels, the quantity of nutrient directly recycled by consumers stops increasing while the total quantity of nutrient recycled still increases linearly with the external nutrient input  $I$  due to a large increase in the quantity of nutrient directly cycled by primary producers. Similarly, consumer biomass production is relatively important at low external nutrient input  $I$  while primary production is dominant and increases linearly with  $I$  at high

inputs (see Fig. S2-4B in supporting information).

Nutrient cycling affects the food web response to nutrient enrichment (*i.e.* external nutrient inputs  $I$ ). First, it affects the relationship between species persistence and nutrient enrichment (Fig. 3B). In food webs with and without nutrient cycling, persistence follows a hump-shaped relationship with external nutrient input  $I$ : first there is a sharp increase of the persistence for low nutrient inputs, then a plateau with maximum persistence and finally a decrease of the persistence for high nutrient inputs. However, maximum persistence is reached for lower input values and effects of enrichment are sharper for the case with nutrient cycling (C) than for the case without nutrient cycling (NC). These sharp changes in species persistence along the gradient of nutrient enrichment are paralleled by strong changes in food web maximum trophic level with an increase and then a decrease of the maximum trophic level with increasing external nutrient input  $I$  (see Fig. S2-2B and S2-2C in supporting information).



**Figure 4.** Responses of species and recycling temporal variability to a nutrient enrichment gradient (increasing  $I$ ) as a function of recycling parameters  $d$  (decomposition rate) and  $\delta$  (proportion of direct recycling). **A**) Effects of nutrient cycling on the average weighted coefficient of variation (CV) of species biomass. CVs are weighted by the contribution of the biomass of each species to the total biomass ( $CV_i \times B_i / B_{tot}$ ). **B**) Average CV of nutrient recycled in total (solid blue), indirectly recycled (long-dashed brown), directly by primary producers (dashed green) and directly by consumers (dotted red) in C food webs. Only food webs with at least one persisting consumer (and consequently at least one persisting primary producer) are kept for calculations. 100 different food webs randomly generated are tested for each combination of parameters and the error bars represent the confidence intervals of the mean.

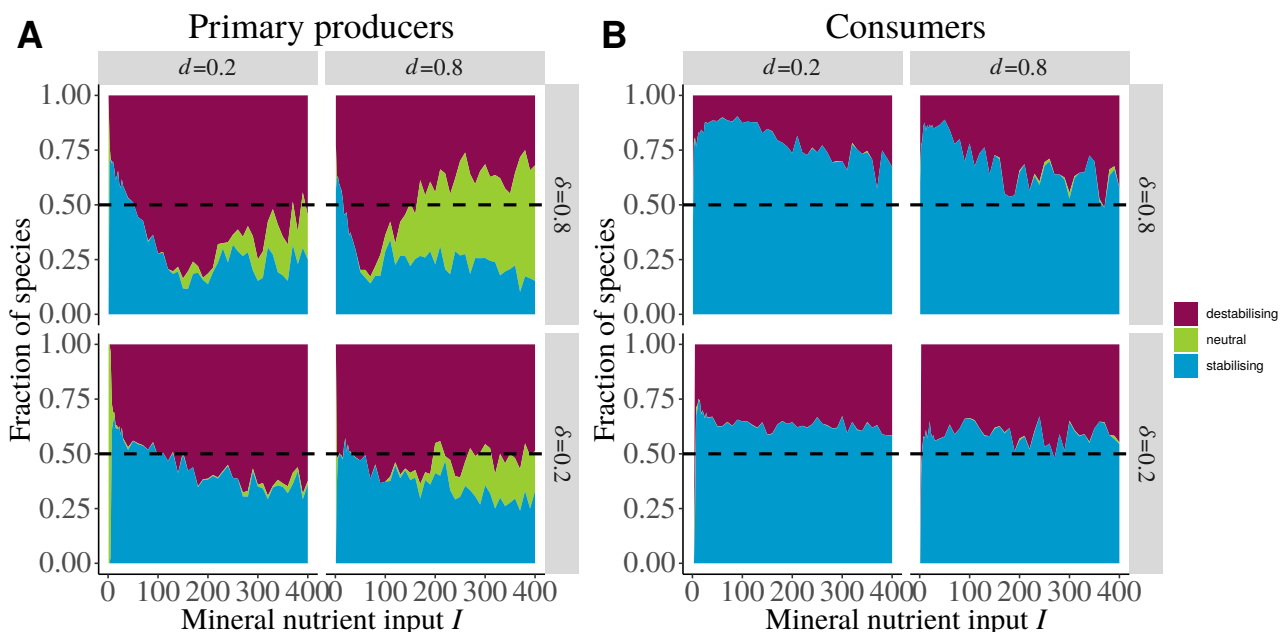
Second, nutrient cycling affects the relation between the average coefficient of variation (CV) of the species biomass and nutrient enrichment (Fig. 4A). As for species persistence, the average species biomass CV first increases and then decreases with increasing external mineral nutrient inputs. This decrease is due to the existence of food webs where only primary producers survived, leading to constant biomasses (see Fig. S2-2D in supporting information). As for species persistence (Fig. 3B), maximum biomass CV is reached for lower input values without nutrient cycling (NC) than for the case with nutrient cycling (C). The CV of the quantity of recycled nutrients (Fig. 4B) and of the nutrient stock (Fig. S2-2A in supporting information) follow a hump-shaped relation with external nutrient input  $I$  but the temporal variability of the quantity of recycled nutrients is about 25 times smaller than the CV of species biomass (see also Fig. S2-1A and S2-1B in supporting information).

## Overall influence of the recycling parameters

Increasing the decomposition rate  $d$  and the fraction of directly recycled nutrients  $\delta$  always increases the quantity of recycled nutrients in the food web (Fig. 3A), leading to greater inputs of nutrients through recycling than external inputs.  $d$  and  $\delta$  both increase the quantity of directly recycled nutrients while only  $d$  increases the quantity of indirectly recycled nutrients. In fact, the detritus stock does not depend on recycling parameters (see Fig. S2-4D in the supporting information) and the mineral nutrient stock is always controlled by primary producers and their quantity is negligible compared to detritus. Thus, the external nutrient input  $I$  is mainly balanced by the loss from detritus  $\ell D$ , leading at equilibrium to  $D^* = I/\ell$  that does not depend on  $d$  and  $\delta$ . Therefore, the average quantity of indirectly recycled nutrients is equal to  $dD^*$ .

Both  $d$  and  $\delta$  affect the relationship between external nutrient input  $I$  and species persistence or species biomass CV (Fig. 3B and 4A). At high  $d$  and  $\delta$ , the increase and decrease of species persistence and biomass CV with increasing nutrient input  $I$  are sharper. However, the general response of the food web remains qualitatively unchanged. In addition, unlike  $d$ , high values of  $\delta$  amplify the destabilising and stabilising effects of feedback loops on primary producer (Fig. 5A) and consumer (Fig. 5B) dynamics respectively (this aspect is detailed in the following). Finally, increasing  $\delta$  increases the CV of the total quantity of recycled nutrients (Fig. 4B) by increasing the contribution of direct recycling (Fig. 3A) that has a higher CV than indirect recycling.

## Effects of nutrient cycling: enrichment vs feedback loop



**Figure 5.** Effect of nutrient cycling on biomass CV at species level. For each combination of parameters, the biomass CV of persisting species is compared between C and SC food webs with the same species. If the CV is higher in the SC food web (without nutrient cycling but with a mineral nutrient input simulating the enrichment effect of nutrient cycling) than in the C food web (with nutrient cycling) with a threshold set at  $10^{-4}$ , then nutrient cycling feedback loops have a stabilising effect on dynamics. We have the same conclusion if the species get extinct in the SC food web and not in the C food web. The fraction of stabilised or destabilised **A)** primary producers and **B)** consumers among all simulated food webs gives the overall effect of nutrient cycling feedback loops at species level.

The comparison between the case with nutrient cycling (case C) and the case without nutrient cycling but with a nutrient input simulating the enrichment effect of nutrient cycling (case SC) allows to separate the effects of nutrient cycling due to enrichment from those due to the creation of additional feedback loops from each trophic levels to the bottom of the food web. When we model food web dynamics without nutrient cycling but including the enrichment effect of nutrient cycling (*i.e.* SC case), the overall relationships between external nutrient inputs and species persistence or biomass CV are similar to those observed in presence of nutrient cycling (Fig. 3B and 4A). Indeed, the curves corresponding to C and SC strongly overlap. Most of the effects of nutrient cycling are thus due

to an enrichment effect caused by recycled nutrients. However, curves do not overlap perfectly for  $\delta = 0.8$ , the average species persistence is higher and species biomass CV is lower (at low nutrient input  $I$ ) in food webs with nutrient cycling (C model). This is emphasised in Fig. 5B (see also Fig. S2-5B-D in supporting information) where more than 50% of consumers from all simulated food webs put together have a lower CV in C food webs than in SC food webs (for  $\delta = 0.8$  and a low  $I$ ) while primary producers tend to have a higher biomass CV (Fig. 5A). For  $\delta = 0.2$ , less primary producers and consumers have respectively higher and lower biomass CVs in SC food webs but the trend seen for  $\delta = 0.8$  is still visible. The decomposition rate  $d$  weekly changes the fractions of species stabilised or destabilised by feedback loops compared to  $\delta$ . It only increases the fraction of primary producers that are not affected (Fig. 5A), probably because of the extinction of higher trophic levels (see also Fig. S2-2B in supporting information) for high external nutrient inputs. Indeed, this leads to food webs where only primary producers persist with constant biomasses whatever the presence or not of feedback loops.

## Discussion

By integrating nutrient cycling and trophic dynamics, our food web model allows to better link population dynamics and ecosystem functioning. Our food web model highlights that nutrient cycling strongly interacts with the paradox of enrichment following two main mechanisms. First, nutrient cycling effects are mostly due to the consecutive increased nutrient availability that promotes species persistence at low nutrient inputs but leads to species extinctions (characteristic of the paradox of enrichment) at high level of nutrient inputs. Second, feedback loops from each species to the bottom resource generated by nutrient cycling only weakly affect species biomass temporal variability beyond effects associated with nutrient enrichment. Recycling loops tend to slightly dampen the destabilising effect of nutrient enrichment due to nutrient cycling on consumer dynamics while they have the opposite effect on primary producer dynamics. These results are thoroughly discussed below and their sensitivity to the parameters (Table 1) is tested in Appendix S3.

### Paradox of enrichment in our food web model

In agreement with previous food web studies (Rall et al., 2008; Binzer et al., 2016), we observe two contrasting responses of species diversity and food web stability to increased external nutrient inputs. While higher nutrient availability consistently increases the temporal variability of species biomasses, it also increases species persistence in nutrient poor ecosystems (*i.e.* low external nutrient inputs) but decreases persistence at high inputs of nutrients. The increase in persistence at low nutrient inputs is likely due to the increased persistence of species at higher trophic levels (Fig. S2-2B and S2-2C in the supporting information). Higher trophic levels are known to require a sufficient ecosystem productivity (limited by nutrient availability) to meet their energetic requirement and persist (*e.g.* Oksanen et al. (1981); Abrams (1993); Leibold (1996)), which can explain why increased persistence is only found in our case for nutrient poor ecosystems. The observed increase in the amplitude of species biomass oscillations (*i.e.* increase of species CVs that destabilises species dynamics, see Fig. 4A) with increasing nutrient inputs is typical of the well-known paradox of enrichment (Rosenzweig, 1971; DeAngelis, 1992; Roy and Chattopadhyay, 2007; Rip and McCann, 2011). Such destabilising effects of nutrient availability on species dynamics might explain the decrease in species persistence we observe at high levels of nutrient inputs. Large oscillations of species biomass (Fig. S2-1A in the supporting information) caused by nutrient enrichment likely trigger species extinctions as their biomass might reach the extinction threshold value (Fig. S3-2 in the supporting information). This counteracts the positive effect of nutrient enrichment on persistence at low nutrient levels and results in an hump-shaped relationship between species persistence and nutrient enrichment. Thus, parameters determining the occurrence of limit-cycles in complex food webs should strongly determine food web response to increased external nutrient inputs as well as nutrient cycling. For instance, the scaling of the attack rate with predator and prey body masses strongly determines the occurrence of limit cycles (Pawar et al., 2019) and varies a lot between studies (Rall et al., 2008; Pawar et al., 2012). However, such differences do not change our main results as the C and SC models respond similarly whatever the values of our scaling constants (Fig. S3-5 in the supporting information). In accordance with our model results, the paradox of enrichment has been found in complex food web models with type II functional responses (Rall et al., 2008; Binzer et al., 2016). In case of type III functional responses (Fig. S3-7 in the supporting information) or high intraspecific

density dependence regulation (Fig. S3-4 in the supporting information), where no such destabilising effects occur (see also Rall et al. (2008)), our results show that persistence does not decline at high levels of nutrient availability. Adaptive foraging, as included in our study, does not affect the occurrence of the paradox of enrichment (Fig. S3-6 in the supporting information) as already observed by Mougi and Nishimura (2008) in a one predator-two prey model. Our results remain indeed qualitatively the same with and without adaptive foraging.

## Nutrient cycling and enrichment effects

Our results show that nutrient cycling mainly interacts with the paradox of enrichment through its impacts on nutrient availability in ecosystems. Indeed, the quantity of recycled nutrients is, in our model, from one to more than ten times larger than the external input of mineral nutrients (depending on the decomposition rate  $d$  and the fraction of direct recycling  $\delta$ ). This ratio is consistent with the flows measured for the biogeochemical nitrogen cycle in natural ecosystems (Gruber and Galloway, 2008; Fowler et al., 2013). Thus, nutrient cycling strongly amplifies food web response to external nutrient inputs: the effects described in the previous section are qualitatively similar with and without nutrient cycling but they occur for lower inputs when nutrient cycling is present. Two main mechanisms rule the enrichment effect of nutrient cycling.

First, factors increasing the recycling speed (*i.e.* higher decomposition rate  $d$  and fraction of direct recycling  $\delta$ ) lead to species persistence and CV values that are obtained for increased levels of nutrient inputs in food webs with a slower nutrient cycling. They thus amplify the enrichment effect of nutrient cycling and also interact with the paradox of enrichment. In fact, nutrient cycling has been shown to increase the total amount of mineral nutrient circulating in the ecosystem and primary production (DeAngelis, 1980; de Mazancourt et al., 1998; Barot et al., 2007; Loreau, 2010). In our model,  $d$  and  $\delta$  mainly rule the flows between compartments but weakly control compartment size. Indeed, the detritus compartment size does not depend on decomposition rate  $d$  (see Fig. S2-4D in the supporting information) and the total biomass is mostly related to external nutrient inputs and species persistence (see Fig. S2-4A in the supporting information). Thus, as compartment size does not depend on  $d$  and  $\delta$ , nutrients released by detritus decomposition ( $d$ ) or direct recycling ( $\delta$ ) must be compensated to keep the matter balance in the ecosystem. Given the absence of nutrient loss by the ecosystem from the species compartment and the small size of the mineral nutrient compartment (due to the control by primary producers), recycled nutrients must reflow in the species compartments. This leads to an increase of biomass production (see Fig. S2-4B in the supporting information), compensated by an increased mortality due to density dependent self-regulation (see Fig. S2-4C in the supporting information) that leads to an increased quantity of recycled nutrients that fuels biomass production and so on. This suggests that the impact of nutrient cycling partly arises in our models from complex interactions between the speed of recycling and nutrient losses (see Fig. S3-3 in the supporting information). These interactions should be further disentangled through new simulations manipulating independently rates of mineral nutrient and detritus loss that are set equal in our model while higher losses for mineral nutrients than for detritus would be more realistic, at least in terrestrial ecosystems. In addition, density dependent mortality seems to have a strong quantitative impact on nutrient cycling in our model. Although it does not affect the qualitative response of species persistence and biomass CV to nutrient enrichment (see Fig. S3-4 in the supporting information), it drastically increases the quantity of nutrients flowing out of the species compartment and then through the entire ecosystem. Other mechanisms limiting species biomass such as predator interference in the Beddington-DeAngelis functional response (Beddington, 1975; DeAngelis et al., 1975) decrease the net growth rate by reducing the resource uptake rate instead of increasing the death rate. As a consequence, such a mechanism would lead to reduced nutrient flows in the ecosystem, thus changing nutrient cycling. Such effects of population dynamics modelling on ecosystem functioning must be explored in future studies.

Second, the amount of recycled nutrients depends on food web structure (relative importance of the trophic levels and the food chain length) and strongly depends on primary production, which increases linearly with nutrient inputs (Loreau, 2010). In fact, nutrient uptake by producers necessarily balances nutrients recycled from all trophic levels at equilibrium (see Fig. S2-4B and S2-4C in the supporting information). At low nutrient inputs, consumers are the main contributors to nutrient cycling, in agreement with experimental and empirical studies (Vanni, 2002; Schmitz et al., 2010) (see Fig. S2-3 in the supporting information). While nutrients recycled per unit of biomass due to

species metabolism are lower for consumers because of their larger body mass, consumers also strongly contribute to recycling through nutrient losses associated to feeding inefficiency. This is particularly true for herbivores whose assimilation efficiency is low ( $e_{ij} = 0.45$ ) so that they produce a lot of detritus by consuming primary producers (see Fig. S2-3B in the supporting information). This is also emphasised by previous ecosystem models (Leroux and Loreau, 2010; Krumins et al., 2015). However, at high nutrient input, food webs are dominated by primary producers (see Fig. S2-4A in the supporting information) that become the main contributors to nutrient cycling. In such case, primary producers release large amounts of detritus and nutrients due to high metabolic rates and large density dependent mortalities (see Fig. S2-4C in the supporting information).

Food web structure influences nutrient cycling through other already identified mechanisms pertaining to the quality of the produced detritus that are not included in our model. In real ecosystems, the fraction of direct recycling and the degradability of detritus can be controlled by the trophic structure of the food web. In aquatic ecosystems, top predators such as fish produce large quantities of highly degradable detritus (Harrault et al., 2012) that sustain a higher biomass of phytoplankton and zooplankton (Vanni and Layne, 1997; Harrault et al., 2014). In terrestrial ecosystems, herbivores also produce excrements that are easily degraded by the soil community and lead to an increase of the primary production (McNaughton, 1984; Belovsky and Slade, 2000). Primary producers can also strongly influence decomposition. In terrestrial ecosystems, plant leaf traits affect the composition and the quality of the litter (Cornwell et al., 2008). Primary producer stoichiometry is also highly variable both between and within species (Sternner et al., 2002; Dickman et al., 2006; Danger et al., 2007, 2009; Mette et al., 2011), which affects detritus quality and stoichiometry. While our results remain qualitatively robust to different values of C:N ratios of primary producers (see Fig. S3-8 in the supporting information), the links between food web structure and the degradability of detritus might strongly influence food web response to nutrient enrichment through their impact on nutrient availability. In addition, primary producer stoichiometry can be a flexible trait responding to nutrient limitation or herbivory, which can limit herbivore assimilation efficiency (Branco et al., 2018), thus affecting the energy transfer in the food chain. Including these mechanisms would thus need to be tested in new versions of our model.

## Nutrient cycling and effects of feedback loops

Though we found that nutrient cycling mostly interacts with the paradox of enrichment through an enrichment effect, we also found small effects of nutrient cycling on biomass dynamics through feedback loops from all trophic levels to mineral nutrients. These effects consist in the decrease in the temporal stability of the biomass of up to 75% of consumers in C models (with nutrient cycling) compared to SC models (without nutrient cycling but with an equivalent enrichment effect) (Fig. 5). In fact, primary producers tend to be destabilised while most of the consumers from all trophic levels are stabilised (see Fig. S2-5 in the supporting information). In addition, more species have their biomass dynamics stabilised by nutrient cycling if the fraction of direct recycling  $\delta$  is high and external inputs  $I$  are low. In fact, indirect recycling keeps nutrient unavailable for primary producers and tends to smooth nutrient cycling dynamics (see Fig. S2-1B and S2-1D in the supporting information). In contrast, direct recycling shortens feedback loops and then increases the coupling between each trophic levels and mineral nutrients. Such a coupling can be seen in the increased biomass CV difference between the C and SC models (see Fig. S2-6 in the supporting information) and in the increase of the total quantity of recycled nutrient CV due to the larger contribution of species direct recycling that have high CV. To try to understand better the responses of biomass dynamics to nutrient cycling feedback loops we built a food chain model (with the same parametrisation as in our food web model) to track the dynamics of each element of the system. Even if the response of biomass repartition (see Fig. S2-8 in the supporting information) and quantity of recycled nutrient (see Fig. S2-9 in the supporting information) to nutrient enrichment  $I$ , decomposition rate  $d$  and fraction of direct recycling  $\delta$  are similar to the food web model, the effects of feedback loops on dynamics are different. The response of each trophic level depends on food chain length but the case with four species is more representative of our food web model where the maximum trophic level is equal to four for intermediate nutrient input  $I$  (see Fig. S2-2B and S2-2C). Unlike in our food web model, primary producers are stabilised by feedback loops while all consumer are destabilised (see Fig. S2-11C in the supporting information). Thus, mechanisms acting in food chain models, such as the predator increasing resource uptake by prey (Brown et al., 2004a), which in turn boosts primary production and reduces the unbalance between species growth rates and loss rates (Rip and McCann, 2011),

do not seem to be involved in our food web model.

One important difference between the food chain and the food web models correspond to the biomass CV difference between the SC and C cases, which is actually larger in the food chain model than in the food web model. In the food web model, the CV of the total quantity of recycled nutrients is smaller by roughly one order of magnitude compared to the average species biomass CV. Nutrient cycling is the outcome of the aggregated nutrient loss from numerous species whose dynamics are not synchronous, which leads to compensation effects: when the biomasses of some species decrease, the biomasses of other species likely increase, thus keeping the total biomass and the total quantity of recycled nutrients less variable (see Fig. S2-1 and S2-7 in the supporting information). This effect is strengthened by the detritus compartment that mixes all detritus released by species and releases them at a fixed rate  $d$ , thus explaining the lower CV of the quantity of recycled nutrients at low fraction of direct recycling  $\delta$ . As nutrient cycling appears to be relatively constant over time compared to species biomass dynamics, mimicking it with a constant nutrient input  $I_{recy}$  as in SC food webs leads to dynamics similar to those of the C food webs. Theory predicts that species diversity stabilises aggregated ecosystem properties through asynchronous species dynamics (Doak et al., 1998; Gonzalez and Loreau, 2008; Loreau and de Mazancourt, 2013). This rationale is supported by numerous experimental studies showing that aggregated ecosystem processes, such as primary production (Tilman, 1996; Tilman et al., 2006; Schläpfer and Schmid, 1999; Loreau, 2000; Hooper et al., 2005) or dead biomass decomposition (Knops et al., 2001; Keith et al., 2008; Gessner et al., 2010; Nielsen et al., 2011) are more stable over time than individual species dynamics and that this stability increases with the number of species. While the asynchrony linked to biodiversity seems to deeply impact the effect of nutrient cycling on food web dynamics, nutrient cycling does not affect synchrony between the biomass dynamics of species. In fact, the asynchrony between primary producer species and consumer species is not significantly modified by the presence of feedback loops (see Fig. S2-7B in the supporting information) in the food web model. Overall, our results suggest that simplicity emerges from food web dynamics, making the prediction of the impact of nutrient cycling on ecosystem functioning easier in complex food webs than in food chains. Barbier et al. (2018) found that food web properties such as biomass distribution among species can be predicted thanks to the statistical distribution of species physiological and ecological parameters. From their results, adding the statistical distribution of recycling parameters ( $\delta$  is fixed in our study but it must vary between species) would enable us to evaluate the quantity of recycled nutrients  $I_{recy}$  and thus to predict ecosystem functioning just by knowing the overall characteristics of the community living in the ecosystem.

To sum up, our food chain and food web models respond differently to the presence of nutrient cycling loops, making the understanding of the underlying mechanisms difficult. Therefore, new models based on simple food chains and manipulating both food chain length and horizontal diversity are needed to fully understand the effects of nutrient cycling on dynamics. More generally, our results also suggest that positive effects of biodiversity on ecosystem stability might also occur through nutrient cycling. To the best of our knowledge, this hypothesis has never been fully tested in biodiversity experiments and could lead to a new research avenue. Moreover, new studies based on stochastic perturbations as in Shanafelt and Loreau (2018) would bring knowledge on the effects of nutrient cycling on other components of the stability of food chains and food webs. While previous studies suggesting that feedback loops generated by nutrient cycling are destabilising (DeAngelis, 1980), our preliminary results from our food chain model suggest that nutrient cycling can have stabilising or destabilising effects on species biomass dynamics depending on trophic levels and food chain length for instance. This discrepancy likely arises from these former results being based on a different stability measure (*i.e.* resilience instead of temporal variability) and because previous studies did not separate enrichment effects from feedback loop effects of nutrient cycling.

## Conclusion and perspectives

We identified two distinct effects of nutrient cycling. First, an enrichment effect due to the recycled nutrients that increase species persistence at low nutrient inputs by increasing resource availability but leads to a decrease in species persistence through a paradox of enrichment at higher nutrient inputs. Second, feedback loops that link each trophic level to the mineral resource through nutrient cycling increase primary producer biomass CV and decrease consumer



biomass CV compared to food webs with similar nutrient availability but without recycling. However, this effect is weak in complex food webs where the effect of nutrient cycling mainly consists in a nutrient enrichment. Thus, ecologists should consider nutrient cycling in theoretical and empirical work to better predict food web response to nutrient inputs as nutrient cycling deeply changes the overall nutrient availability.

Real ecosystems are known to differ by their dependence on external inputs of mineral nutrients (Polis et al., 1997; Vadeboncoeur et al., 2003; Jickells, 2005; Bokhorst et al., 2007), and ecosystems relying less on such inputs likely depend more on nutrient cycling than ecosystems depending more on external inputs. Therefore, nutrient cycling, as suggested by our results, could influence the food webs of these ecosystems in contrasted ways. For example, in ecosystems such as eutrophic lakes (Vadeboncoeur et al., 2003) with high inputs of nutrients, nutrient cycling could mostly have a general negative effect by promoting species extinction while it could have a positive effect in ecosystems with low inputs of nutrients such as Antarctic terrestrial ecosystems (Bokhorst et al., 2007) or infertile landscapes (Hopper, 2009). In the same vein, in ecosystems with efficient nutrient cycling, nutrient losses are low so that nutrient cycling represents a very important source of nutrient and more likely leads to negative effects if the ecosystem already receives abundant external nutrient inputs.

Experiments designed to test the effects of the mechanisms involved in our model would be interesting. For example, it would be possible in mesocosms to manipulate both inputs of mineral nutrients and the efficiency of nutrient cycling (Harrault et al., 2014), e.g. exporting an increasing proportion of detritus, and to measure the response in terms of food web functioning and population dynamics. It would also be interesting to compare food webs of different types of natural ecosystem with contrasting nutrient cycling and mineralisation rates. Typically, our model probably better corresponds to an aquatic food web (*i.e.* fully size-structured web) and aquatic and terrestrial food webs should be compared.

Even if the detritus compartment affects the effects of nutrient cycling on food webs, its role cannot be fully appreciated in our model because there are no decomposers and no brown food web. In fact, detritus are more than a transient pool for nutrients since, in real food webs, they are resources for decomposers and are recycled through the whole brown food web (Moore et al., 2004). Another important step will be to include in models a true brown food web containing decomposers feeding on detritus in parallel to the green food webs relying on photosynthesis (Moore et al., 2004; Zou et al., 2016). The interactions between green and brown food webs are conditioned by stoichiometric constraints on primary producers and detritus that affect the competition/mutualist interactions between primary producers and decomposers (Daufresne and Loreau, 2001; Cherif and Loreau, 2013; Zou et al., 2016)

To go further, the flexible stoichiometry of primary producers (and phytoplankton in particular) can also deeply affect food web dynamics and consumer persistence as it can limit herbivore assimilation efficiency (Loladze et al., 2000; Branco et al., 2018). In fact, Urabe and Sterner (1996) demonstrated experimentally that increasing light availability first increases phytoplankton and zooplankton biomass productions but then led to zooplankton extinction because of the low nutritional quality of phytoplankton biomass if the light to nutrient ratio was too high.

Thus, stoichiometric constraints and green and brown food web interactions can deeply change the functioning and the stability of ecosystems (Daufresne and Loreau, 2001; Moore et al., 2005; Attayde and Ripa, 2008; Zou et al., 2016) but these results have so far not been tested in complex food web models.

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## Supporting information, data and code accessibility

The supporting information (see Supporting\_information\_final.pdf) contains the following section:

- S1 Appendix - Parameter calculation
- S2 Appendix - Complementary results
- S3 Appendix - Sensitivity analysis

The C++ code of the simulations and the R code of the figures are available on Zenodo (doi:10.5281/zenodo.3697083).

## Conflict of interest disclosure

The authors of this preprint declare that they have no financial conflict of interest with the content of this article. Sébastien Barot and Élisabeth Thébault are PCI Ecology recommenders.

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## Interplay between the paradox of enrichment and nutrient cycling in food webs

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### S1 Appendix - Parameter calculation

#### Allometric parameter calculation

The value of the primary producers growth rate was taken from Savage et al. (2004) and Binzer et al. (2012):

$$r_i = e^{I_r} M_i^{-1/4} e^{E a_r (T_0 - T / k T T_0)} \quad (11)$$

$e^{I_r}$	allometric scaling constant at 20°C ( $g^{1/4} \cdot s^{-1}$ )
$M_i$	
$e^{E a_r (T_0 - T / k T T_0)}$	
	body mass ( $g$ )
	temperature dependency term

We considered that temperature was constant at 20°C (thus  $T = T_0$ ) and with  $I_r = -15.68$  (Binzer et al., 2012) we have:

$$r_i = r M_i^{-1/4} \quad (12)$$

With  $r = 0.87 \text{ kg}^{1/4} \cdot \text{year}^{-1}$ . Metabolic rates were taken from Brose et al. (2006b) and Brose (2008) with  $x/r = 0.138$  for primary producers,  $x/r = 0.314$  for invertebrates and  $x/r = 0.88$  for ectotherm vertebrates. Since we did not apply the time scale normalisation by the growth rate of primary producers as done in Brose et al. (2006b), we have  $x = 0.12$  for primary producers,  $x = 0.27$  for invertebrates and  $x = 0.78$  for ectotherm vertebrates. We used the values for invertebrates for consumers in our simulations.

#### Handling time

In this model, the handling time  $h_{ij}$  also follows an allometric scaling. We used the expression defined by Petchey et al. (2008) and also used by Thierry et al. (2011). The original expression has been divided by prey body mass to have a mass specific allometric parametrisation:



$$h_{ij} = \begin{cases} \frac{h_i}{b - \frac{M_j}{M_i}} \frac{1}{M_j} & \text{if } \frac{M_j}{M_i} < b \\ \infty & \text{if } \frac{M_j}{M_i} > b \end{cases} \quad (13)$$

$h_i$	allometric scaling constant ( $year \cdot kg^{-1}$ )
$b$	maximum predator-prey body mass ratio (0.05)
$M_i$	body mass of the predator ( $kg$ )
$M_j$	body mass of the prey ( $kg$ )

The maximum prey-predator body mass ratio  $b$  delimits the diet breadth. The handling time function is U-shaped (Fig. S1-1) if the predator-prey body mass ratio is below  $b$ , otherwise the handling time tends to infinity and the prey is not consumed by the predator. Unfortunately, no values of the allometric scaling constant  $h_i$  could be found in the literature. However, the maximum ingestion rate  $y_i$  is well quantified (Yodzis and Innes, 1992; Brose et al., 2006b; Vucic-Pestic et al., 2010) and corresponds to the reverse of the handling time. Following Brose et al. (2006b), the ingestion rate is set proportional to the metabolic rate:

$$y_i = yx_i \quad (14)$$

With  $y = 8$  for invertebrates and  $y = 4$  for ectotherm vertebrates. Then, we assumed that the values from Brose et al. (2006b), which do not depend on the body mass of the prey, are the average over all possible prey body masses (interval  $[0, bM_i]$  defined in equation 13). Thus, we can state that:

$$y_i = \frac{1}{bM_i} \int_0^{bM_i} \frac{1}{h_{ij}} dM_j \quad (15)$$

Thus, by replacing  $h_{ij}$  by the expression from equation 13:

$$\begin{aligned} y_i &= \frac{1}{bM_i} \int_0^{bM_i} \frac{1}{\frac{h_i}{b - \frac{M_j}{M_i}} \frac{1}{M_j}} dM_j \\ &= \frac{1}{h_i b M_i} \int_0^{bM_i} \left(b - \frac{M_j}{M_i}\right) M_j dM_j \\ &= \frac{1}{h_i b M_i} \left[ \frac{bM_j^2}{2} - \frac{M_j^3}{3M_i} \right]_0^{bM_i} \\ &= \frac{b^2 M_i}{6h_i} \end{aligned} \quad (16)$$

Thus:

$$h_i = b^2 M_i / 6y_i \quad (17)$$

And by replacing  $h_i$  in equation 13 by the expression found in equation 17:

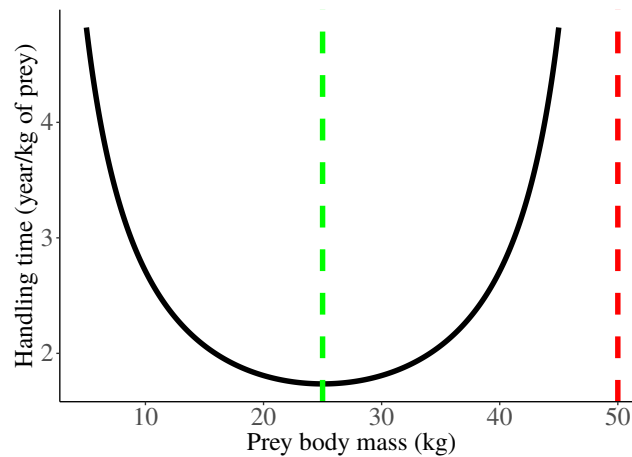
$$h_{ij} = \frac{b^2}{6y_i} \frac{M_i}{\left(b - \frac{M_j}{M_i}\right) M_j} \quad (18)$$

$y_i$  is defined as in equation 4a:

$$y_i = yM_i^{-1/4} \quad (19)$$

$y$  | allometric scaling constant ( $kg^{1/4} \cdot year^{-1}$ ) expressed as  $8 \cdot x$  (Brose et al., 2006b)  
 $M_i$  | body mass of the organism ( $kg$ )

Handling time is minimum for  $M_j = \frac{b}{2}M_i$ . The value of the maximum predator-prey body mass ratio  $b$  is set to 0.05 so that the handling time is minimal for prey 40 times smaller than their predators. This value is consistent with the average predator-prey body mass ratio found by Brose et al. (2006a). To limit the number of equations, the interactions involving prey out of the interval  $[0.1bM_i, bM_i]$  were neglected.



**Figure S1-1.** Handling time as a function of prey body mass ( $b = 0.05$ ,  $M_i = 1000kg$ ). The red dashed line represents the upper limit of prey body mass that predators can handle ( $M_i/M_j < b$ ) and the green dashed line represents the optimal prey body mass minimising the handling time ( $M_j = \frac{b}{2}M_i$ ).

## Stoichiometry and C:N ratios

The limiting nutrients considered in our model could be any mineral nutrient but we chose nitrogen to parametrise the carbon to nutrient ratio. C:N ratios were taken from data of pelagic communities (Anderson, 1992) with C:N=6.6 for primary producers (value for phytoplankton) and C:N=5 for consumers (average C:N ratios of bacteria (5.1), protozoa (5.5) and copepods (4.67)). The amount of nutrients released by consumers from non-assimilated prey biomass depends on both the C:N ratio of prey and consumers. The C:N ratio of non-assimilated biomass  $\alpha_{Dij}$  can be calculated by using the constraints on mass conservation and maintenance of species homeostasis (equation 9). The ingested biomass by consumer species  $i$  of prey species  $j$  contains a mass  $C_j$  of carbon and  $N_j$  of nutrients ( $\alpha_j = C_j/N_j$ ). A fraction  $e_{ij}$  of  $C_j$  is converted into a mass  $C_i$  of carbon of the consumer while the remaining fraction  $1 - e_{ij}$  is converted into a mass  $C_{Dij}$  of detritus. We define  $N_i$  as the assimilated mass of nutrients by the consumer ( $\alpha_i = C_i/N_i$ ) and  $N_{Dij}$  as the non assimilated mass of nutrients excreted in the detritus pool (with  $\alpha_{Dij} = C_{Dij}/N_{Dij}$ ). By mass conservation, we have the two following relations:

$$N_j = N_i + N_{Dij} \quad (20a)$$

$$C_j = C_i + C_{Dij} = e_{ij}C_j + (1 - e_{ij})C_j \quad (20b)$$

As the predator and the prey keep their C:N ratios  $\alpha_i$  and  $\alpha_j$  constant, we can derive the expression of  $\alpha_{Dij}$  as a function of  $e_{ij}$ ,  $\alpha_i$  and  $\alpha_j$ :

$$\frac{C_j}{\alpha_j} = \frac{C_i}{\alpha_i} + \frac{C_{Dij}}{\alpha_{Dij}} = \frac{e_{ij}C_j}{\alpha_i} + \frac{(1 - e_{ij})C_j}{\alpha_{Dij}} \quad (21)$$

$$\alpha_{Dij} = \frac{\alpha_j \alpha_i (1 - e_{ij})}{\alpha_i - \alpha_j e_{ij}}$$

## Adaptive foraging equation

We detail in this part the expression of  $\partial g_i / \partial \omega_{ik}$  that is part of equation (6).  $g_i$  is the total growth rate of species  $i$  and is defined as  $\frac{dB_i}{dt} = g_i B_i$ . However, we notice that :

$$\frac{\partial g_i}{\partial \omega_{ik}} = \frac{\partial}{\partial \omega_{ik}} \left( \sum_{\ell=prey} e_{i\ell} F_{i\ell} \right) \quad (22)$$

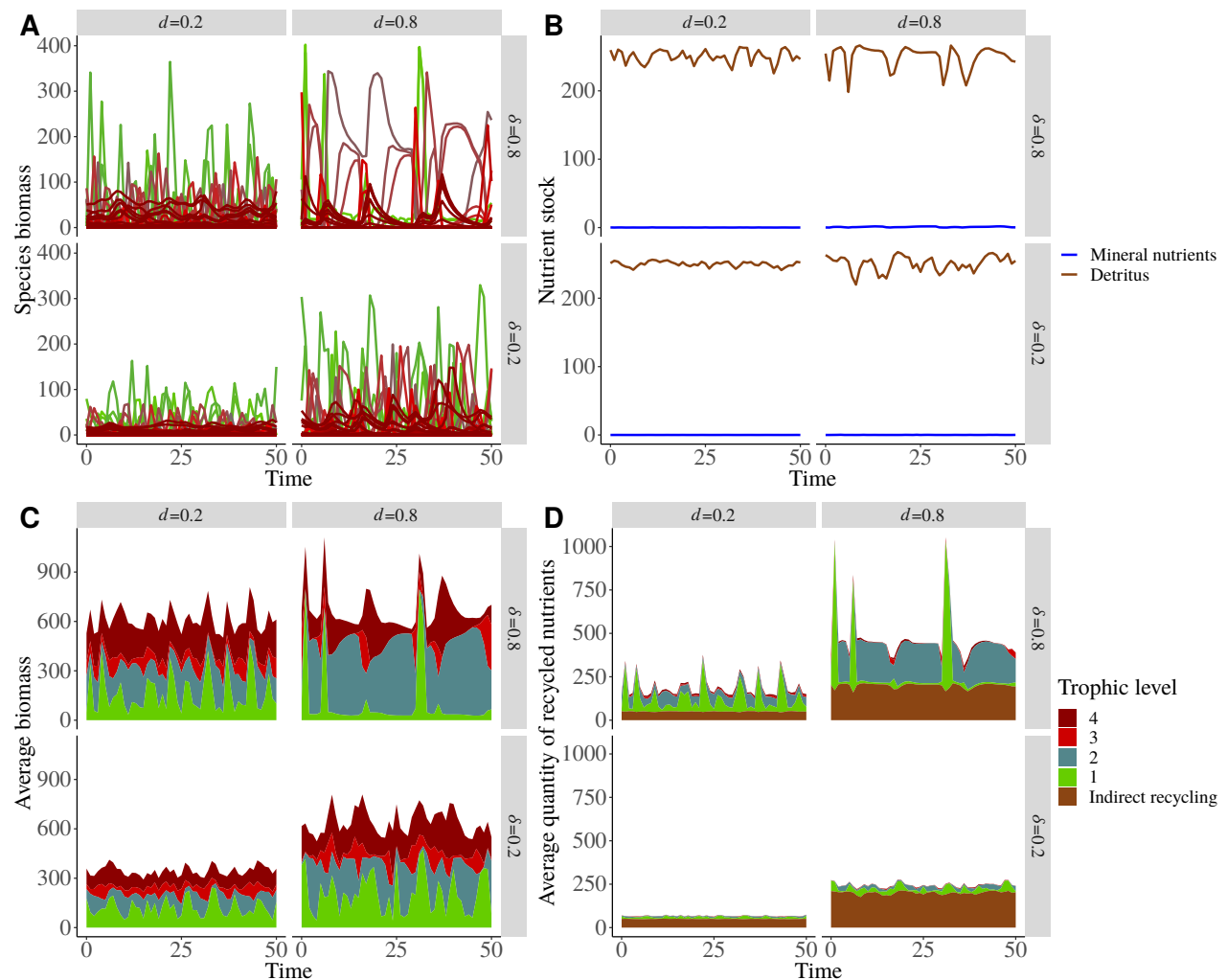
As only  $F_{i\ell}$  depends on  $\omega_{ik}$  in equation (3b). Thus:

$$\begin{aligned} \frac{\partial g_i}{\partial \omega_{ik}} &= e_{ik} \frac{\partial F_{ik}}{\partial \omega_{ik}} + \sum_{\ell \neq k} e_{i\ell} \frac{\partial F_{i\ell}}{\partial \omega_{ik}} \\ &= e_{ik} \left( \frac{a_i B_k (1 + \sum_m \omega_{im} a_i h_{im} B_m) - \omega_{ik} a_i B_k (a_i h_{ik} B_k)}{(1 + \sum_m \omega_{im} a_i h_{im} B_m)^2} \right) \\ &\quad + \sum_{\ell \neq k} \frac{e_{i\ell} \omega_{i\ell} a_i B_\ell (-a_i h_{ik} B_k)}{(1 + \sum_m \omega_{im} a_i h_{im} B_m)^2} \\ &= \frac{e_{ik} a_i B_k + \sum_m e_{ik} a_i^2 \omega_{im} h_{im} B_k B_m - e_{ik} a_i^2 \omega_{ik} h_{ik} B_k^2 - \sum_{\ell \neq k} e_{i\ell} a_i^2 \omega_{i\ell} h_{i\ell} B_k B_\ell}{(1 + \sum_m \omega_{im} a_i h_{im} B_m)^2} \\ &= \frac{e_{ik} a_i B_k + \sum_{m \neq k} e_{ik} a_i^2 \omega_{im} h_{im} B_k B_m - \sum_{\ell \neq k} e_{i\ell} a_i^2 \omega_{i\ell} h_{i\ell} B_k B_\ell}{(1 + \sum_m \omega_{im} a_i h_{im} B_m)^2} \\ &= \frac{a_i B_k \left( e_{ik} + \sum_{\ell \neq k} a_i \omega_{i\ell} B_\ell (e_{ik} h_{i\ell} - e_{i\ell} h_{ik}) \right)}{(1 + \sum_m \omega_{im} a_i h_{im} B_m)^2} \end{aligned} \quad (23)$$

## S2 Appendix - Complementary results

### Complex food webs

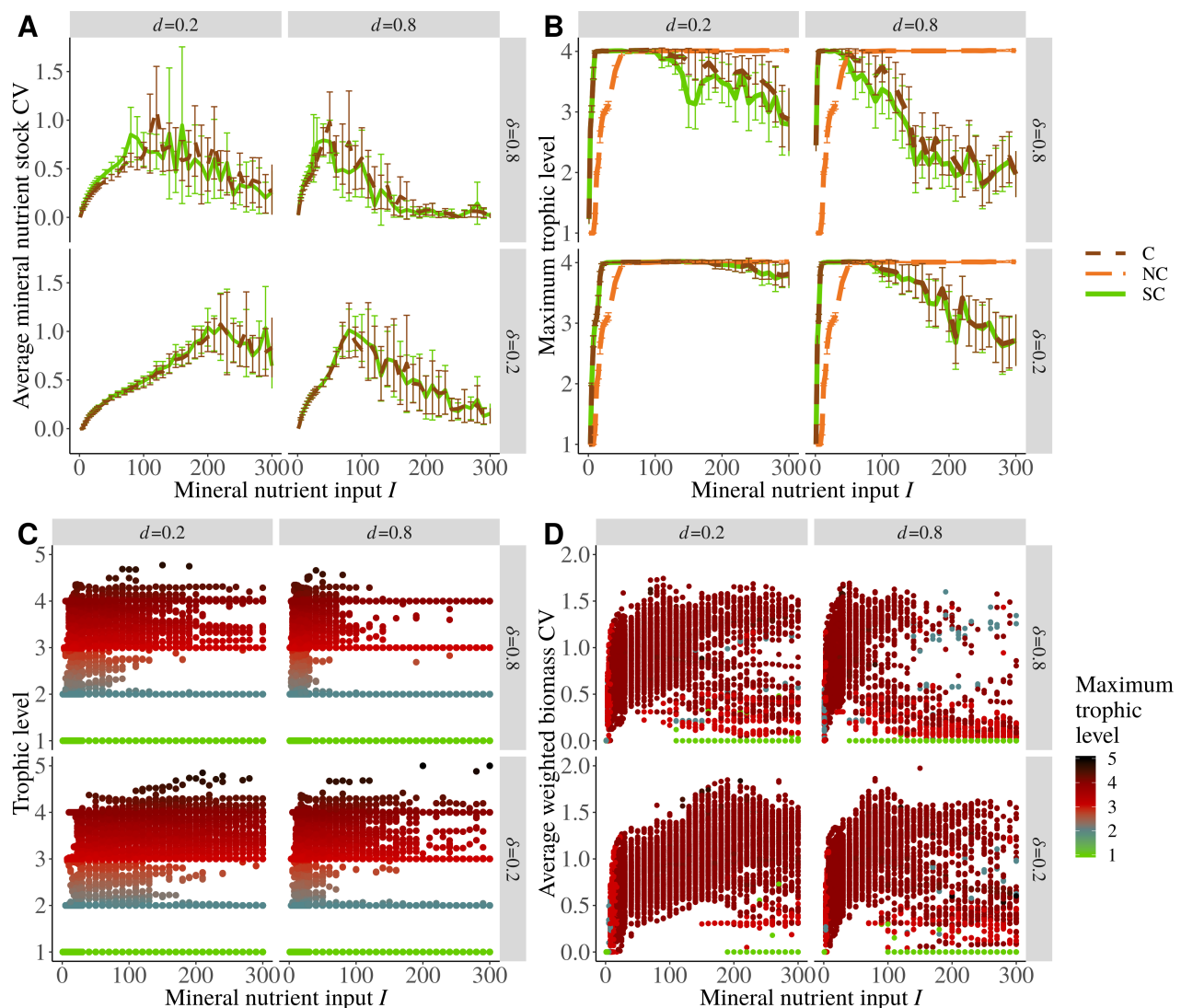
#### Overview of the dynamics of the food web



**Figure S2-1.** Dynamics of species biomasses, abiotic compartments and nutrients recycled in a C food web for  $I = 50$ . **A)** Biomass dynamics of each species. Lower trophic levels are in green and higher trophic levels are in dark red. **B)** Mineral nutrients (blue) and detritus (brown) dynamics. **C)** Species biomasses aggregated by trophic levels (from green to dark red areas). **D)** Nutrients directly recycled by species aggregated by trophic levels and indirectly recycled nutrients (brown area).

Our complex food web model generates highly variable species biomasses (Fig. S2-1A) while aggregated biomasses are relatively less variable (Fig. S2-1C). The quantity of recycled nutrients by each species is also highly variable while the total quantity of recycled nutrients is less variable (Fig. S2-1D). In addition, the aggregated quantities of recycled nutrients are more stable than the quantities of recycled nutrients at species level. We also observe that primary producers and herbivores are the main contributors to nutrient cycling (Fig. S2-1D) respectively because of their high biomass and their low assimilation efficiency ( $e_{ij} = 0.45$ ). The low contribution of the carnivores can be attributed to their high assimilation efficiency ( $e_{ij} = 0.85$ ) and their low metabolic rate due to their large body mass.

## Complementary results on species dynamics



**Figure S2-2.** Overall response of food webs to nutrient cycling and to an enrichment gradient  $I$  as a function of recycling parameters  $d$  (decomposition rate) and  $\delta$  (fraction of direct recycling). **A**) Average coefficient of variation of the mineral nutrient stock. The C food webs (dashed brown) are the food webs with nutrient cycling and the SC food webs (solid green) are the food webs without nutrient cycling but with a simulated enrichment due to nutrient cycling. **B**) Average maximum trophic level. The trophic level 1 corresponds to primary producers and NC food webs (long-dashed orange) are the food webs without nutrient cycling. **C**) Trophic level of each species in each simulated C food web. The colour gradient also represents the trophic levels (from primary producers in green to top predators in black). **D**) Average species biomass CV in each simulated C food web. The colour scale represents the maximum trophic level sustained by each simulated food web.

Nutrient stock CV (Fig. S2-2A) responds similarly to nutrient enrichment and nutrient cycling feedback loop presence than the CV of species biomass (Fig. 4A). Indeed, we first see an increase followed by a decrease with increasing mineral nutrient inputs  $I$ . In addition, we do not see significant differences between C food webs with nutrient cycling and SC food webs without nutrient cycling but with a simulated enrichment due to nutrient cycling, thus, nutrient cycling does not seem to modify the general variability of the mineral nutrient stock.

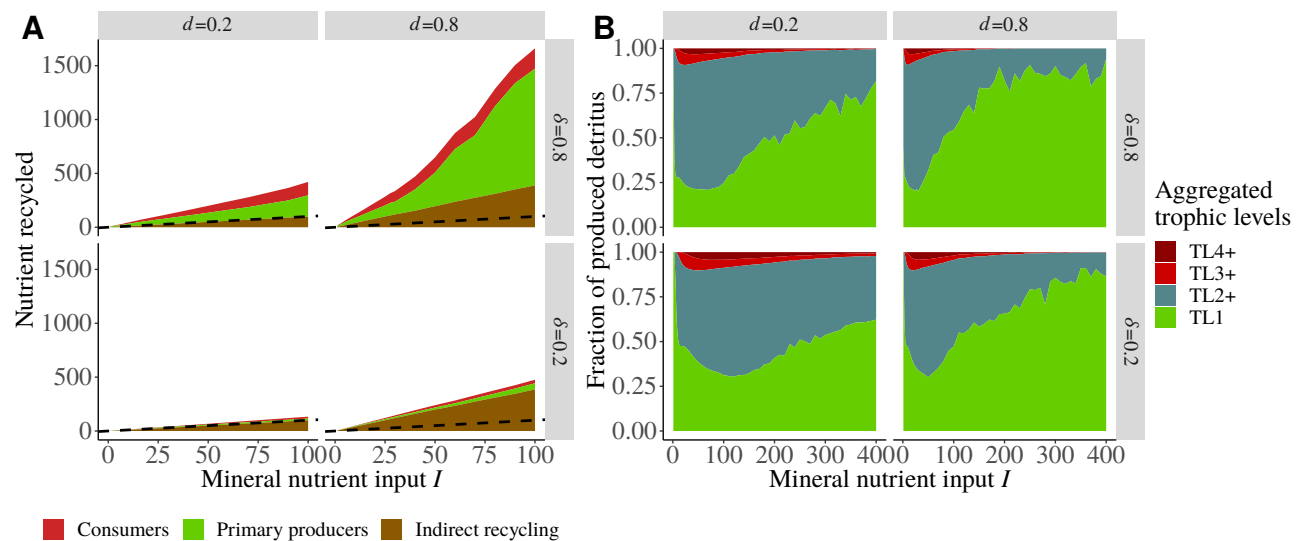
In food webs with nutrient cycling, maximum trophic level (Fig. S2-2B) follows a hump-shaped relationship with external nutrient inputs: first there is a sharp increase in food web maximum trophic level for low nutrient inputs, then a plateau and finally a decrease in food web maximum trophic level for high nutrient inputs. The decrease of the maximum trophic levels is correlated to the decrease of persistence, suggesting that higher trophic levels are the first species that get extinct due to the paradox of enrichment.

Fig. S2-2C describes the general distribution of trophic levels in simulated food webs. Lower trophic levels tend to be

well separated with consumer eating prey one trophic level below. The similar body masses of primary producers added to the constraint of the feeding niche must lead to this structure but we also notice that omnivory occurs more frequently in higher trophic levels.

The average CV of species biomass in a food web is correlated with the maximum trophic level of the food web (Fig. S2-2D). It is high when food webs have at least two trophic levels (and seems to be higher if high trophic levels persist), or it is null when food webs contain only primary producers as the system reaches fix points.

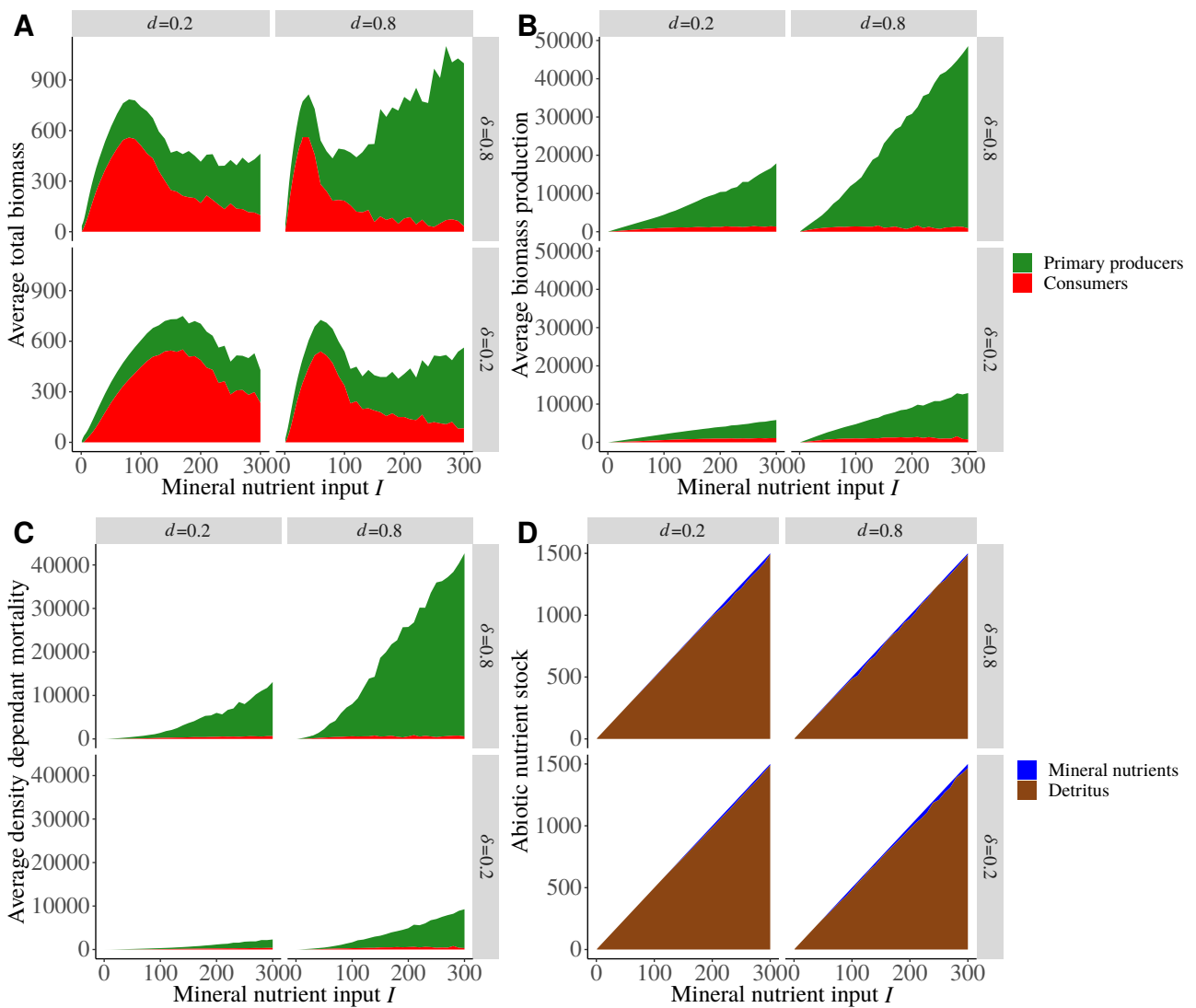
### Response of nutrient stocks and flows to nutrient enrichment



**Figure S2-3.** Detailed origins of recycled nutrients and detritus. **A)** Zoom in Fig. 3A for  $I \in [0, 100]$ . **B)** Fraction of detritus produced by each aggregated trophic level (fraction  $(1 - \delta)$  of indirect recycling plus fraction  $(1 - e_{ij})$  of non assimilated biomass, see equation (7b)). TL1 represents basal species (primary producers) and higher trophic levels are aggregated. Species with a trophic level comprised in the interval  $[i, i + 1[$  are in the group TL $i$ +. For instance, TL2+ gathers strict herbivores and omnivores eating both primary producers and herbivores.

As explained in the main text, the quantity of recycled nutrients increases with external nutrient inputs  $I$ , the fraction of direct recycling  $\delta$  and the decomposition rate  $d$  (Fig. S2-3A). In detail, primary producer and consumer contributions vary with  $I$ . At low nutrient inputs  $I$ , consumers contribute significantly to nutrient recycling as they have a high biomass (Fig. S2-4A). This must be explained by the high species persistence (Fig. 3B in the main text) combined with high trophic levels survival (Fig. S2-2B). Moreover, herbivores contribute strongly (Fig. S2-3B) to indirect recycling due to their low assimilation efficiency ( $e_i = 0.45$ ) that release a lot of detritus when they consume primary producer biomass. However, at high external inputs  $I$ , primary producers are responsible of most of direct (Fig. S2-3A) and indirect (Fig. S2-3B) recycling, due to their sheer biomass that is much higher than consumer biomass (Fig. S2-4A).

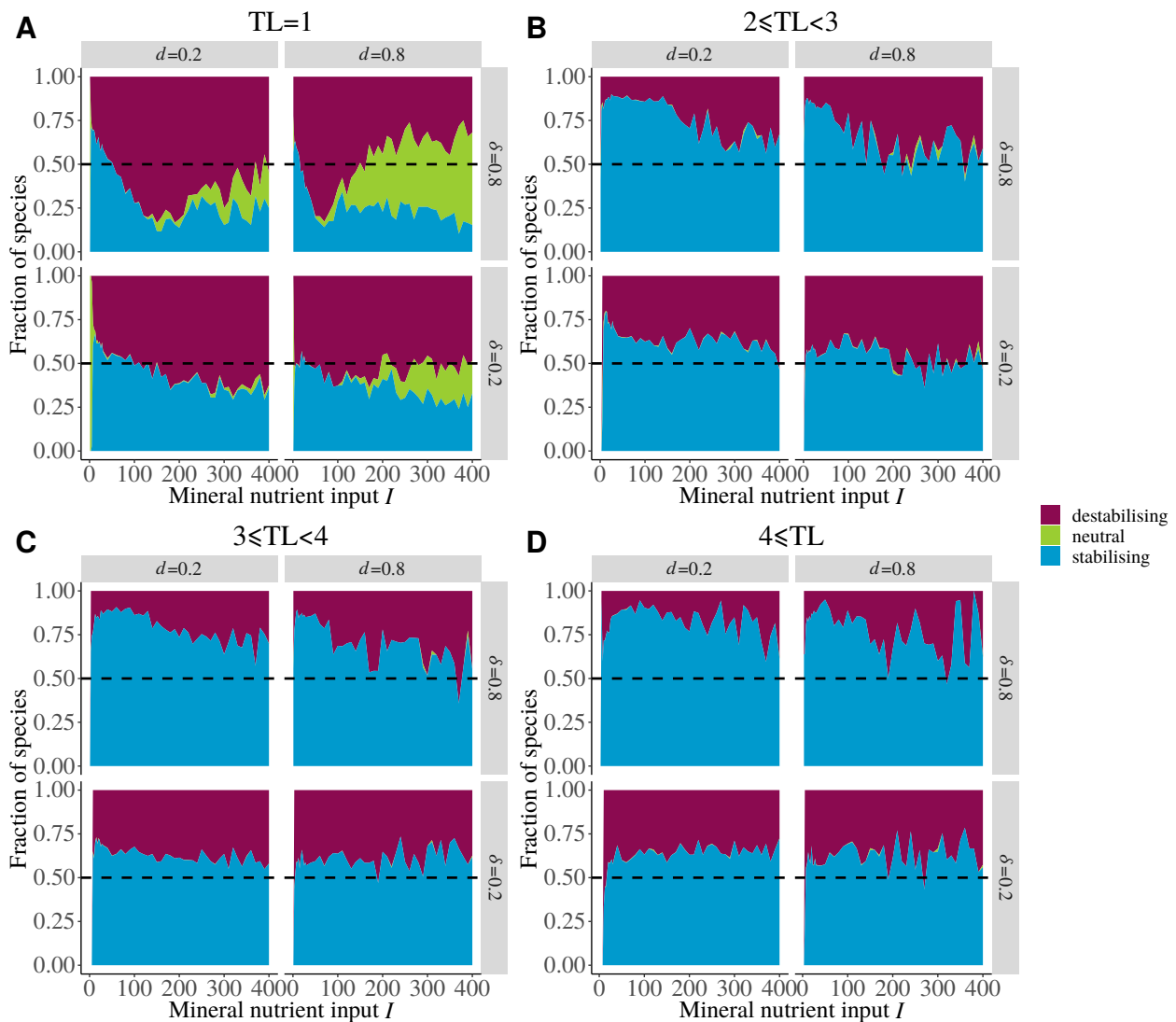
Mineral nutrient stock is negligible compared to detritus stock that increases linearly with external nutrient inputs (Fig. S2-4D), suggesting that it is controlled by primary producers in the food web. As the external inputs are balanced by the losses from the mineral nutrient and detritus compartments ( $I = \ell N + \ell D$ ) (see equations (7a) and (7b)), detritus loss must balance the quasi totality of external nutrient inputs, leading to  $I \simeq \ell D$ . This explains the linear increase of detritus stock and their insensitivity to recycling parameters  $d$  and  $\delta$ . While mineral nutrient and detritus stocks are not affected by  $d$  and  $\delta$ , increasing  $d$  and  $\delta$  mainly increases the flows between those compartments. In fact, increasing  $d$  and  $\delta$  increases primary production through nutrient availability (Fig. S2-4B), that is balanced by a higher mortality due density dependent mortality (Fig. S2-4C) that quadratically increases when biomass linearly increases. This increased mortality increases the quantity of recycled nutrients (Fig. 3A) that fuels biomass production (Fig. S2-4B).



**Figure S2-4.** Response of biomass, nutrient stocks and flows to an enrichment gradient  $I$  as a function of recycling parameters  $d$  (decomposition rate) and  $\delta$  (fraction of direct recycling). Only C food webs (with nutrient cycling) are presented. **A)** Average aggregated biomass of primary producers (green) and consumers (red). **B)** Average primary and secondary productions. 100 food webs are simulated and only values of primary producer and consumer biomass and production where these categories of species persisted are kept. **C)** Average cumulated biomass lost due to density dependent mortality ( $\sum \beta_i B_i^2$ ). **D)** Average mineral nutrient (blue) and detritus stocks in C food webs with at least one persisting species.

### Comparison between species biomass CV in C and SC models

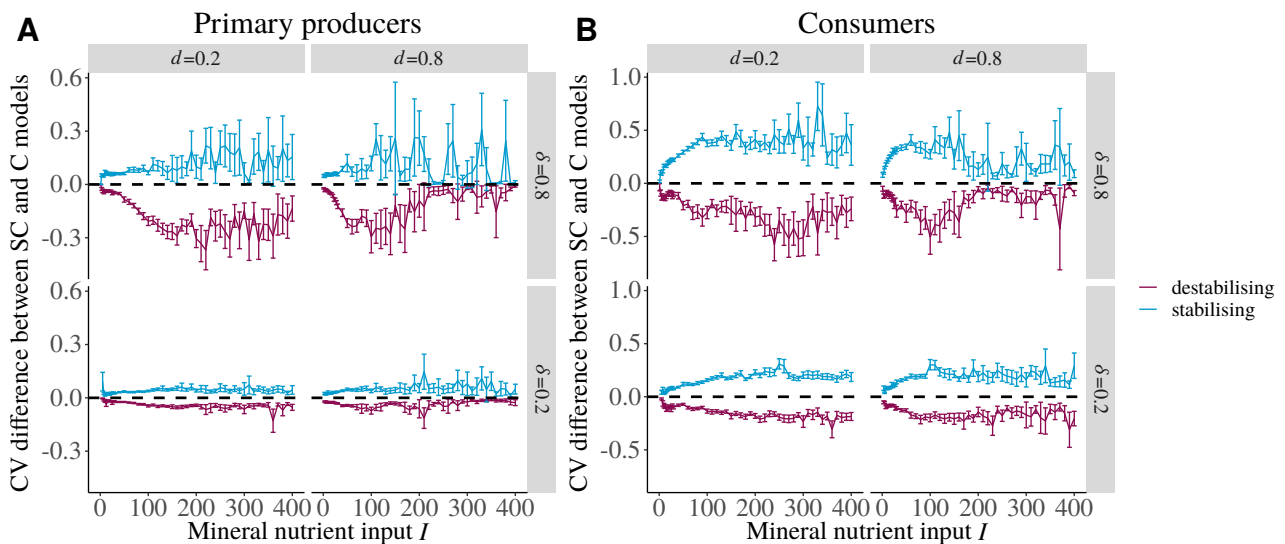
The effects of the presence of recycling loops depend on the considered trophic level. Primary producers dynamics (Fig. S2-5A) are mostly destabilised by recycling feedback loops but they become largely unaffected at high nutrient inputs as they are the last surviving species (system with only primary producers reach fixed points with CV=0). Consumers, whatever their trophic level, have less variable biomasses in presence of nutrient cycling feedback loops (Fig. S2-5B-D). The response of primary producers and consumers to recycling parameters ( $d$  and  $\delta$ ) are the same than the general response presented in Fig. 5. In addition, the destabilising effect for primary producers and stabilising effects for consumers of recycling feedback loops are stronger (*i.e.* larger CV difference) when they occur for more species (for  $\delta = 0.8$  in Fig. S2-6).



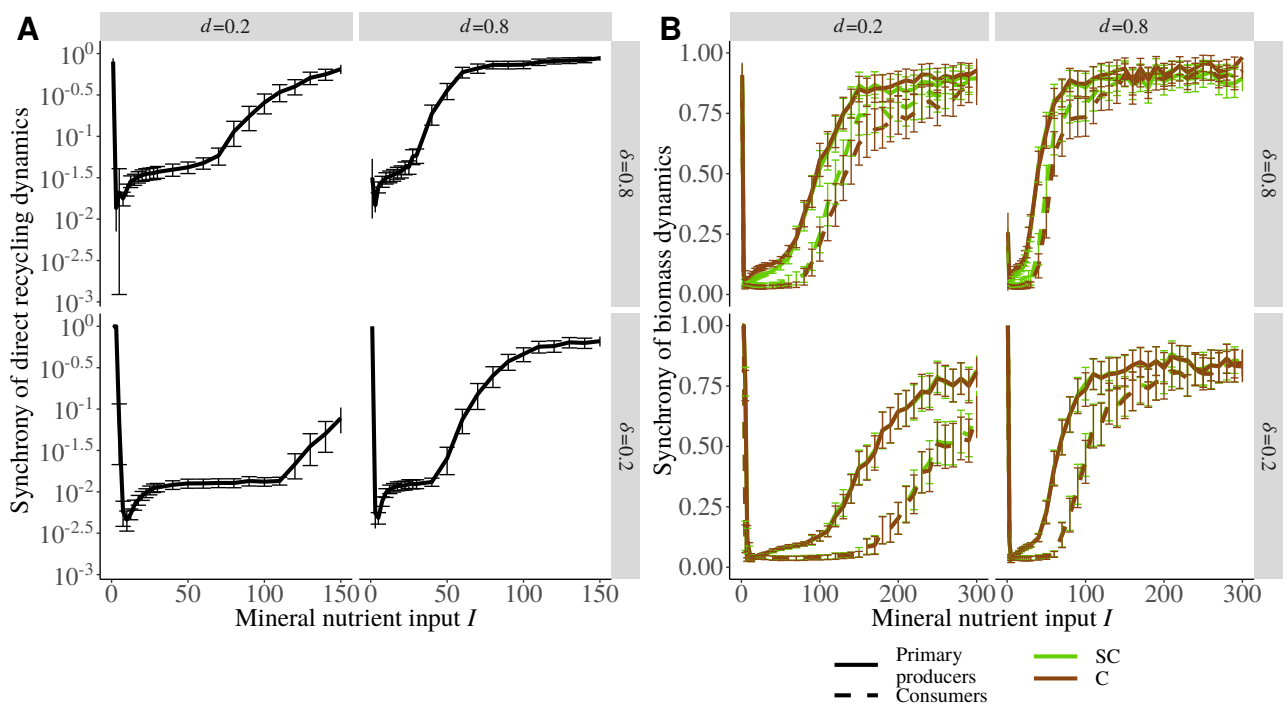
**Figure S2-5.** Effect of nutrient cycling on biomass CV at species level. For each combination of parameters, the biomass CV of the same species between C and SC food webs is compared. If the CV is higher in the SC food web (without nutrient cycling but with a mineral nutrient input simulating the enrichment effect of nutrient cycling) than in the C food web (with nutrient cycling), then nutrient cycling feedback loops have a stabilising effect on dynamics. If the difference is below  $10^{-4}$ , recycling loops are assumed to have neutral effects on dynamics. We also consider species extinction in the SC food web and not in the C food web as a stabilising effect of recycling feedback loops. The fraction of stabilised or destabilised species among all simulated food webs gives the overall effect of nutrient cycling feedback loops at species level dynamics for **A)** primary producers, **B)** herbivores and omnivorous carnivores, **C)** predators with a trophic level comprised between 3 and 4 and **D)** top predators.

The temporal stability of ecosystem aggregated processes, such as total biomass production, relies on the asynchrony between the dynamics of each species Yachi and Loreau (1999); McCann (2000); Hooper et al. (2005). Asynchrony can be calculated as the ratio of the CV of the aggregated process to the average CV from species level dynamics following Loreau and de Mazancourt (2008) (see also Fig. S2-7). If the synchrony  $\varphi$  is low (its value is between 0 and 1), then the aggregated process dynamics are less variable than each of its component dynamics. The synchrony between the quantity of nutrient directly recycled by each species (Fig. S2-7A) or between the biomasses of each species (Fig. S2-7B) first drops at very low nutrient inputs  $I$  and then slowly increase with  $I$ . This is the opposite to the response of species persistence that first increases and then decreases with  $I$  (see Fig. 3B in the main text). Therefore, synchrony must be directly linked to species persistence as species richness promotes the buffering effect of aggregated processes (Yachi and Loreau, 1999). Finally, the recycling parameters  $d$  (decomposition rate) and  $\delta$  (fraction of direct recycling) have no effect on biomass synchrony. Thus, the stabilising effects seen in Fig. S2-5 and S2-6 are likely not due to changes in the asynchrony between species biomasses or recycling.





**Figure S2-6.** Average CV difference between SC models and C models in cases where species are stabilised or destabilised for **A)** primary producers and **B)** consumers.



**Figure S2-7. A)** Average synchrony between the quantities of directly recycled nutrient by each species in C food webs (with nutrient cycling). It is calculated as  $\varphi = CV_{I_{recy}}^2 / \overline{CV}_{S_{recy}}^2$  with  $CV_{I_{recy}}$  the CV of the total quantity of recycled nutrients and  $\overline{CV}_{S_{recy}}$  the average CV of the quantity of nutrient directly recycled by each species weighted by the quantity of nutrient directly recycled by each species. **B)** Average synchrony between species biomass dynamics. It is calculated as  $\varphi = CV_{tot}^2 / \overline{CV}_S^2$  with  $CV_{tot}$  the CV of the total biomass and  $\overline{CV}_S$  the average species biomass CV weighted their biomass. Solid lines are the values for primary producers and dashed lines for consumers. Brown lines are the values calculated in C food webs (with nutrient cycling) and green lines values from SC food webs (without nutrient cycling but with a simulated enrichment due to nutrient cycling).

## Food chain study

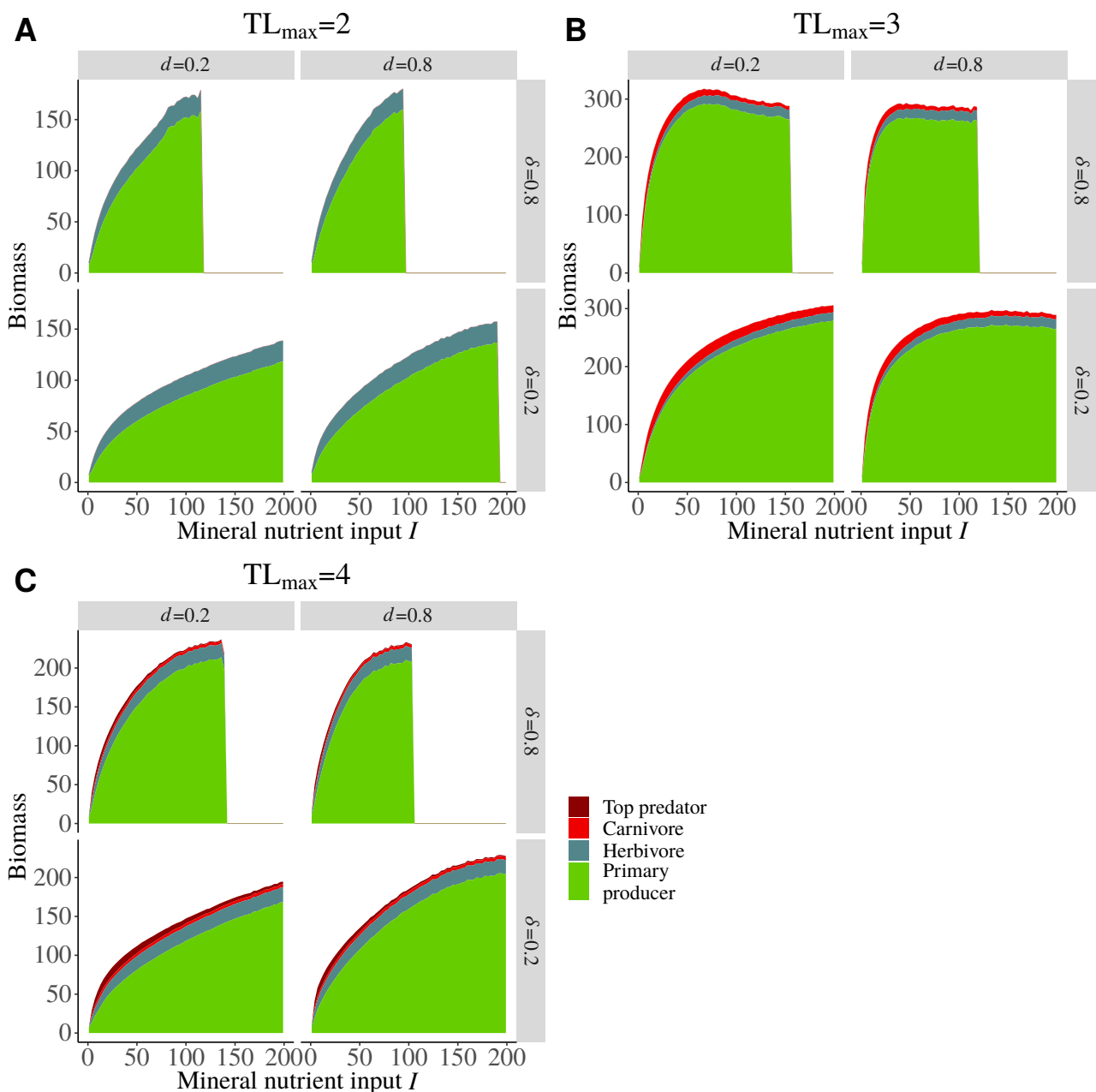
### The food chain model

The food chain model is a simplified version of the food web model, with only four species, a primary producer, a herbivore, a carnivore and a top-predator. It is thus built with the same equations and the same parameters as the

food web model except for the adaptive foraging that is not relevant in such a model. In the simulations, the body masses of the four species are respectively  $10^{-4}$ ,  $4.10^{-3}$ , 0.16 and 6.4 kg (each consumer being 40 times bigger than its prey), and their initial biomass are respectively 1, 0.5, 0.1 and 0.1  $\text{kg}\cdot\text{v}^{-1}$ .

### Overall response of the food chain

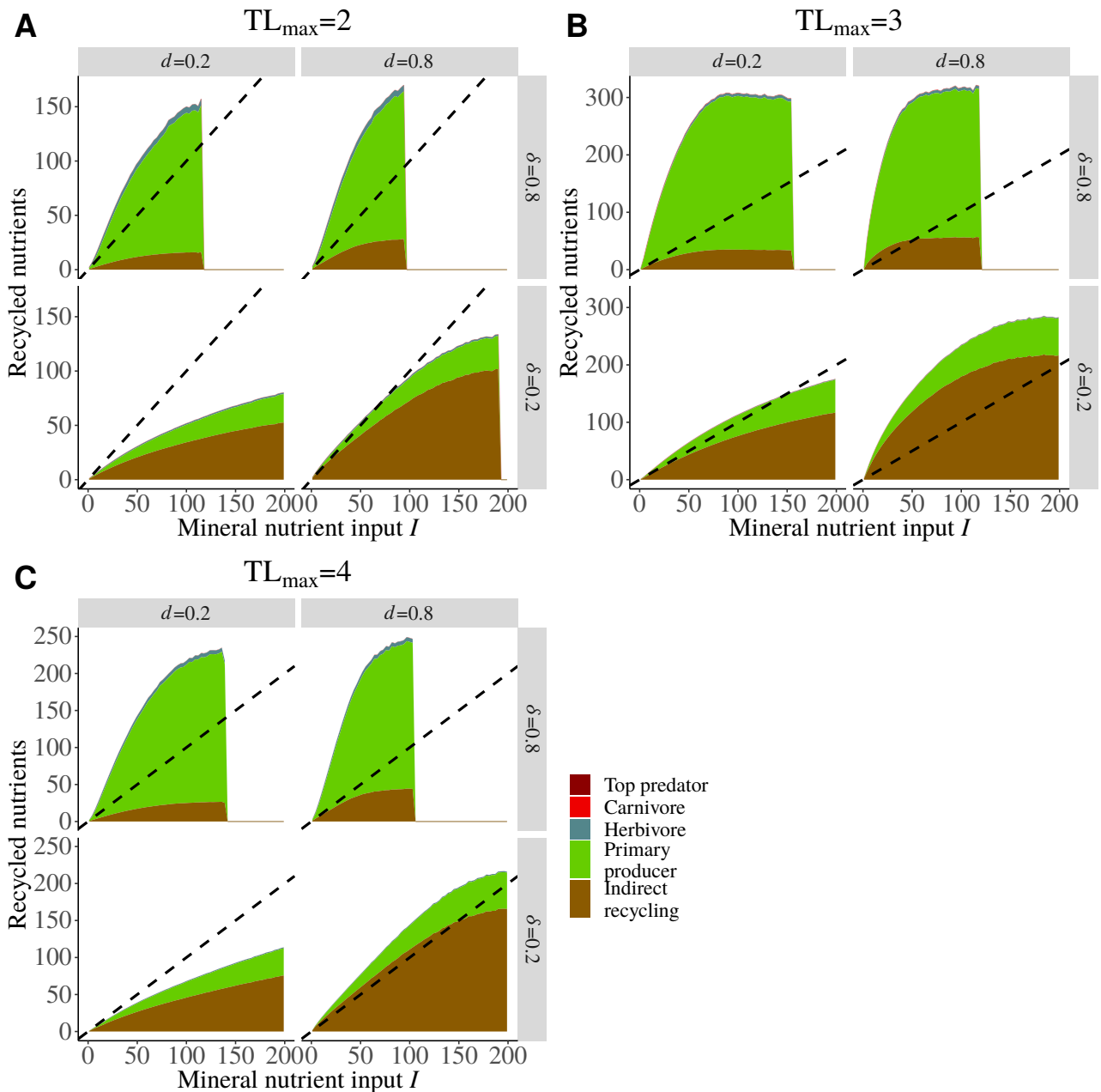
The biomasses of the different species form a bottom-heavy pyramid, higher trophic levels being rare (Fig. S2-8). Adding trophic levels also changes biomass repartition: an even food chain length (Fig. S2-8A and S2-8C) leads to a herbivore biomass higher and a primary producer biomass lower than in a food chain with an odd food chain length (Fig. S2-8B). The total biomass increases with external nutrient inputs  $I$  and this increase is sharper for high values of decomposition rate  $d$  or fraction of direct recycling  $\delta$ . For  $\delta = 0.8$  the food chain even collapses at  $I \simeq 120$ . Compared to the food chain model, consumer total biomass is much higher in the food web model (Fig. S2-4A) because there are more consumer species in the food web model than in the food chain model.



**Figure S2-8.** Average biomass of primary producers (green), herbivores (light blue), carnivores (red) and top predators (dark red) in C food chains. Three food chain lengths are tested: **A**) two species, **B**) three species and **C**) four species.

Nutrient cycling also represents a significant part of the total nutrient input in the mineral nutrient pool (Fig. S2-9)

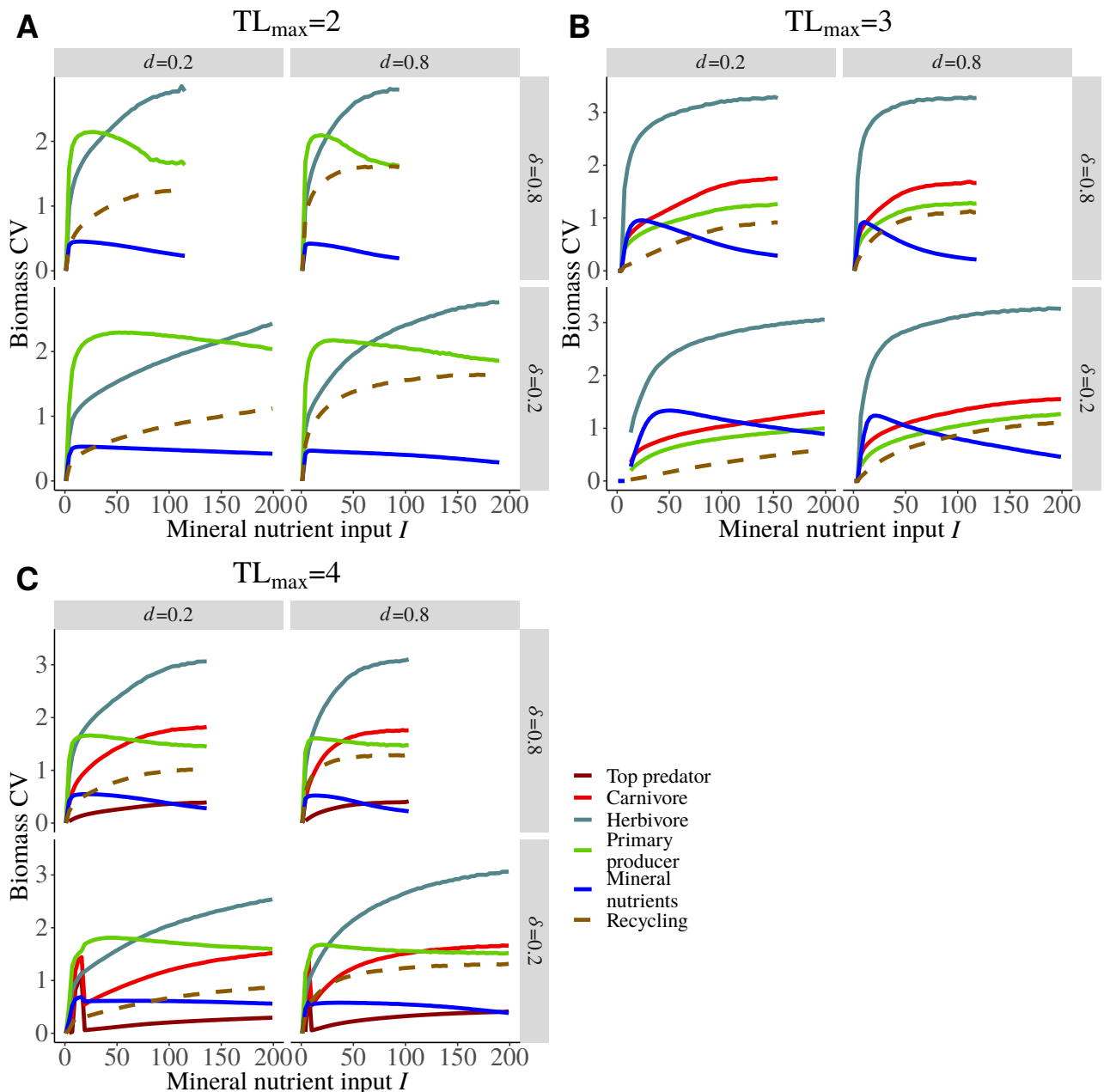
but it is slightly less important than in the food web model probably due to the lower total biomass in the food chain model. Increasing the fraction of direct recycling  $\delta$  and the decomposition rate  $d$  increase the quantity of recycled nutrients as found in the food web model. The total quantity of recycled nutrients is also sensitive to food chain length. Food chains with even food chain length (Fig. S2-9A and S2-9C) recycle more nutrients than food chains with odd food chain length (Fig. S2-9B). Total biomass has exactly the same response (Fig. S2-8) because of trophic cascades: with even food chain length, primary producers are controlled by herbivores and as they are the most abundant species, the total biomass decrease. As nutrient cycling directly depends on species biomass (see equations (3a) and (3b)), the quantity of recycled nutrients also follows the trophic cascade pattern.



**Figure S2-9.** Average quantity of nutrients directly recycled by primary producers (green), herbivores (light blue), carnivores (red) and top predators (dark red) and indirectly (brown) in C food chains. Three food chain lengths are tested: **A)** two species, **B)** three species and **C)** four species.

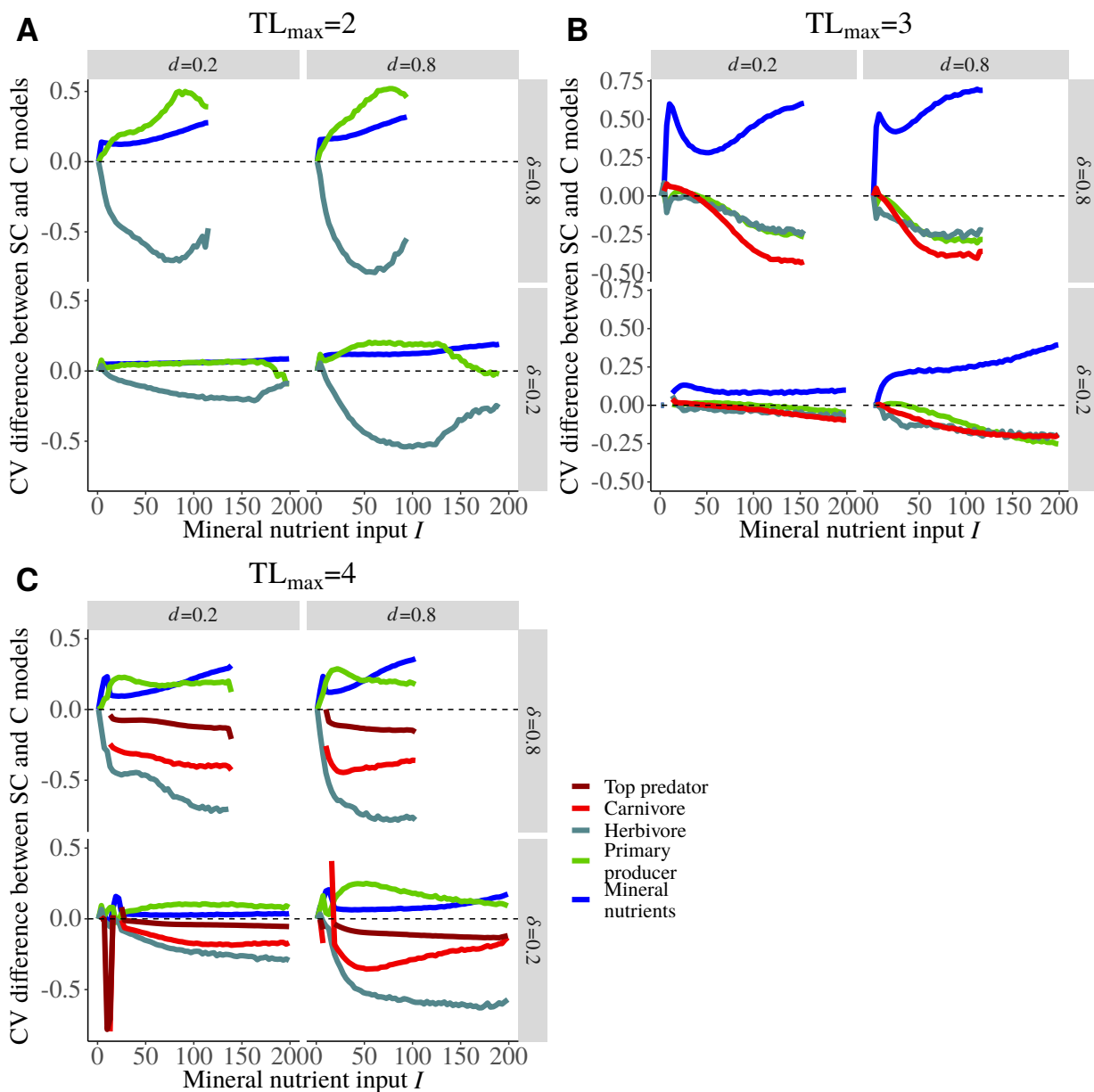
Species biomass and detritus stock CV increase with external nutrient input  $I$  (Fig. S2-10). However, primary producer biomass in food chains with even food chain length only (Fig. S2-10A and S2-10C) first increase and then decrease with  $I$ . Mineral nutrient stock CV has the same relation with  $I$  whatever the food chain length. Such an increase of biomass CV is consistent with our results from the food web model (Fig. 4A in the main text) and the paradox of enrichment predictions, except for primary producers whose biomass CV decreases with  $I$ . This result is

counter-intuitive and at this point we cannot explain it.



**Figure S2-10.** Biomass CV of recycled nutrients (dashed brown), mineral nutrients (blue), primary producers (green), herbivores (light blue), carnivores (red) and top predators (dark red) in C food chains. Three food chain lengths are tested: **A**) two species, **B**) three species and **C**) four species.

In addition, increasing food chain length increases or decreases species biomass time variability depending on their trophic level. For instance, primary producers are more variable when they are controlled by herbivores (Fig. S2-10A and S2-10C). This results are consistent with Shanafelt and Loreau (2018) who found that adding trophic levels to a food chain without nutrient cycling generates trophic cascades in both biomass and biomass CV. In fact, species at even distance from the top-consumer had a lower biomass and a higher biomass CV than when they were at odd distance from the top-consumer. However, our results are less clear with, for instance, the herbivore biomass CV that is always higher than carnivore biomass CV while Shanafelt and Loreau (2018) found that the herbivore biomass CV was alternatively higher or lower than the carnivore biomass CV with increasing food chain length. This suggests that nutrient cycling deeply changes species dynamics in food chains.

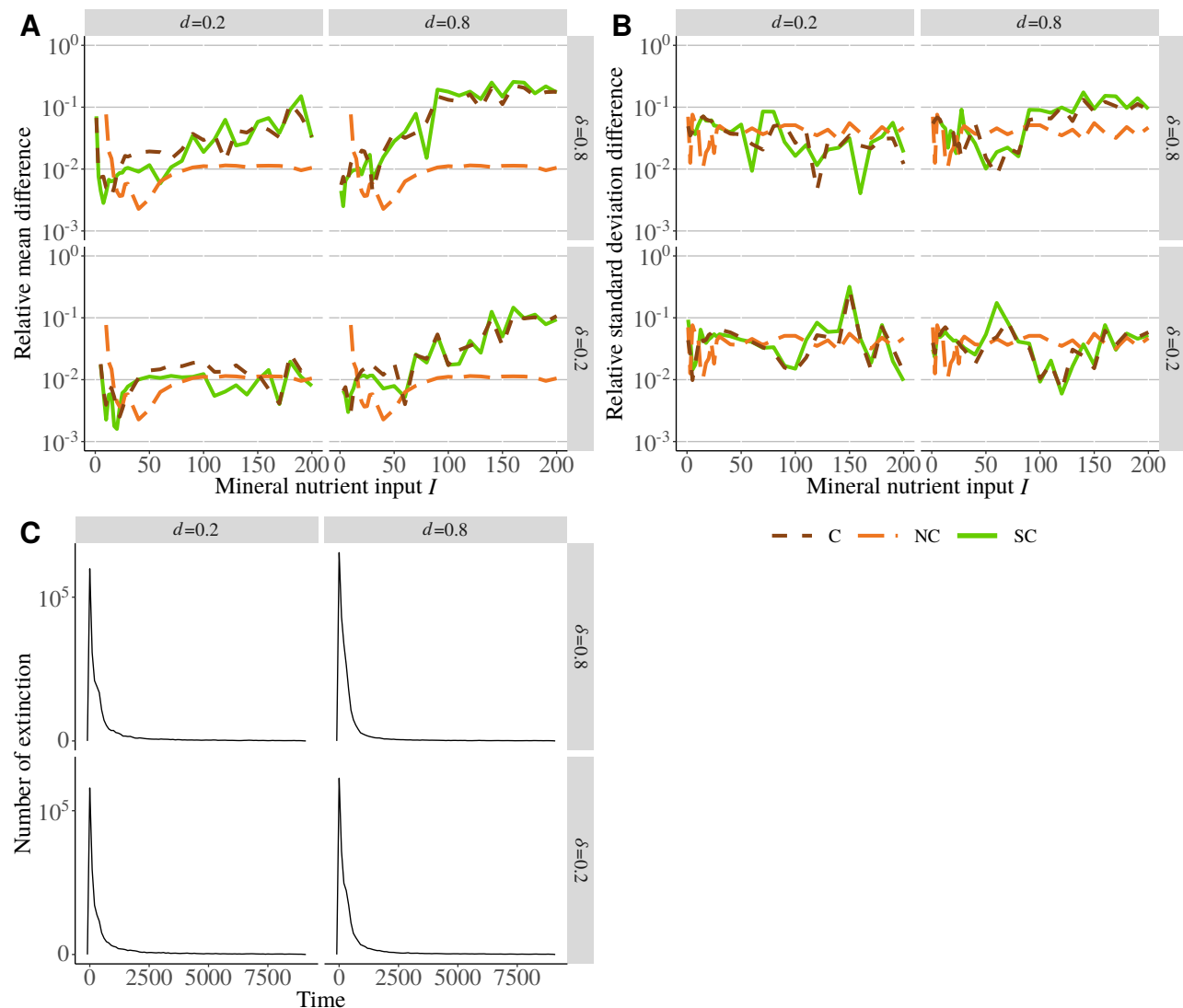


**Figure S2-11.** Difference between the biomass CV of mineral nutrients (blue), primary producers (green), herbivores (light blue), carnivores (red) and top predators (dark red) between SC food chains and C food chains. Positive values correspond to a higher CV in SC food chain and thus to a stabilising effect of nutrient cycling on dynamics. Three food chain lengths are tested: **A)** two species, **B)** three species and **C)** four species.

The presence of recycling feedback loops, once the enrichment effect of nutrient recycling is accounted for, has contrasting effects on species temporal variability depending on food chain length. Primary producers are stabilised for even food chain lengths (Fig. S2-11A and S2-11C), herbivores are destabilised whatever the food chain length, carnivores tend to be weakly stabilised at low nutrient input  $I$  for  $TL_{max}=3$  (Fig. S2-11B) and top predators are destabilised (Fig. S2-11C). More generally, primary producers have contrasting responses while consumers tend to be destabilised by nutrient cycling feedback loops. In addition, mineral nutrients are always stabilised by the presence of nutrient cycling feedback loops. As found in the food web model, the stabilising or destabilising effects of nutrient cycling feedback loops are stronger for high values of  $d$  and  $\delta$  and correspond to a higher quantity of recycled nutrients. This higher quantity of recycled nutrients (those directly recycled in particular) should intensify the coupling within the food chain and thus explain this increased effect on dynamics.

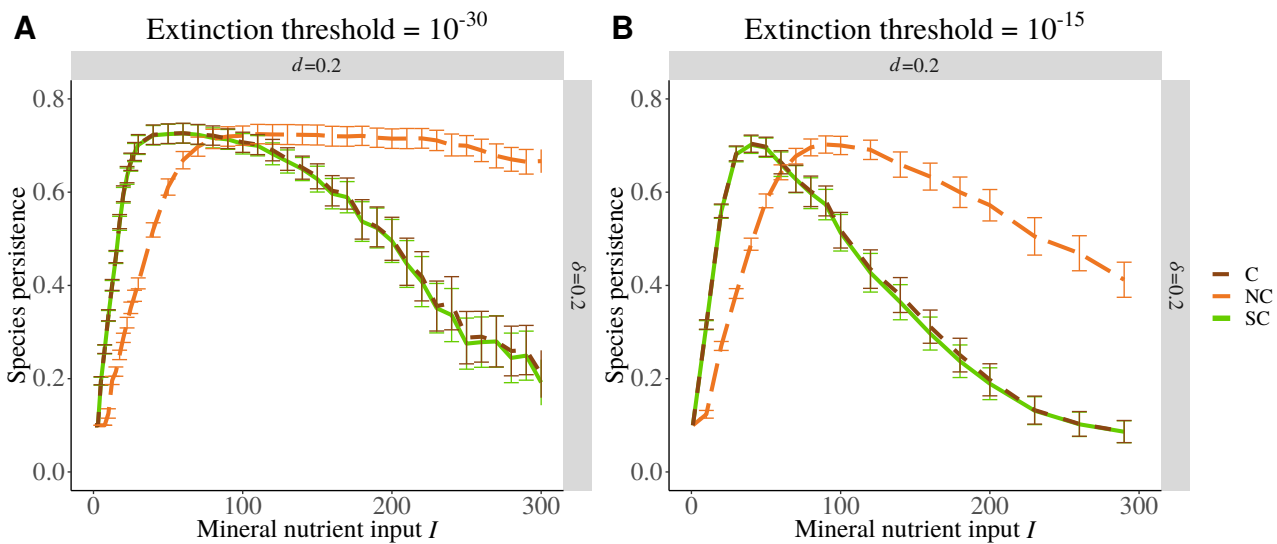
### S3 Appendix - Sensitivity analysis

#### Sensitivity to the way simulations were run



**Figure S3-1.** Sensitivity of the final community to the number of generated food webs and the number of time steps. **A)** Relative difference of the mean value of output variables (averaged for six variables: species persistence, average quantity of recycled nutrients, average primary and secondary productions, average quantity of nutrient directly recycled by primary producers and consumers) between simulations with 100 or 200 generated food webs for each combination of parameters. **B)** Relative difference of the corresponding standard deviations. **C)** Distribution of the number of extinctions over the 100 generated food webs along the transitory period. Extinctions are also cumulated over all the values of mineral nutrient input  $I$ .

As our food web model uses randomly generated communities, we average our different measures over 100 different communities (*i.e.* with randomly drawn body mass distributions). We assessed the number of required communities by calculating the relative difference between the means calculated with 100 or 200 different food webs for six variables. At low nutrient input we have a good precision for mean with a relative difference below 1% (Fig. S3-1A) and a difference lower than 10% for the standard deviation (Fig. S3-1B). The increase in the relative difference for the mean at high nutrient inputs must be due to the higher variability of food webs composition (*e.g.* maximum trophic level) due to multiple extinctions. Thus, 100 simulated food webs are enough to capture the accurate response of the model. Most extinctions occur within the first 2500 years of simulation, as shown by Fig. S3-1C. Thus, 9000 years are enough to get the final community and to get over the transitory regime.

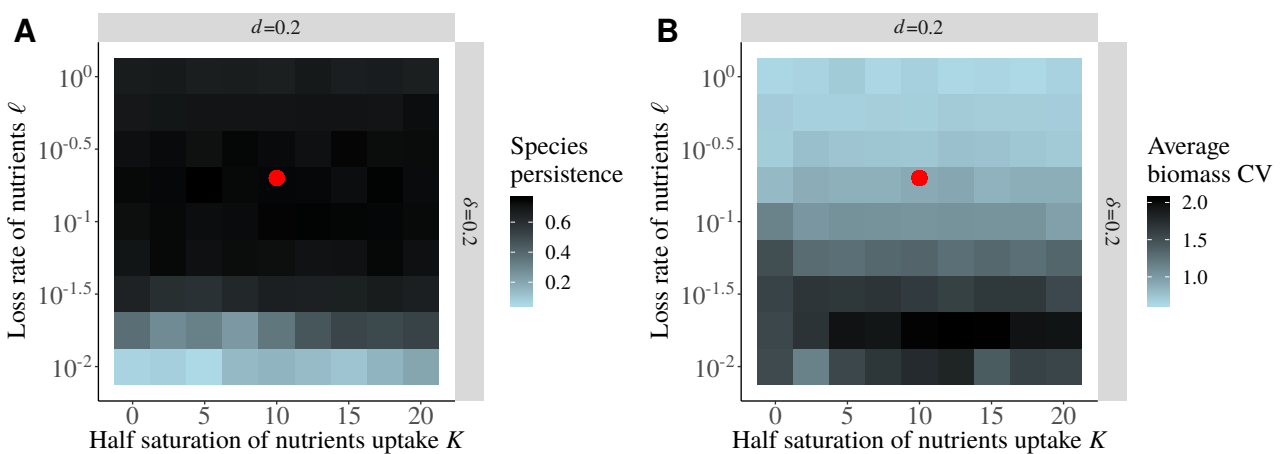


**Figure S3-2.** Sensitivity of the final community to the extinction threshold (*i.e.* the biomass under which the species is considered as extinct). **A)** Species persistence with an extinction threshold equal to  $10^{-30}$  as in the main text. **B)** Species persistence with an extinction threshold equal to  $10^{-15}$ . 100 replicates are tested for each parameter combination.

We raised the extinction threshold up to  $10^{-15}\text{kg.v}^{-1}$  (Fig. S3-2B) compared to the value used in the main study ( $10^{-30}\text{kg.v}^{-1}$ ) (Fig. S3-2A). Species persistence is lower with this new threshold only at high nutrient inputs when species CVs increase with nutrient inputs. This demonstrates that extinction are due to an increase in oscillation amplitude that pushes species biomasses close to the extinction threshold.

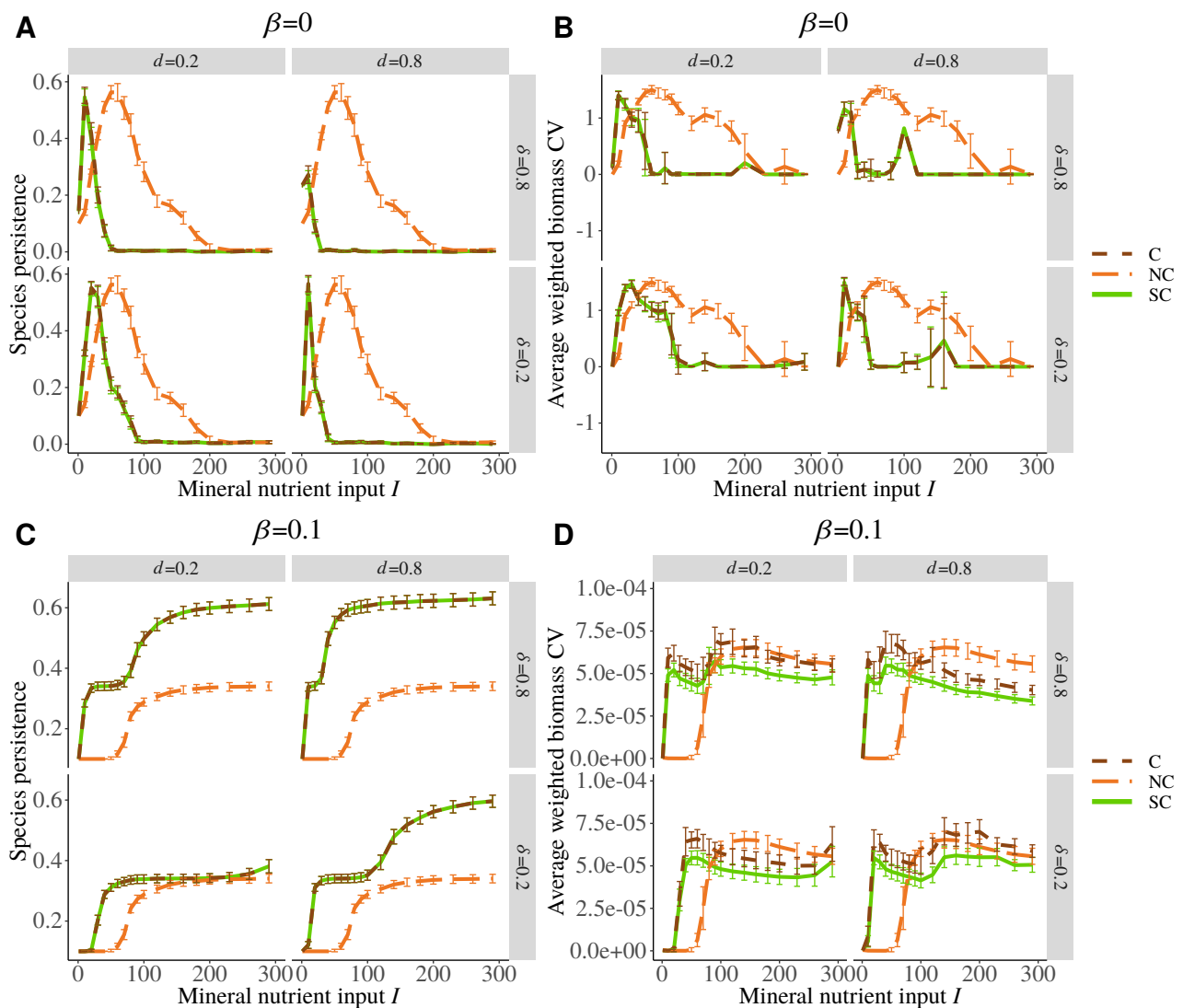
### Effects of attack rate and density dependent mortality rate allometric coefficients, of the nutrient loss rate and the half saturation of nutrient uptake

The decrease of species persistence with the decrease of the loss rate  $\ell$  in Fig. S3-3A is due to the enrichment caused by the accumulation of nutrients. In fact, decreasing  $\ell$  for a constant nutrient input  $I$  increases the availability of mineral nutrients and is equivalent to an increase of nutrient inputs. The average CV of species biomasses (Fig. S3-3B) first increases with  $\ell$  and then decreases. On the contrary, the half saturation of nutrient uptake  $K$  only slightly affects species persistence and the CV of species biomasses when compared to  $\ell$ . For  $\ell$  higher than  $10^{-1.25}$  ( $\sim 0.05$ , corresponding to a loss of 5% of the nutrient stock), changing  $\ell$  and  $K$  does not affect species persistence and the CV of species biomasses. Then, we arbitrarily set  $\ell$  and  $K$  to maximise species persistence for  $I \simeq 50$ .



**Figure S3-3.** Effects of the half saturation constant of nutrient uptake  $K$  and the loss rate of mineral nutrients and detritus  $\ell$  on **A)** species persistence and **B)** the CV of species biomasses. Each square is the average of 100 simulated food webs (except for **B)** where only data from persistent food webs are represented). The mineral nutrient input is  $I = 40$ , the fraction of direct recycling is  $\delta = 0.2$  and the decomposition rate of detritus  $d = 0.2$ . The red dots represent the combinations of parameters used in the main study ( $K = 10$  and  $\ell = 0.2$  in C and D).

We included a density dependent mortality rate ( $\beta_i$ ) in our model to ensure a minimum species persistence. With a density dependent mortality rate allometric constant  $\beta = 0$ , the food web is so prone to the paradox of enrichment (see the higher average biomass CV in Fig. S3-4B) that no species can persist in the C model when recycling parameters are high (Fig. S3-4A). A high value of  $\beta$  increases so much the death rate that strong nutrient inputs are needed to have a high species persistence (Fig. S3-4C) and biomass temporal variability is extremely low (Fig. S3-4D), thus resolving the paradox of enrichment. In addition, the average biomass CV is significantly higher in C models than in SC models for all combinations of  $d$  and  $\delta$ , which differs to our results with intermediate values of  $\beta$ . However, the absolute value of biomass CV is so low ( $10^{-5}$  that is even below the threshold used in Fig. 5 in the main text) that the effect on the overall dynamics seems negligible. Finally, whatever the value of  $\beta$ , the enrichment effect of nutrient cycling is always dominant to explain the difference between the C and the NC models as both curves representing the C and SC models overlap strongly as in Fig. 3B in the main text, making our results robust to  $\beta$ .

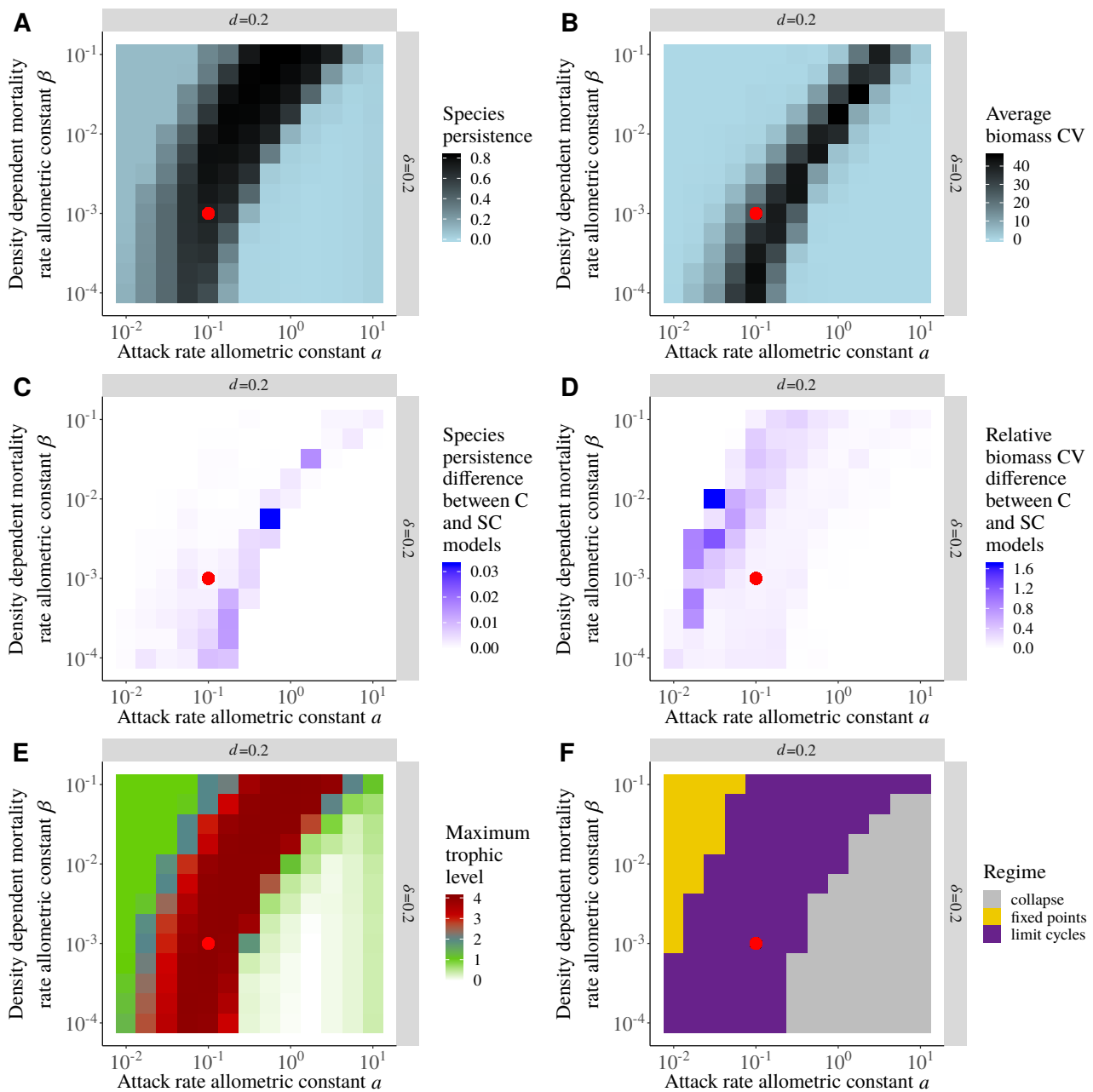


**Figure S3-4.** Sensitivity to the density dependent mortality rate allometric constant  $\beta$ . **A)** Species persistence and **B)** average weighted species biomass CV without density dependent mortality ( $\beta = 0$ ) and **C),D)** with a strong density dependent mortality ( $\beta = 0.1$ ). 100 replicates are tested for each parameter combination.

Species persistence in food webs is maximised only for restricted combinations of values of the attack rate allometric constant  $a$  and the density dependent mortality rate allometric constant  $\beta$  (Fig. S3-5A). In fact, if  $a$  is high and  $\beta$  low, consumers strongly exploit their prey and weakly self regulate, leading to the extinction of their prey and the collapse of the entire food web (Fig. S3-5F). The reverse combination leads to the extinction of consumers that cannot eat enough to compensate the loss of biomass due to a strong self regulation (Fig. S3-5E). The response of the CV of species biomasses to  $a$  and  $\beta$  is qualitatively similar to the response of species persistence (Fig. S3-5B) but occurs for smaller values of  $\beta$ .  $\beta$  strongly dampens species biomass oscillations and a large part of the parameter space leads to



food webs with very low average CV of species biomasses (regime similar to fixed points). Therefore, we chose  $a$  and  $\beta$  to maximise species persistence but with a minimal  $\beta$ . Indeed, a high  $\beta$  strongly stabilise species dynamics and might obscure potential effects of nutrient cycling on stability.



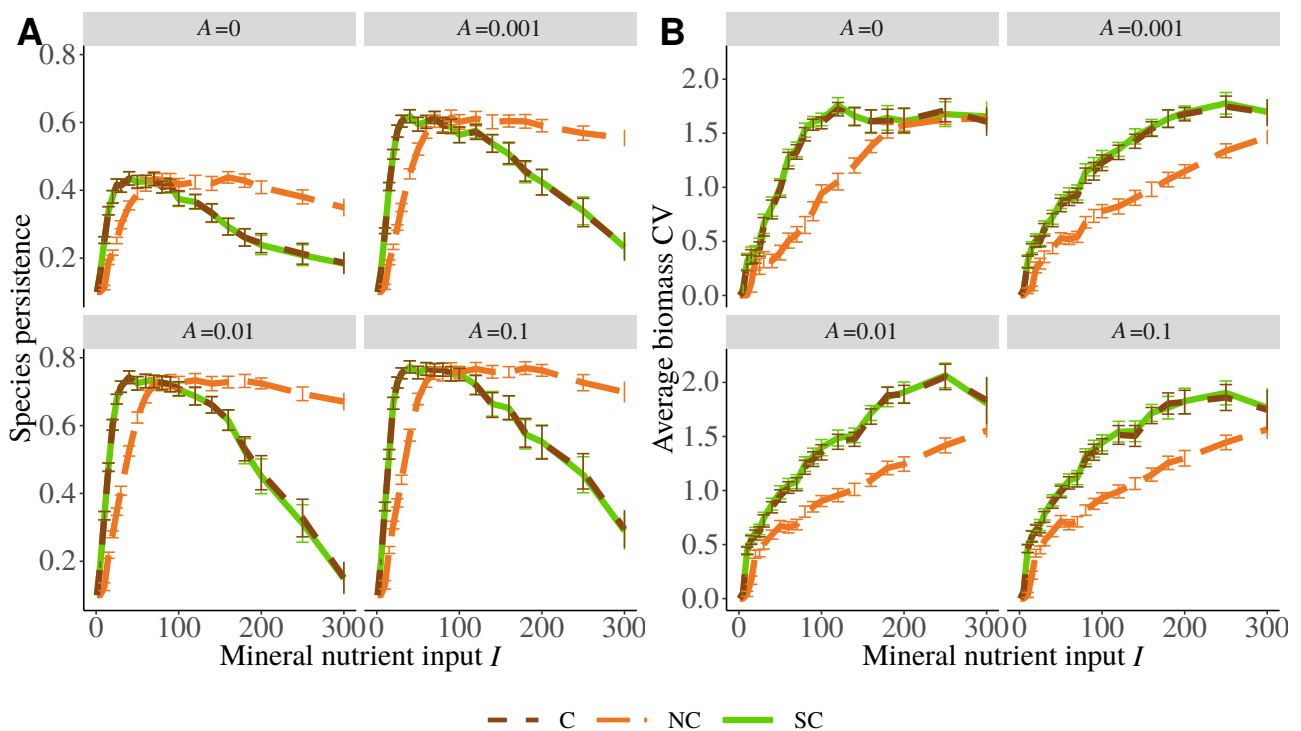
**Figure S3-5.** Effects of the attack rate allometric constant  $a$  and the density dependent mortality rate allometric constant  $\beta$  on **A)** the average species persistence and **B)** the average species biomass coefficient of variation. Average of the absolute value of the difference between the C and SC models for **C)** species persistence and **D)** species biomass CV. **E)** Average maximum trophic level. **F)** Regime of food webs that can display limit cycles or fixed points (average biomass CV lower than  $10^{-4}$ ). When species persistence is mostly equal to zero, we consider that food webs collapse. Each square is the average of 100 simulated food webs (except for **B)**, **D)** and **E)** where only data from persistent food webs are represented). The mineral nutrient input is  $I = 40$ , the fraction of direct recycling is  $\delta = 0.2$  and the decomposition rate of detritus  $d = 0.2$ . The red dots represent the combinations of parameters used in the main study ( $a = 0.1$  and  $\beta = 0.001$ ).

In spite of the high variability of species persistence and species biomass CV representing different possible regimes (fixed points or limit cycles in Fig. S3-5F) depending on the values of the attack rate allometric constant  $a$  and the density dependent mortality rate allometric constant  $\beta$ , we do not see a significant difference between the responses of the C (with nutrient cycling) and the SC models (without nutrient cycling but with a simulated enrichment effect). Relative to the average values of species persistence (Fig. S3-5A) and biomass CV (Fig. S3-5B), the difference between

the C and SC models are generally negligible (Fig. S3-5C and D). The significant differences occur only for species biomass CV when food webs are by the border between fixed point and limit cycle domains (Fig. S3-5F) as they can switch between food webs with only primary producers and food webs with consumers (Fig. S3-5E). Therefore, nutrient cycling mainly consists in an enrichment effect and weakly affects food web dynamics, whatever the value of the attack rate allometric constant  $\alpha$  and the density dependent mortality rate allometric constant  $\beta$ . Thus, our results are robust to the arbitrary choice of these parameters.

### Sensitivity of the results to the value of adaptive foraging rate

We included adaptive foraging in our model as a mechanism promoting species persistence. Increasing the adaptive rate  $A$  increases species persistence (Fig. S3-6A), as demonstrated by Kondoh (2003); Heckmann et al. (2012), while the qualitative response of species persistence to increased nutrient inputs remains unchanged (*i.e.* maximum of persistence occurring for the same values of nutrient input  $I$ ). The CV of species biomasses (Fig. S3-6B) increases more sharply without adaptive foraging but the general response to nutrient enrichment remains qualitatively very similar for varying values of adaptive rate. In conclusion, our main results remain virtually unchanged when the rate of adaptive foraging is changed and we chose  $A = 0.01$  as it promotes a high species persistence (higher values of adaptive rate only slightly increase species persistence).

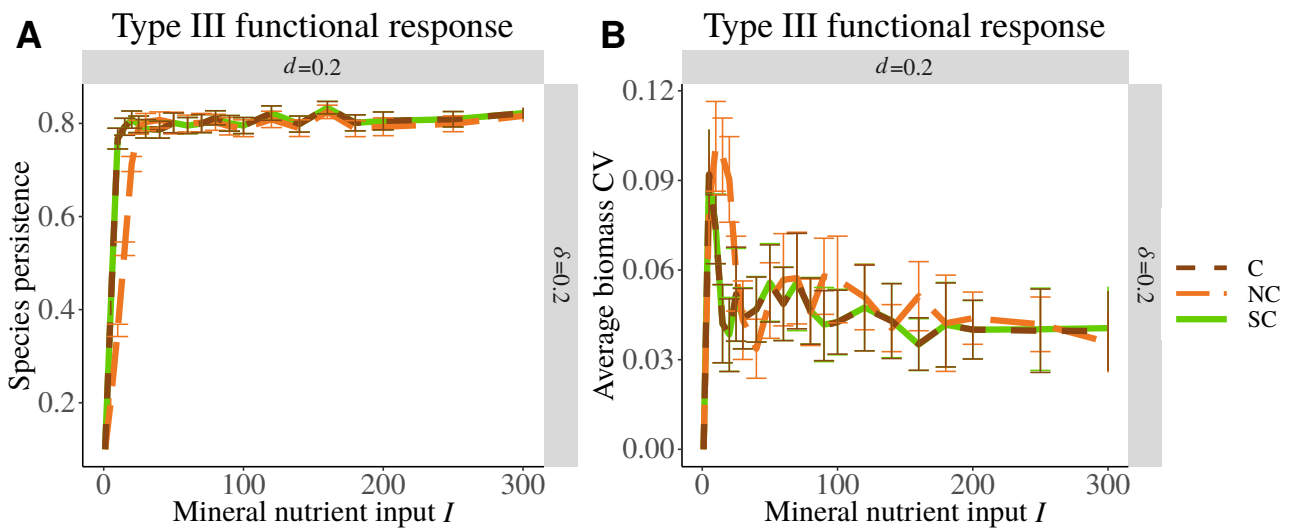


**Figure S3-6.** Effects of the adaptive rate  $A$  of adaptive foraging on **A)** species persistence and on **B)** the average species biomass CV. We set  $d = 0.2$  and  $\delta = 0.2$ ,  $A = 0.01$  is the value used in the main text. 100 replicates are tested for each parameter combination.

### Sensitivity of the results to the type of functional response

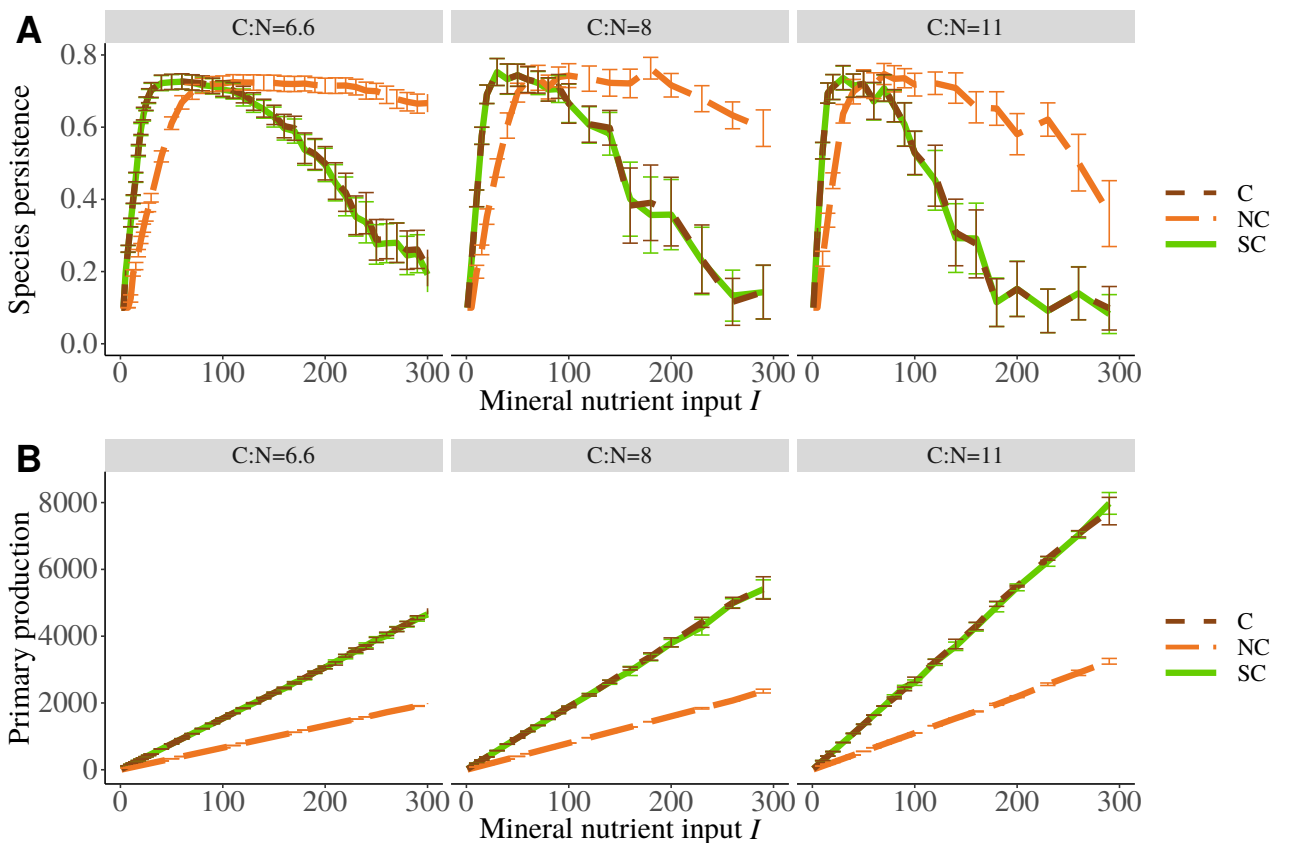
The type II functional response leads to a decrease of species persistence at high nutrient inputs while species persistence stays maximum in food webs with a type III functional response (Fig. S3-7A). In addition, the CV of species biomasses is much lower in food webs with a type III functional response compared to food webs with a type II functional response. Thus, we do not observe a paradox of enrichment with a type III functional response in our model. This is consistent with the results of Rall et al. (2008). However, our results are qualitatively similar to those obtained with a type II functional response with a sharper increase of species persistence and a maximum of persistence reached for lower mineral nutrient inputs in C food webs than is NC food webs. We also still observe that the curves

of the C and SC food webs strongly overlap. The major enrichment effect of nutrient cycling and its preponderance compared to the weak stabilising effect of positive feedback loops is thus robust to the type of functional response.



**Figure S3-7.** Effects of a type III functional response on **A)** species persistence and on **B)** the average species biomass CV. The type II functional response was used in the main text and 100 replicates are tested.

### Sensitivity of the results to the C:N ratio of primary producers



**Figure S3-8.** Effects of primary producers C:N ratio on **A)** species persistence and **B)** primary production. Primary producers C:N ratio is equal to 6.6 in the main text and 36 replicates are tested for C:N=8 and C:N=11.

The increase of species persistence (Fig. S3-8A) at low nutrient inputs and its decrease at high nutrient inputs are sharper if the C:N ratio of primary producers is high. The maximum species persistence is reached for lower nutrient inputs and the decrease of species persistence starts at lower nutrient inputs. This could be explained by the increase

of primary production as the C:N ratio of primary producers increases (Fig. S3-8B). As the C:N ratio of primary producers increases, the growth of primary producers become less limited by the availability mineral nutrients. Therefore, increasing the C:N ratio of primary producers increases the productivity of the food webs and amplifies their response to nutrient enrichment.

In our model, the C:N ratio of primary producers does not strongly affects the response of the food web because the C:N ratio of detritus does not affect their decomposition. However, the C:N ratio of primary producers will be a central parameter in further models including a brown food web with decomposers (Attayde and Ripa, 2008; Zou et al., 2016) whose consumption rate strongly depends on detritus stoichiometry (Daufresne and Loreau, 2001). In nature, primary producer stoichiometry is highly variable between taxa but also within species depending on external conditions such as nutrient availability or light exposure (Sterner et al., 2002; Dickman et al., 2006; Danger et al., 2007, 2009; Mette et al., 2011). Its variations strongly impact ecosystem functioning through food quality and dead organic matter stoichiometry (Dickman et al., 2008; Cherif and Loreau, 2013).

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