

694 **Supplementary Material for**

695 **Quality matters: stoichiometry of resources modulates**
696 **spatial feedbacks in aquatic-terrestrial meta-ecosystems**

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712 **S1 Additional figures referenced in the main text**

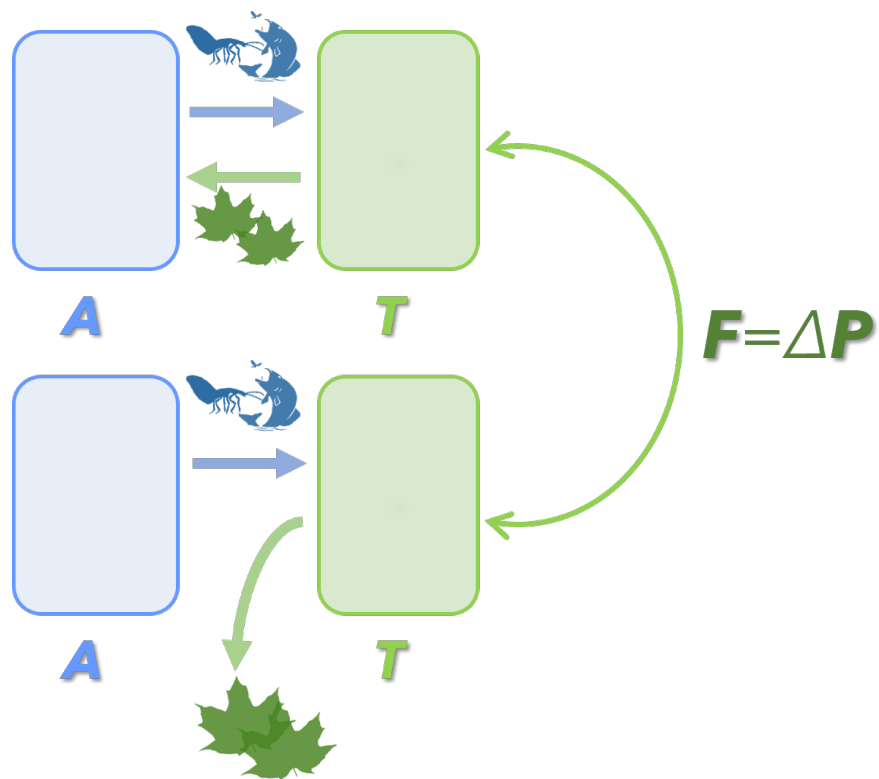


Figure S1.1: **Quantifying the feedback.**

We quantified the feedback (\mathcal{F} , here on terrestrial production) by subtracting the terrestrial production (\mathcal{P} , either primary or secondary) when ecosystems were bidirectionally connected (top) and when subsidies exported by terrestrial ecosystems were lost from the meta-ecosystem (bottom). Therefore, the feedback strength is defined as a difference in ecosystem functioning between two scenarios: when there is a bidirectional exchange of subsidies or not.

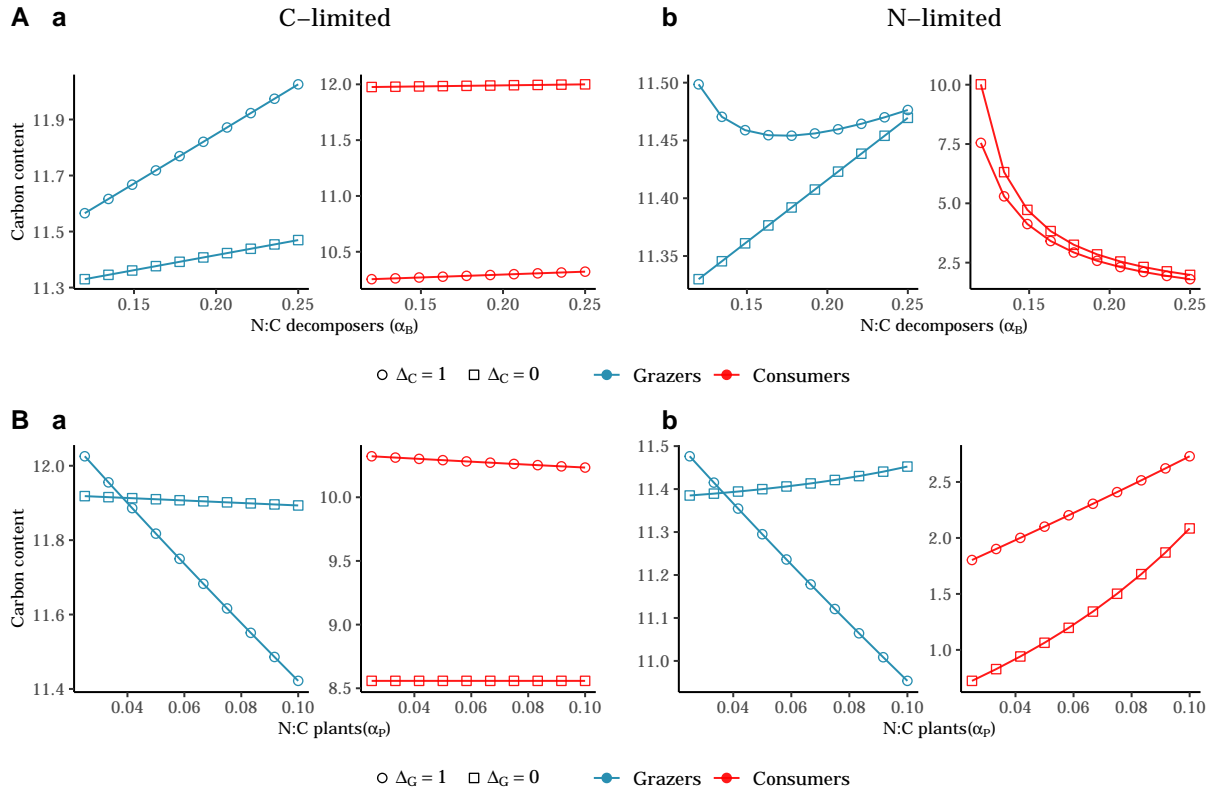


Figure S1.2: Variations of consumer densities measured by carbon content along the gradients of the stoichiometry of basal species.

We compare the carbon content of both consumers (red) and grazers (blue) along the gradient of N:C of decomposers (α_B ; A) and plants (α_P ; B) between scenarios where primary consumers subsidies are regionally transported (circles) or locally recycled (squares). Decomposers are either carbon-limited (left; a) or nitrogen-limited (right; b). Other parameters: in (A): $\alpha_P = 0.025$ and $\Delta_C = 0$ meaning that all detritus produced by consumers of decomposers were locally recycled and in (B): $\alpha_B = 0.25$ and $\Delta_G = 0$ meaning that all detritus produced by grazers were locally recycled.

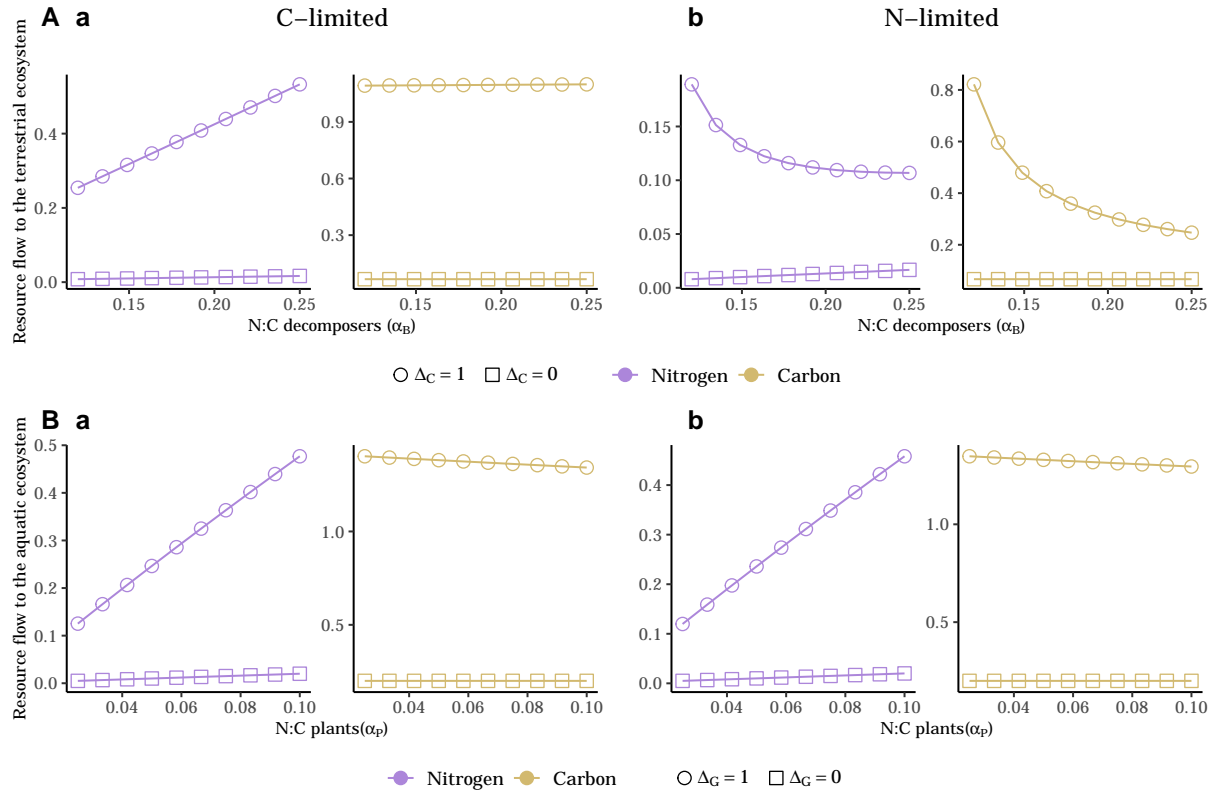


Figure S1.3: Changes in the flows of carbon and nitrogen exported along the gradients of the stoichiometry of primary producers.

We compare the flows of resources (carbon in orange, nitrogen in purple) to the aquatic and terrestrial ecosystems along the gradient of N:C of decomposers (α_B ; A) and plants respectively (α_P ; B) between scenarios where primary consumers subsidies are regionally transported (circles) or locally recycled (squares). Decomposers are either carbon-limited (left, a) or nitrogen-limited (right; b). Other parameters: in (A): $\alpha_P = 0.025$ and $\Delta_C = 0$ meaning that all detritus produced by consumers of decomposers were locally recycled and in (B): $\alpha_B = 0.25$ and $\Delta_G = 0$ meaning that all detritus produced by grazers were locally recycled.

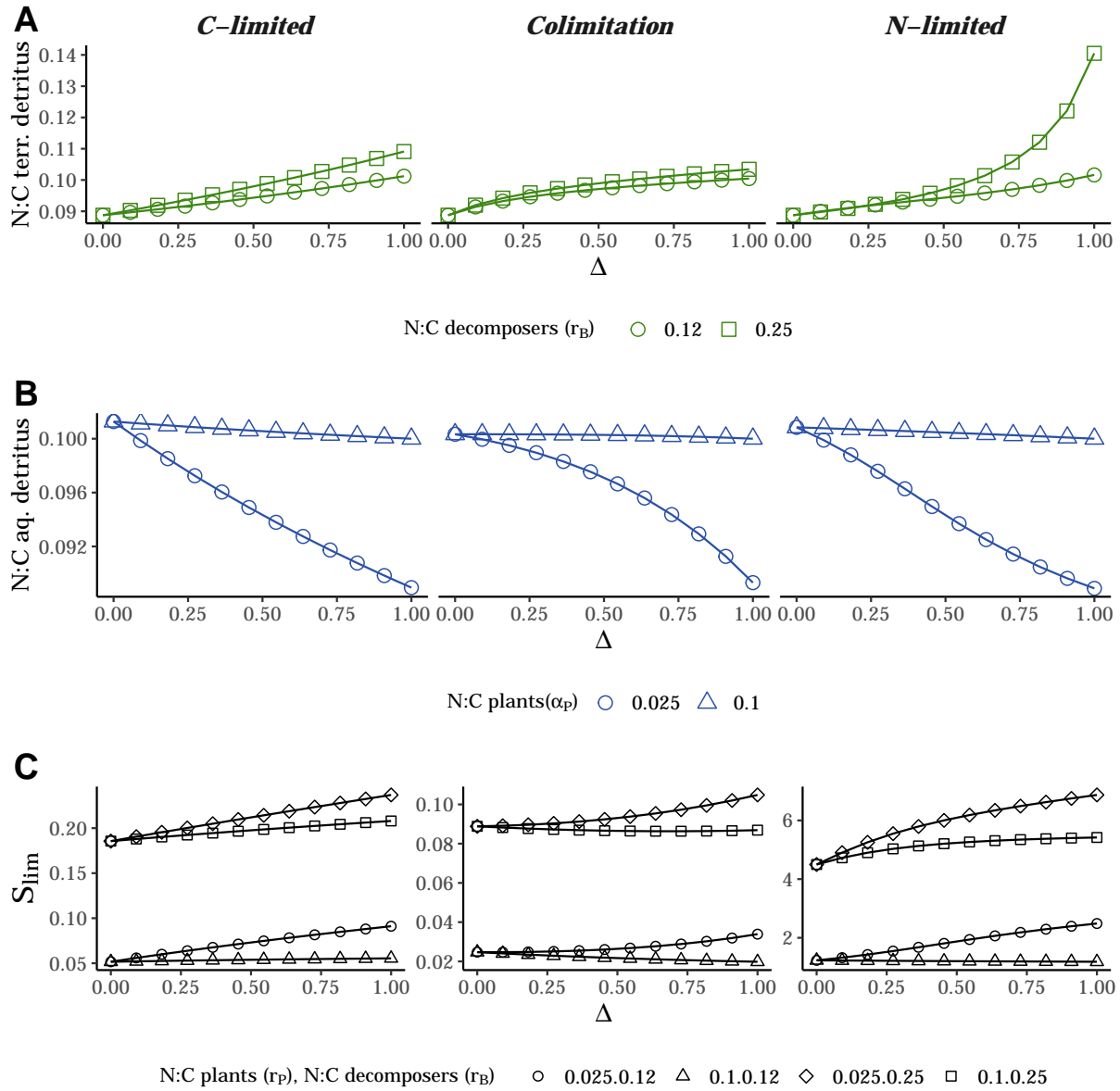


Figure S1.4: **Variation of detritus N:C and stoichiometric ratio S_{lim} in aquatic and terrestrial ecosystems under the three decomposers limitation.**

We show the variation of the N:C ratio of detritus in both ecosystems (A for Terrestrial (terr.), B for aquatic (aq.)) as a function of the fraction of subsidies being regionally transferred (Δ). We also represent the variation of the stoichiometric ratio S_{lim} (see Appendix A). A value below (resp. above) 1 indicates that decomposers are under carbon (resp. nitrogen) limitation. These analyses were performed for the three types of limitations of decomposers: C-limitation (left column), co-limitation (middle column), and N-limitation (right column). Other parameters : for (A), $\alpha_p=0.025$; for (B), $\alpha_B=0.12$.

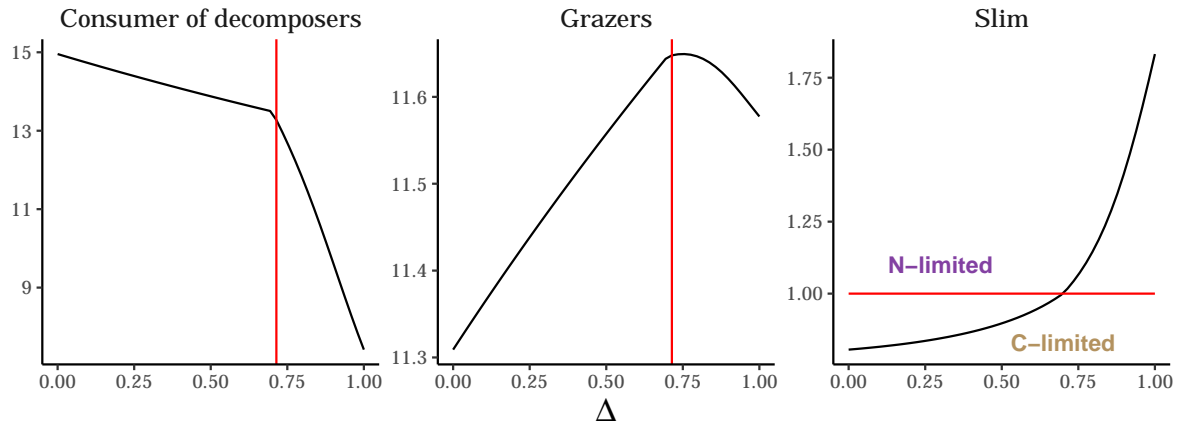


Figure S1.5: Switch in decomposers limitation from carbon to nitrogen with increasing meta-ecosystem connectivity.

When decomposers threshold limitation (S_{lim}) are near the threshold elemental ratio of 1, an increase in exchange of resources between ecosystems can relax carbon limitation until decomposers become nitrogen-limited (above red line). We also show the consumer of decomposers and grazers carbon stocks at equilibrium and how their dynamics change with the limitation of decomposers. To see this switch in decomposers limitation by spatial flows, we set $I_{N_A} = 2.5$, $I_{D_A} = 10$, $l_{D_A} = 2$, $l_{D_A} = 1$.

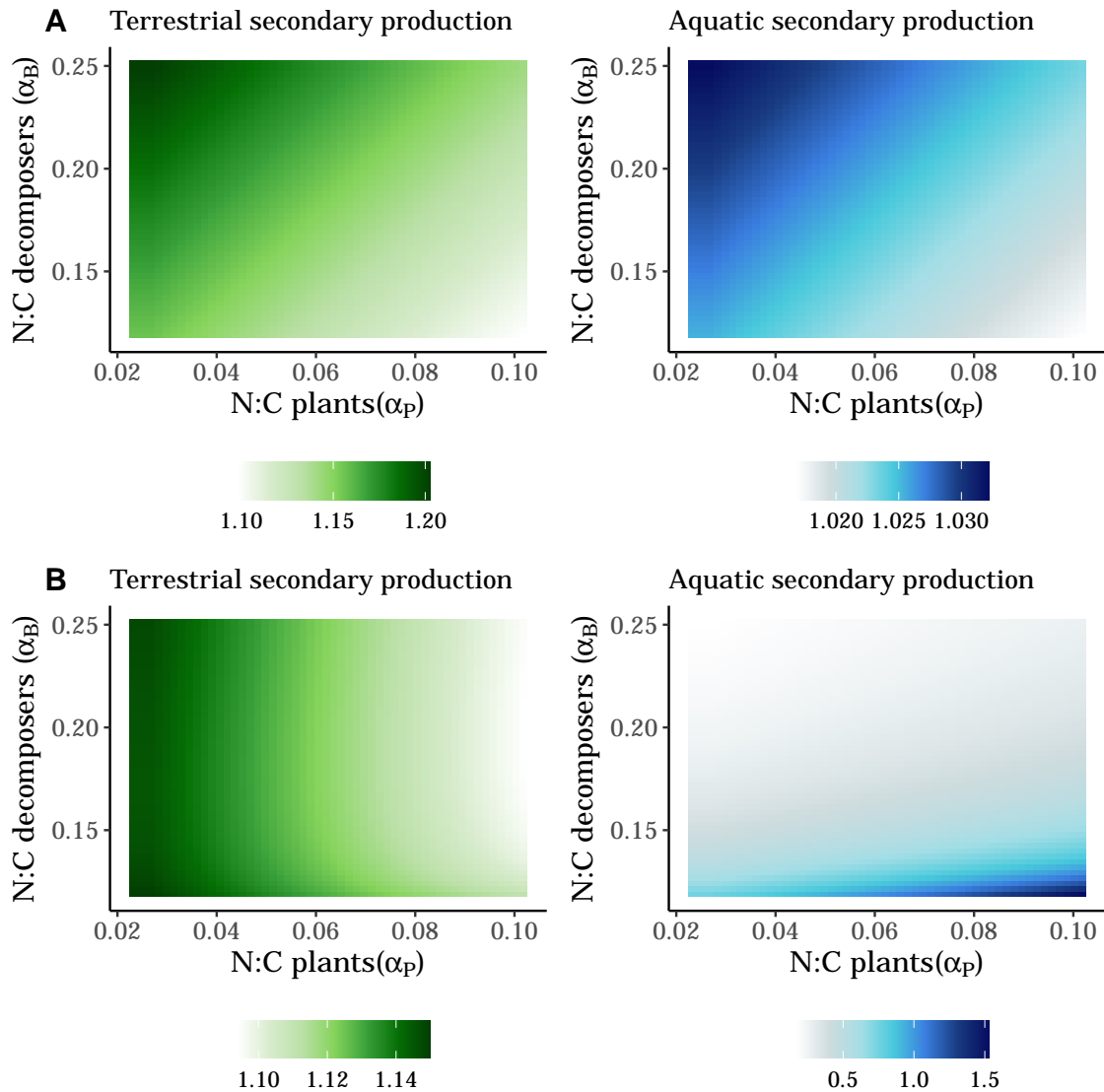


Figure S1.6: Stoichiometry of basal species drives secondary production at terrestrial-aquatic ecotone.

We show the variations in secondary production in aquatic (left) and terrestrial (right) ecosystems when ecosystems are connected through spatial flows ($\Delta = 1$) over the stoichiometric space of basal species (plant N:C in x-axis and decomposer N:C in y-axis). In panel (A), decomposers are carbon limited, while they are limited by nitrogen in panel (B). Production in both ecosystems is expressed in carbon units.

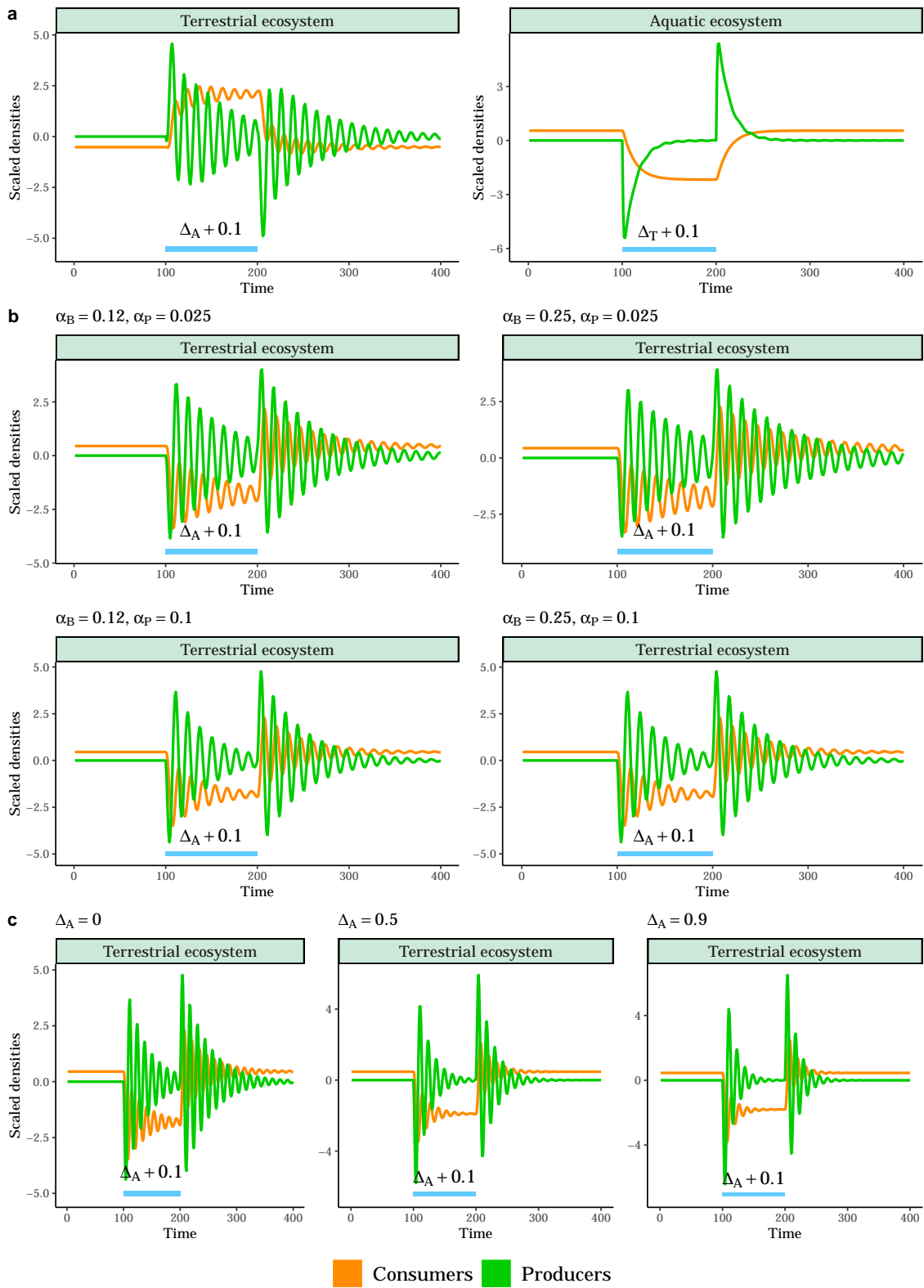


Figure S1.7: Caption on next page

713 **Caption for Fig. S1.7. Evaluating the spatial subsidies effect through the short-term**
714 **response of ecosystems.**

715 Starting from meta-ecosystem equilibrium, we increased the fraction of subsidies exported
716 to the aquatic (resp. terrestrial) ecosystem, $\Delta_T = \{\Delta_P, \Delta_C\}$ (resp. $\Delta_T = \{\Delta_B, \Delta_C\}$) by
717 0.1 ($\Delta_{\text{transient}} = \Delta + 0.1$) between $t = 100$ and $t = 200$ (blue rectangle), and observed the
718 response in terrestrial (resp. aquatic) ecosystem.

719 (a) Response of aquatic (left) and terrestrial (right) ecosystems to a transient increase in
720 terrestrial (left) and aquatic (right) subsidies exports under C-limitation of decomposers.
721 In both cases, consumers (H & C), as well as decomposers increase in density. As for the
722 long term response, complementarity of ecosystems drives an increase in trophic level
723 densities and therefore production in both ecosystems.

724 (b) Response of the aquatic ecosystem to a transient increase in exports of terrestrial
725 subsidies under N-limitation of decomposers for different stoichiometric ratio of plants
726 ($\alpha_P \in \{0.025, 0.1\}$) and decomposers ($\alpha_B \in \{0.12, 0.25\}$). As in Fig. 5, decomposer and
727 consumer densities decrease in 3 out of the 4 stoichiometric conditions. This is the spatial
728 competition between ecosystems induced by a mismatch in stoichiometry. In the one
729 case where consumers and decomposers increase in response to more subsidies from the
730 terrestrial, the mass-effect outbalances the stoichiometric mismatch mechanisms, therefore
731 increasing aquatic ecosystem production.

732 (c) Response of the aquatic ecosystem to a transient increase in exports of terrestrial
733 subsidies under N-limitation of decomposers for 3 levels of terrestrial ecosystem inputs
734 ($\Delta_X \in \{0, .5, .9\}$, where $X \in \{P, B, C, H\}$). This example illustrates the interaction between
735 stoichiometric mismatch and mass-effect mechanisms. At low coupling, stoichiometric
736 mismatches dominate the mass-effect and therefore decomposer and consumer densities
737 decrease during the transient increase of terrestrial inputs. However, for higher fraction
738 of spatial subsidies transferred, the effect is reverted as seen in Fig. 5: the mass-effect
739 mechanism outbalances the stoichiometric mismatches, therefore increasing aquatic ecosystem

⁷⁴⁰ production.

⁷⁴¹ To simplify the reading, nitrogen and detritus are not represented. Other parameters: (a):

⁷⁴² $\Delta_X = 0.5, \alpha_P = 0.025, \alpha_B = 0.12$. (b): $\Delta_X = 0$. (c): $\alpha_P = 0.1, \alpha_B = 0.25$.

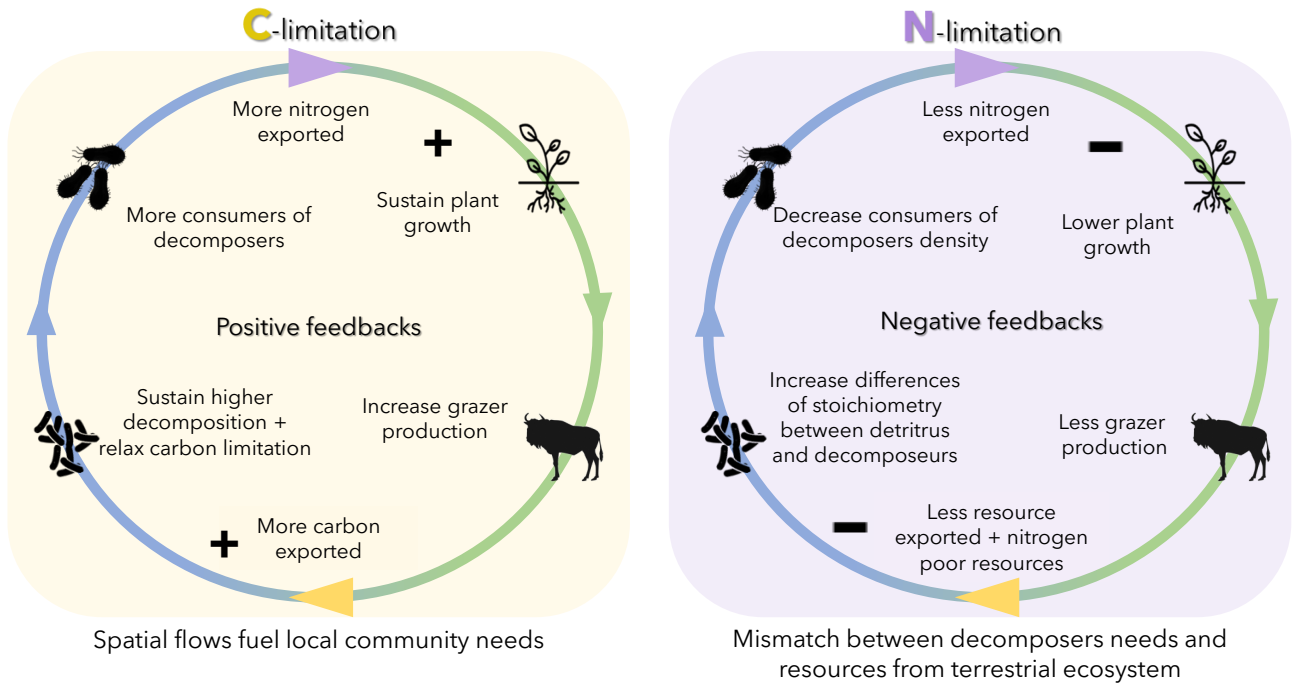


Figure S1.8: **Mechanisms and pathways of the feedbacks between aquatic and terrestrial ecosystem.** This figure does not explicitly show the mechanisms related to changes in stoichiometry of plants or decomposers.

743 S2 Extracting cross-ecosystem data flows

744 We aimed at providing a quantitative and qualitative (N:C ratio) panorama of resource
745 cross-ecosystem flows linking freshwater and terrestrial ecosystems. For that, we gathered
746 in two separate databases estimates of carbon (C) and Nitrogen (N) spatial flows on the
747 one hand and N:C ratios of resource spatial flows on the other hand. For the spatial
748 flow database, we started from the database used in Gounand *et al.*, 2018b providing
749 estimates of carbon (C) flows linking many types of ecosystems, in $gC.m^{-2}.yr^{-1}$, with the
750 area referring to the receiving ecosystem. We selected the papers reporting flows between
751 forests, grassland, desert, agroecosystem, and stream or lake. This led to 324 values of C
752 flow. We added the nitrogen quantification of the same flows when provided in the paper
753 (following the same procedure as in Gounand *et al.* to convert the value in $gN.m^{-2}.yr^{-1}$),
754 leading to 204 values for N flow. When not directly provided, we derived N flows by
755 combining N:C ratios and C flow values. Some N:C ratios were provided in the study.
756 If not, we used ratios of the more similar type of material possible provided by another
757 study (*i.e.*, at best of the same species in another study; if not available of the same genus,
758 family, order or phylum in this other). Notably, the coarser estimates (same phylum) were
759 estimated using the C and N content in dry mass (see Table.S2.1). Finally, we completed
760 the database with a few papers that were not in Gounand *et al.*, 2018b but were relevant (6
761 papers; see references 89 to 94 in the database, containing 17 N flow values), for instance,
762 some that only contained nutrient and not carbon flow measures.

763 For the stoichiometric ratio database, we collected N:C ratios of resource cross-ecosystem
764 flows at the freshwater-terrestrial interface. We recorded the ratios present in the studies
765 used in the spatial flow database or calculated them when both C and N flow estimates
766 were provided in the same study (36 N:C ratios). We completed the database with twenty
767 additional studies reporting only N:C ratios (ref 95 to 115).

768 In total, the two databases gather 324 C spatial flows, 204 N spatial flows, and 227 N:C
769 ratios.

Table S2.1: Conversion table for extracting N:C ratio from body mass.

Material	1 KJ	1g WW	1g DW	1g AFDW	Individual	Reference
Biological tissue	0.02 gC	0.09 gC	0.45 gC	0.5 gC		Weathers et al. 2013
Non woody plant detritus			0.3003 gC			Opitz et al. 1996
Terrestrial arthropods			0.496 gC and 0.1 gN			Small et al. 2013
Emergent aquatic insects (adults)			0.463 gC 0.1025 gN			Small & Pringle 2010
Emergent chironomids (adults)			0.0919 gN			Gratton et al. 2008
Amphibians (salamanders and frogs)			0.44579 gC and 0.11354 gN			Fritz & Whiles 2018
Salamanders			0.4528 gC and 0.1193 gN			Fritz & Whiles 2018
Salamander eggs and Cicadas (<i>Cicada magicada</i>)			0.463 gC and 0.0892 gN 0.55086 gC and 0.10955 gN			Fritz & Whiles 2018 Pray et al. 2009
Salmon (<i>Oncorhynchus nerka</i>)					222.72 gC 56.072 gN	Mathiesen et al. 1988

770

771 Below we summarize the empirical data in tables (Table. S2.2 for stoichiometric ratio
772 and Table. S2.3 for carbon and nitrogen flows).

Table S2.2: Summary of stoichiometric ratio of subsidies exported at terrestrial-freshwater ecotone.

q25, q50 and q75 being the first, second (median) and third quantiles of the N:C ratio of flows (molar) respectively. n is the number of data points. The data references as available in the Zenodo link.

Ecosystem	n	min	q25	q50	q75	max	Data references
Forest	122	0.00591	0.0187	0.02674	0.03846	0.2646	64, 88, 91, 110, 114, 115
Grassland	46	0.00952	0.01715	0.15129	0.18317	0.26316	91, 37, 71, 24, 26, 96, 81, 97, 98, 99, 30, 57, 82, 58, 103, 104, 105, 106, 107, 111, 112, 115
Lake	15	0.10532	0.1756	0.18182	0.20137	0.26312	37, 96, 101, 102, 111, 113
Stream	35	0.14925	0.18258	0.20152	0.2146	0.31075	95, 97, 100, 74, 108, 109, 111

773

774

Table S2.3: Summary of carbon and nitrogen flows at terrestrial-freshwater ecotone.

q25, q50 and q75 being the first, second (median) and third quantiles respectively. n is the number of data points. The data references as available in the Zenodo link. Fresh. = Freshwater and Terr. = Terrestrial

Direction	Resource	n	min	q25	q50	q75	max	Data references
Fresh. to terr.	C	105	0.00224	0.21722	1.00621	6.00359	467.87459	1, 10, 11, 19, 23, 33, 34, 35, 36, 38, 39, 40, 41, 42, 43, 44, 45, 56, 61, 65, 66, 67, 70, 72, 73, 75, 77, 78, 79, 80, 84, 87
Fresh. to terr.	N	104	0.00046	0.04041	0.18643	0.80139	79.30078	1, 10, 11, 19, 23, 33, 34, 35, 36, 38, 39, 40, 89, 42, 43, 44, 45, 56, 61, 67, 70, 72, 73, 75, 77, 78, 117, 80, 84, 87, 91, 65
Terr. to fresh.	C	208	0.10532	3.97656	47.125	191.175	2085.756	2, 3, 4, 5, 6, 7, 8, 9, 12, 13, 14, 15, 16, 17, 18, 20, 21, 22, 24, 25, 26, 27, 28, 29, 30, 31, 32, 36, 37, 39, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 62, 63, 64, 65, 68, 69, 71, 74, 76, 81, 82, 83, 85, 86, 88
Terr. to fresh.	N	93	0.00624	0.29661	0.992	2.711	208	3, 4, 9, 22, 24, 26, 30, 31, 36, 37, 39, 49, 53, 56, 57, 58, 64, 68, 69, 71, 81, 82, 83, 85, 88, 90, 91, 92, 93, 65, 94

775 **S3 Derivation of ϕ_I and ϕ_D , full model system and parameters**
 776 **values**

Table S3.1: State variables considered in the meta-ecosystem model.

Symbol	Unit	Meaning
B_{NA}	N	Nitrogen content in the decomposers
B_{CA}	C	Carbon content in the decomposers
C_{CA}	C	Carbon content in the consumers of decomposers
P_{CT}	C	Carbon content in the plants
G_{CT}	C	Carbon content in the grazers
D_{NA}	C	Nitrogen content in the aquatic detritus
D_{CA}	C	Carbon content in the aquatic detritus
D_{NT}	N	Nitrogen content in the terrestrial detritus
D_{CT}	C	Carbon content in the terrestrial detritus
N_A	N	Nitrogen stock in the aquatic ecosystem
N_T	N	Nitrogen stock in the terrestrial ecosystem

777

778

779 N:C ratios of organisms were constrained using published stoichiometric data : N:C
 780 of plants and decomposers varied between 0.025-0.1 and 0.12-0.25 respectively (Elser
 781 et al., 2000; Cleveland & Liptzin, 2007; Buchkowski et al., 2019). We fixed the N:C ratio of
 782 consumers to 0.1 as no major differences between grazers and consumers of decomposer
 783 have been documented. We used two different sets of parameters in order to understand
 784 the interactions and processes at the meta-ecosystem scale under carbon and nitrogen
 785 limitation of decomposers. The two parameter sets can be found in Table S3.3. We chose
 786 to vary the fractions of subsidies that were locally or regionally recycled (Δ) and the
 787 stoichiometry of organisms to account for both quantity and quality of subsidies (Sitters
 788 et al., 2015). Note that changing the stoichiometry of organisms directly changes their
 789 nitrogen content but not necessarily their carbon content.

Table S3.2: **Parameters meaning and symbol.**

The values are given for the C- and N-limited scenarios respectively

Parameter	Unit	Meaning
Terrestrial ecosystem		
I_{N_T}	N.day ⁻¹	Nitrogen inflow in terrestrial ecosystem
I_{D_T}	C.day ⁻¹	Detritus inflow in terrestrial ecosystem
l_{D_T}	day ⁻¹	Loss rate of detritus in terrestrial ecosystem
l_{N_T}	day ⁻¹	Loss rate of nitrogen in terrestrial ecosystem
m_T	day ⁻¹	Mineralization rate in terrestrial ecosystem
e_G	dimensionless	Growth efficiency of grazers
a_P	N ⁻¹ .day ⁻¹	Nitrogen consumption rate of plants
a_G	C ⁻¹ .day ⁻¹	Consumption rate of grazers on plants
d_G	day ⁻¹	Loss rate of grazers
d_P	day ⁻¹	Loss rate of plants
Aquatic ecosystem		
I_{N_A}	N.day ⁻¹	Nitrogen inflow in aquatic ecosystem
I_{D_A}	C.day ⁻¹	Detritus inflow in aquatic ecosystem
l_{D_A}	day ⁻¹	Loss rate of detritus in aquatic ecosystem
l_{N_A}	day ⁻¹	Loss rate of nitrogen in aquatic ecosystem
m_A	day ⁻¹	Mineralization rate in aquatic ecosystem
e_B	dimensionless	Growth efficiency of decomposers
e_C	dimensionless	Growth efficiency of consumers
a_{BN}	day ⁻¹	Nitrogen consumption rate of decomposers
a_{BD}	day ⁻¹	Detritus consumption rate of decomposers
a_C	C ⁻¹ .day ⁻¹	Consumption rate of consumers
d_B	day ⁻¹	Loss rate of decomposers
d_C	day ⁻¹	Loss rate of consumers
Spatial flows		
$\Delta_B, \Delta_C, \Delta_P, \Delta_G$	dimensionless	Fraction of subsidies transferred to the other ecosystem
Stoichiometric ratio		
α_B	N/C (molar)	Stoichiometric ratio of decomposers
α_C	N/C (molar)	Stoichiometric ratio of consumer
α_P	N/C (molar)	Stoichiometric ratio of plants
α_G	N/C (molar)	Stoichiometric ratio of grazers

790 We performed a sensitivity analysis to make sure that our results were robust to
 791 variations in parameter values. We established the range of variation of each parameter
 792 so that (i) we stayed in the same scenario of decomposer limitation and (ii) all trophic
 793 levels were coexisting along the ranges of parameter values explored (see Table S7.1). We
 794 evaluated the quantitative effect of parameter variation by taking the range of variation
 795 of production (*i.e.*, $|max(Production) - min(Production)|$) over the range of parameter
 796 values explored for two different stoichiometries of decomposers ($\alpha_B \in \{0.12, 0.25\}$) and
 797 two stoichiometries of plants ($\alpha_P \in \{0.025, 0.1\}$).

798 Derivation of ϕ_I and ϕ_D

Stoichiometric homeostasis of decomposers implies :

$$\frac{dB_{N_A}}{dt} = \alpha_B \frac{dB_{C_A}}{dt}$$

799 which constrains the immobilization and decomposition flows :

$$\phi_I = \frac{\alpha_B - \alpha_D}{\alpha_B} \phi_D, \text{ with } \alpha_D = \frac{D_{N_A}}{D_{C_A}}$$

800 We explored in the main text two scenarios: decomposers are limited by nitrogen or
 801 by carbon. When decomposers are N-limited, decomposers immobilize nitrogen and
 802 modulate their decomposition to maintain their homeostasis. Therefore: ϕ_I constrains ϕ_D .
 803 To the contrary, in the C-limited case, the decomposition process (ϕ_D) constrains the uptake
 804 or release of nitrogen (ϕ_I). Thus, we get the following formulas for the immobilization and
 805 decomposition flows for carbon and nitrogen-limited decomposers :

	ϕ_I	ϕ_D
806 C-limited	$\frac{\alpha_B - \alpha_D}{\alpha_B} \phi_D$	$a_B D_{C_A}$
N-limited	$a_{BN} N_A$	$\frac{\alpha_B}{\alpha_B - \alpha_D} \phi_I$

In the nitrogen-limited environment, decomposers feed on both nitrogen and detritus. Under such limitation, a decrease in N:C ratio of detritus limits the decomposition rate of decomposers (*i.e.*, ϕ_D decreases due to an increase of $\alpha_B - \alpha_D$). On the contrary, when decomposers are C-limited they decompose detritus into nitrogen and immobilize (when $\alpha_B - \alpha_D > 0$) or excrete (when $\alpha_B - \alpha_D < 0$) nitrogen. At equilibrium, decomposers are C-limited (resp. N-limited) if the limitation threshold S_{lim} is below (resp. above) the threshold elemental ratio (TER, Frost *et al.*, 2006) that equals 1 :

$$\text{where } S_{lim} = \frac{(\alpha_B - \bar{\alpha}_D)a_B\bar{D}_{C_A}}{\alpha_B a_{BN}\bar{N}_A}, \quad \bar{\alpha}_D = \frac{\bar{D}_{N_A}}{\bar{D}_{C_A}}$$

807 , where the bar is used for equilibrium quantities.

808 The carbon or nitrogen limitations of decomposers might change with the stoichiometry
 809 of both decomposers and detritus and with the resource stocks at equilibrium. We assumed
 810 donor-control flows for decomposers (Cherif & Loreau, 2013; Daufresne & Loreau, 2001),
 811 meaning that decomposition and immobilization flow only depend on the quantity of
 812 resources but not on the decomposer density. Note that using Lotka-Volterra functional
 813 response for decomposers gave qualitatively the same results, as decomposers' density was
 814 constant due to top-down control by their consumers, but the species and stock dynamics
 815 were oscillating under N-limitation. We used the Liebig law, which assumes that the
 816 limiting resource is the scarcer one in the ecosystem, to express the decomposition and
 817 immobilization flows :

$$\phi_I = \min\left(\overbrace{\frac{(\alpha_B - \alpha_D)}{\alpha_B} e_B a_{BD} D_{C_A}}^{\text{C-limited}}, \overbrace{a_{BN} N_A}^{\text{N-limited}}\right)$$

$$\phi_D = \min\left(\overbrace{e_B a_{BD} D_{C_A}}^{\text{C-limited}}, \overbrace{\left(\frac{\alpha_B - \alpha_D}{\alpha_B}\right)^{-1} a_{BN} N_A}^{\text{N-limited}}\right)$$

818 **Full model system**

819 With the spatial flow of subsidies, the nitrogen dynamics of plants, consumers, and grazers,
820 and both the decomposition and immobilization flows, we get the following system. First,
821 for terrestrial ecosystem :

$$\begin{aligned}
\frac{dG_{C_T}}{dt} &= \overbrace{e_G a_G P_{C_T} G_{C_T}}^{\text{Consumption of grazers (carbon)}} - \overbrace{d_G G_{C_T}}^{\text{Loss of carbon by grazers}} \\
\frac{dG_{N_T}}{dt} &= \overbrace{e_G a_G P_{C_T} G_{C_T} \alpha_G - d_G G_{C_T} \alpha_G}^{\text{Same but for nitrogen part}} \\
\frac{dP_{C_T}}{dt} &= \overbrace{a_P N_T P_{C_T}}^{\text{Photosynthesis}} - \overbrace{a_G P_{C_T} G_{C_T}}^{\text{Consumption by grazers}} - \overbrace{d_P P_{C_T}}^{\text{Loss of carbon by plants}} \\
\frac{dP_{N_T}}{dt} &= \overbrace{a_P N_T P_{C_T} \alpha_P - a_G P_{C_T} G_{C_T} \alpha_P - d_P P \alpha_P}^{\text{Same but for nitrogen part}} \\
\frac{dD_{N_T}}{dt} &= \overbrace{I_{D_T} \frac{D_{N_T}}{D_{C_T}}}^{\text{Inflow of detritus}} - \overbrace{l_{D_T} D_{N_T}}^{\text{Leaching of detritus}} + \overbrace{\alpha_G d_G G_{C_T} (1 - \Delta_G)}^{\text{Grazers-produced detritus locally recycled}} + \\
&\quad \overbrace{\alpha_P d_P P_{C_T} (1 - \Delta_P)}^{\text{Plants-produced detritus locally recycled}} + \overbrace{\alpha_C d_C C_{C_A} \Delta_C}^{\text{Consumers-produced detritus regionally transferred}} + \\
&\quad \overbrace{\alpha_B d_B B_{C_A} \Delta_B}^{\text{Decomposers-produced detritus regionally transferred}} - \overbrace{m_T D_{N_T}}^{\text{Mineralization of detritus}} \\
\frac{dD_{C_T}}{dt} &= \overbrace{I_{D_T} - l_{D_T} D_{C_T} + d_G G_{C_T} (1 - \Delta_G) + d_P P_{C_T} (1 - \Delta_P) + d_C C_{C_A} \Delta_C + d_B B_{C_A} \Delta_B - m_T D_{C_T}}^{\text{Same as above but for the carbon part of detritus}} \\
\frac{dN_T}{dt} &= \overbrace{I_{N_T}}^{\text{Nitrogen inflow}} - \overbrace{l_{N_T} N_T}^{\text{Leaching of nitrogen}} + \overbrace{(\alpha_P - e_G \alpha_G) a_G P_{C_T} G_{C_T} (1 - \Delta_G)}^{\text{Nitrogen from stoichiometric imbalance of grazers}} + \\
&\quad \overbrace{(\alpha_B - e_C \alpha_C) a_C B_{C_A} C_{C_A} \Delta_C}^{\text{Nitrogen from stoichiometric imbalance of consumers of decomposers}} \\
&\quad - \overbrace{\alpha_P a_P N_T P_{C_T}}^{\text{Nitrogen uptake from plants}} + \overbrace{m_T D_{N_T}}^{\text{Mineralization of detritus into nitrogen}}
\end{aligned}$$

And for aquatic ecosystem :

$$\begin{aligned}
\frac{dC_{C_A}}{dt} &= \overbrace{e_C a_C B_{C_A} C_{C_A}}^{\text{Consumption by consumers (carbon)}} - \overbrace{d_C C_{C_A}}^{\text{Loss of carbon by consumers}} \\
\frac{dC_N}{dt} &= \overbrace{e_C a_C B_{C_A} C_{C_A} \alpha_C - d_C C_{C_A} \alpha_C}^{\text{Same but for nitrogen part}} \\
\frac{dB_{C_A}}{dt} &= \overbrace{\phi_D}^{\text{Decomposition of detritus (carbon)}} - \overbrace{d_B B_{C_A}}^{\text{Loss of carbon by decomposers}} - \\
&\quad \overbrace{a_C B_{C_A} C_{C_A}}^{\text{Consumption by consumers (carbon)}} - \overbrace{m_A B_{C_A}}^{\text{Heterotrophic respiration}} \\
\frac{dB_{N_A}}{dt} &= \overbrace{\phi_I \alpha_B}^{\text{Immobilization of detritus}} + \overbrace{\phi_D \frac{D_{N_A}}{D_{C_A}}}^{\text{Decomposition of detritus (nitrogen)}} - \\
&\quad \overbrace{a_C B_{C_A} C_{C_A} \alpha_B}^{\text{Consumption by consumers (nitrogen)}} - \overbrace{d_B B_{C_A} \alpha_B}^{\text{Loss of nitrogen by decomposers}} - \overbrace{m_A B_{C_A} \alpha_B}^{\text{Nutrient mineralization}} \\
\frac{dD_{N_A}}{dt} &= \overbrace{I_{D_A} \frac{D_{N_A}}{D_{C_A}}}^{\text{Inflow of detritus}} - \overbrace{l_{D_A} D_{N_A}}^{\text{Leaching of detritus}} + \overbrace{\alpha_C d_C C_{C_A} (1 - \Delta_C)}^{\text{Consumers-produced detritus locally transferred}} + \\
&\quad \overbrace{\alpha_B d_B B_{C_A} (1 - \Delta_B)}^{\text{Decomposers-produced detritus locally transferred}} + \overbrace{\alpha_G d_G G_{C_T} \Delta_G}^{\text{Grazers-produced detritus regionally recycled}} + \\
&\quad \overbrace{\alpha_P d_P P_{C_T} \Delta_P}^{\text{Plants-produced detritus regionally recycled}} - \overbrace{\phi_D \frac{D_{N_A}}{D_{C_A}}}^{\text{Decomposition of detritus}} \\
\frac{dD_{C_A}}{dt} &= \overbrace{I_{D_A} - l_{D_A} D_{C_A} + d_C C_{C_A} (1 - \Delta_C) + d_B B_{C_A} (1 - \Delta_B) + d_G G_{C_T} \Delta_G + d_P P_{C_T} \Delta_P - \phi_D}^{\text{Same but for carbon}} \\
\frac{dN_A}{dt} &= \overbrace{I_{N_A}}^{\text{Nitrogen inflow}} - \overbrace{l_{N_A} N_A}^{\text{Leaching of nitrogen}} + \overbrace{(\alpha_B - e_C \alpha_C) a_C B_{C_A} C_{C_A} (1 - \Delta_C)}^{\text{Nitrogen from stoichiometric imbalance of consumers of decomposers}} + \\
&\quad \overbrace{(\alpha_P - e_G \alpha_G) a_G P_{C_T} G_{C_T} \Delta_G}^{\text{Nitrogen from stoichiometric imbalance of grazers}} \\
&\quad - \overbrace{\phi_I \alpha_B}^{\text{Immobilization by decomposers}} + \overbrace{m_A B_{C_A} \alpha_B}^{\text{Mineralization of detritus into nitrogen by decomposers}} \\
\phi_I &= \min\left(\frac{\alpha_B - \frac{D_{N_A}}{D_{C_A}}}{\alpha_B}\right) e_B a_{BD} D_{C_A}, a_{BN} N_A \\
\phi_D &= \min\left(e_B a_{BD} D_{C_A}, \left(\frac{\alpha_B - \frac{D_{N_A}}{D_{C_A}}}{\alpha_B}\right)^{-1} a_{BN} N_A\right)
\end{aligned}$$

822 **Details on the simulation method**

823 The model was run over a long time (10000-time steps), which was more than enough to
824 converge to the equilibrium of each trophic level and resources (with Type I functional
825 or donor-controlled responses, the systems typically converge in about 1000 to 2000 time
826 steps). Running the model for such a long time is necessary to compute the feedbacks. A
827 trophic level (*resp.*, a resource) was considered extinct (*resp.* empty) if its value was below
828 10^{-5} .

829 **Parameter values**

830 We focused our analysis on the qualitative behavior that could emerge in ecosystems
831 coupled by spatial flows with different stoichiometric compositions, rather than exploring
832 the full range of parameter values. By compiling data from the literature, we found values
833 of N:C to be lower in aquatic consumers than in their resource (bacterial decomposers),
834 while N:C is typically higher in grazers than in plants (Fig. 1B). Nevertheless, we performed
835 analyses on the parameter values (Appendix S7), the structure of the trophic chains
836 (Appendix S4), and the functional responses (Appendix S6). Functional response parameters
837 were taken from the literature and some of them were assumed to allow coexistence (all
838 resource stocks and trophic levels having a positive value) in each isolated ecosystem.
839 Note that coexistence was facilitated by the inflow of detritus in the aquatic ecosystem
840 (I_{D_A}) that generates a continuous input of carbon in the aquatic ecosystem. More precisely,
841 parameters captured the differences in energy transfer and primary productivity between
842 net heterotrophic and net autotrophic ecosystems (*i.e.* forest doing more primary production
843 while streams are more efficient to transfer energy up to the higher trophic levels; Shurin
844 et al., 2006; Gounand et al., 2020; Harvey et al., 2021). Therefore, we set $a_C > a_G$ and
845 $e_C > e_G$. Similarly, we accounted for differences in mineralization rates, with aquatic
846 ecosystems being more efficient to mineralize organic matter compared to terrestrial ones
847 ($m_T < m_A$; Gounand et al., 2020). There are two parameter sets for C- and N-limitation.
848 These parameter sets were also chosen so that decomposers remained in the same limitation
849 all over the range of basal species stoichiometry.

850

Table S3.3: Parameters values for the simulations performed.

The values are given for the C- and N-limited scenarios respectively

Class	Parameter	Value	Source
Terrestrial ecosystem	I_{N_T}	7	Assumed value
	I_{D_T}	7	Assumed value
	l_{D_T}	1	Assumed value
	l_{N_T}	1	Assumed value
	m_T	0.1	Assumed value
	e_G	0.25	Assumed value
	a_P	0.34	Cherif & Loreau, 2013
	a_G	0.2	Assumed value
	d_G	0.1	Attayde & Ripa, 2008
	d_P	0.1	Attayde & Ripa, 2008
Aquatic ecosystem	I_{N_A}	7, 2	Assumed values
	I_{D_A}	7, 12	Assumed values
	l_{D_A}	1	Assumed value
	l_{N_A}	1	Assumed value
	m_A	0.5	Zelnik et al., 2021
	e_B	0.5	del Giorgio & Cole, 1998
	e_C	0.5	Zelnik et al., 2021
	a_{BN}	1, 0.25	Zou et al., 2016
	a_{BD}	0.83	Boit et al., 2012
	a_C	0.3	Assumed value
	d_B	0.1	Attayde & Ripa, 2008
	d_C	0.1	Assumed value
Spatial flows	$\Delta_B, \Delta_C, \Delta_P, \Delta_G$	[0,1]	vary
Stoichiometric ratio	α_B	[0.12-0.25]	Cleveland & Liptzin, 2007 Buchkowski et al., 2019
	α_C		Elser et al., 2000 Martinson et al., 2008
	α_P		Cleveland & Liptzin, 2007 Buchkowski et al., 2019
	α_G		Mcgroddy et al., 2004 Elser et al., 2000 Martinson et al., 2008

851 **S4 Adding a trophic level**

852 In this section, we relaxed the hypothesis on the structure of the two ecosystems by adding
853 a top predator in both the net autotrophic (T_G) and net heterotrophic ecosystems (T_C). Top
854 predators of grazers and consumers of decomposers (T_G and T_C respectively) consume
855 primary consumers at a rate a_{TG} and a_{TC} but only a fraction e_{TG}, e_{TC} of the ingested food is
856 assimilated. We considered that the stoichiometry of these top predators is similar between
857 ecosystems ($\alpha_{TG} = \alpha_{TC} = 0.1$). Both top predators are held at a fixed stoichiometry. As
858 primary consumers, top predators excrete the excess of nitrogen due to stoichiometric
859 imbalance between their resource need and their prey stoichiometry: rate $\beta_{Ti}f_{Ti}(i, Ti)$,
860 where $\beta_{Ti} = (\alpha_i - e_{Ti}\alpha_{Ti})$ and $i \in \{G, C\}$. Finally, each top predator has its decay rate d_{TG}
861 or d_{TC} . The detritus produced also fuels the detritus pool of each ecosystem. The results
862 are presented in Figs. S4.1-4, and show qualitatively similar results compared to the ones
863 in the main text. Interestingly, in a C-limited scenario when plants and decomposers are
864 no longer controlled by their respective consumers, plants reach high biomass and seem to
865 drive the effects at the meta-ecosystem scale (*i.e.*, not much variation is observed along
866 the stoichiometric ratio of decomposers). In the N-limited scenario, the stoichiometric
867 ratio of decomposers has a drastic impact in exacerbating (low α_B) or reducing (high
868 α_B) the stoichiometric mismatch with the detritus. This drives the patterns observed in
869 Fig. S4.2-left: productions in the aquatic ecosystem is maximized when the stoichiometric
870 mismatch between decomposers and their detritus is low (low α_B), and when terrestrial
871 ecosystem export carbon poor plant subsidies (low α_P).

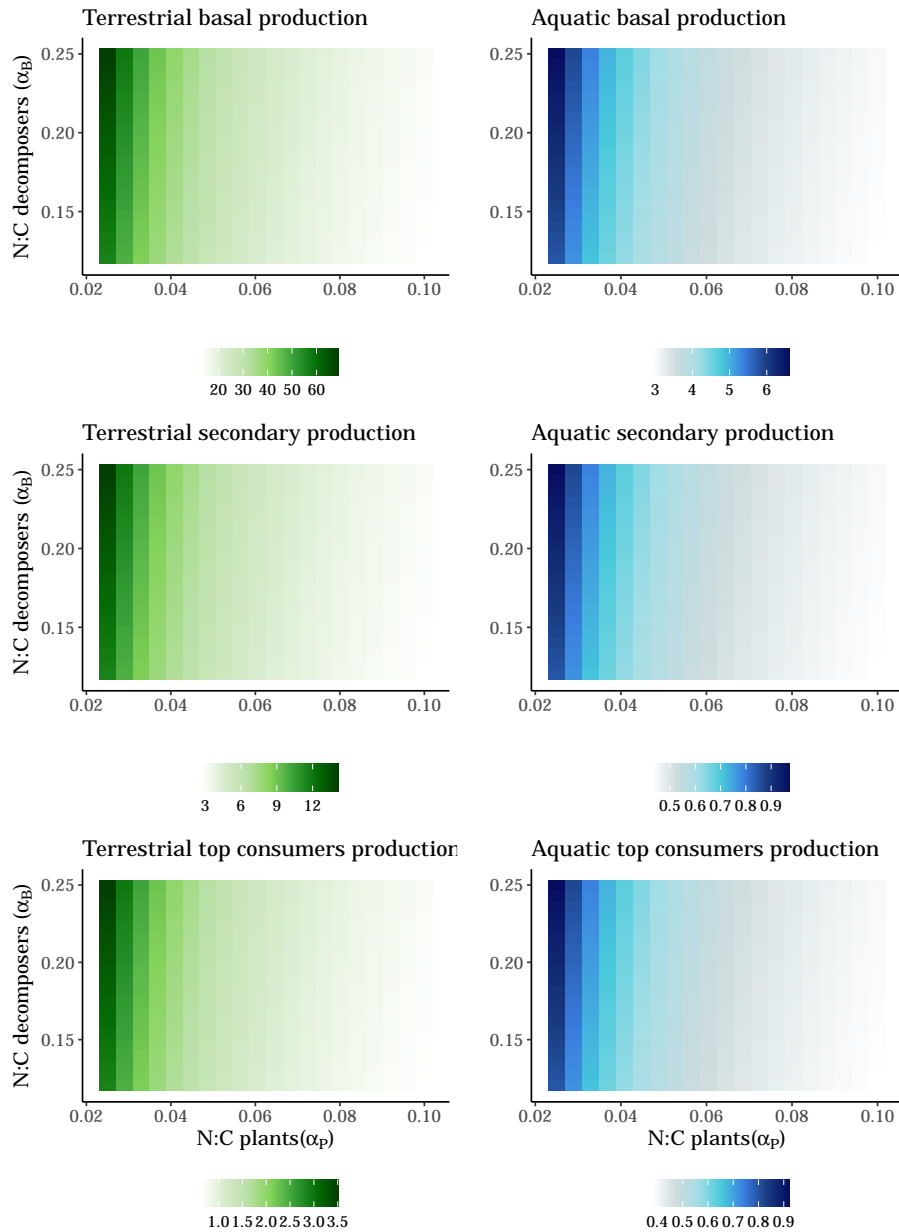


Figure S4.1: **Sensitivity analysis of the food-web structure: C-limited decomposers..** We performed sensitivity analysis on the food-webs structure by adding top predators in both ecosystems. We measured the primary, secondary, and top production in both terrestrial and aquatic ecosystems. The parameters used are the same as in the C-limited scenario with an exception for a_P , a_G , and a_C which were set to 0.1, 0.4, and 0.5 respectively to allow coexistence. Top predator parameters were chosen so that we keep coexistence for the range of stoichiometric parameters explored: $a_{TC}=0.1$, $e_{TC}=1$, $a_{TG}=0.5$, $e_{TG}=0.25$, $d_{TC} = 0.05$ and $d_{TH} = 0.15$. Here decomposers are carbon limited.

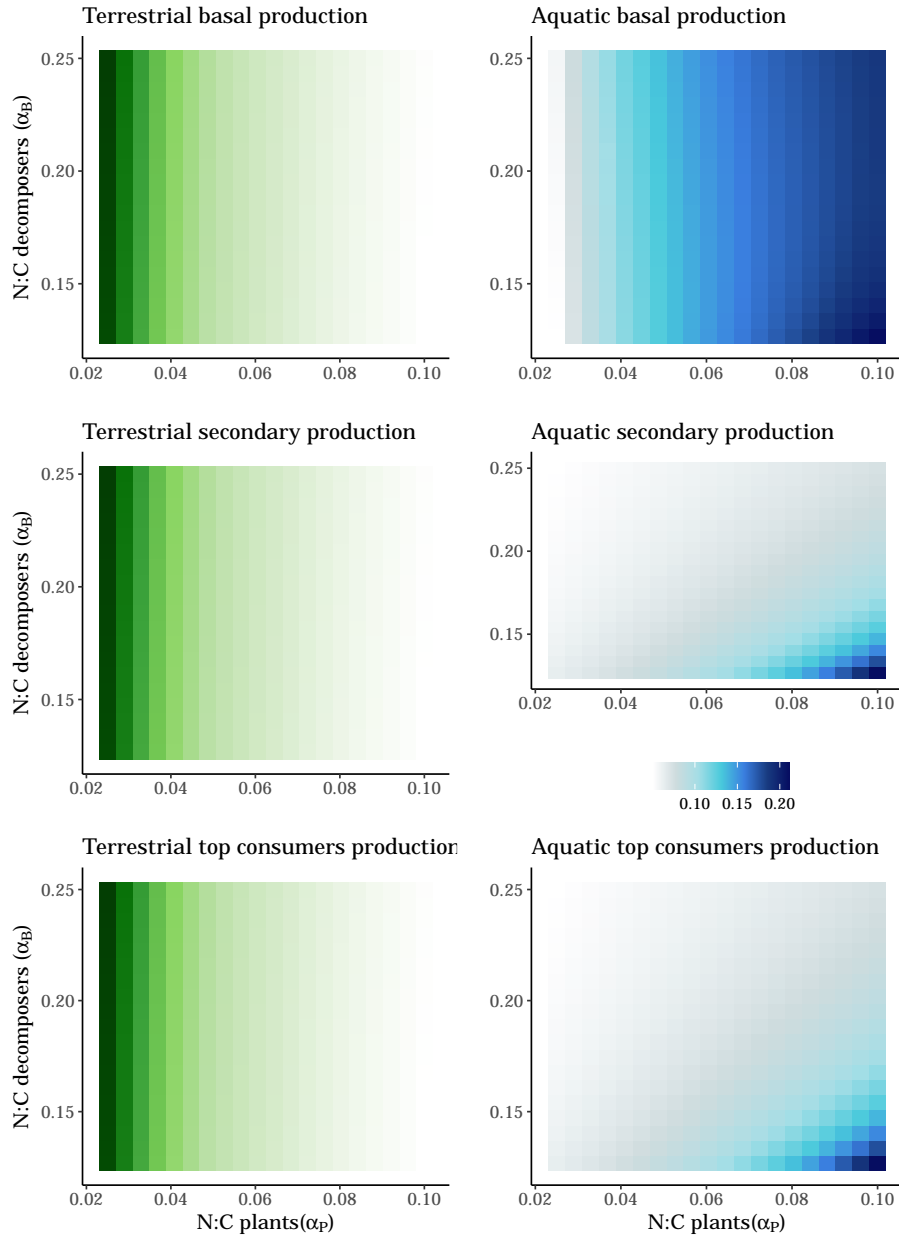


Figure S4.2: **Sensitivity analysis of the food-web structure: N-limited decomposers..**
 The legend is the same as in Fig. S4.1. We set: $I_{N_A}=5$, $l_{N_G}=2$, $I_{D_A}=12$, $l_{D_A}=1.5$ and $a_{BN}=0.1$ such that decomposers are nitrogen limited.

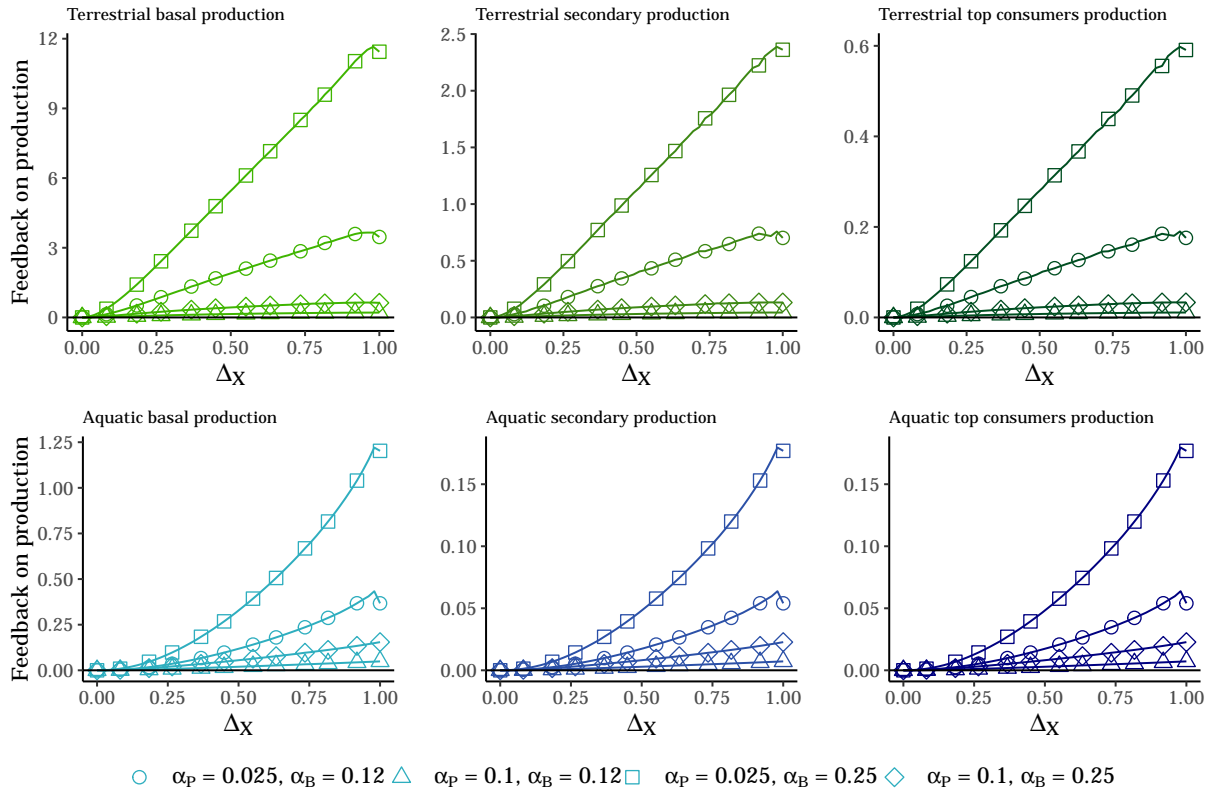


Figure S4.3: **Sensitivity analysis of the food-web structure: feedbacks under C-limited decomposers..**

We computed the feedback as shown in Fig. S1.1 and Eq. 4. The feedback is computed for each trophic level (columns) in both ecosystems (rows). Here decomposers are limited by carbon.

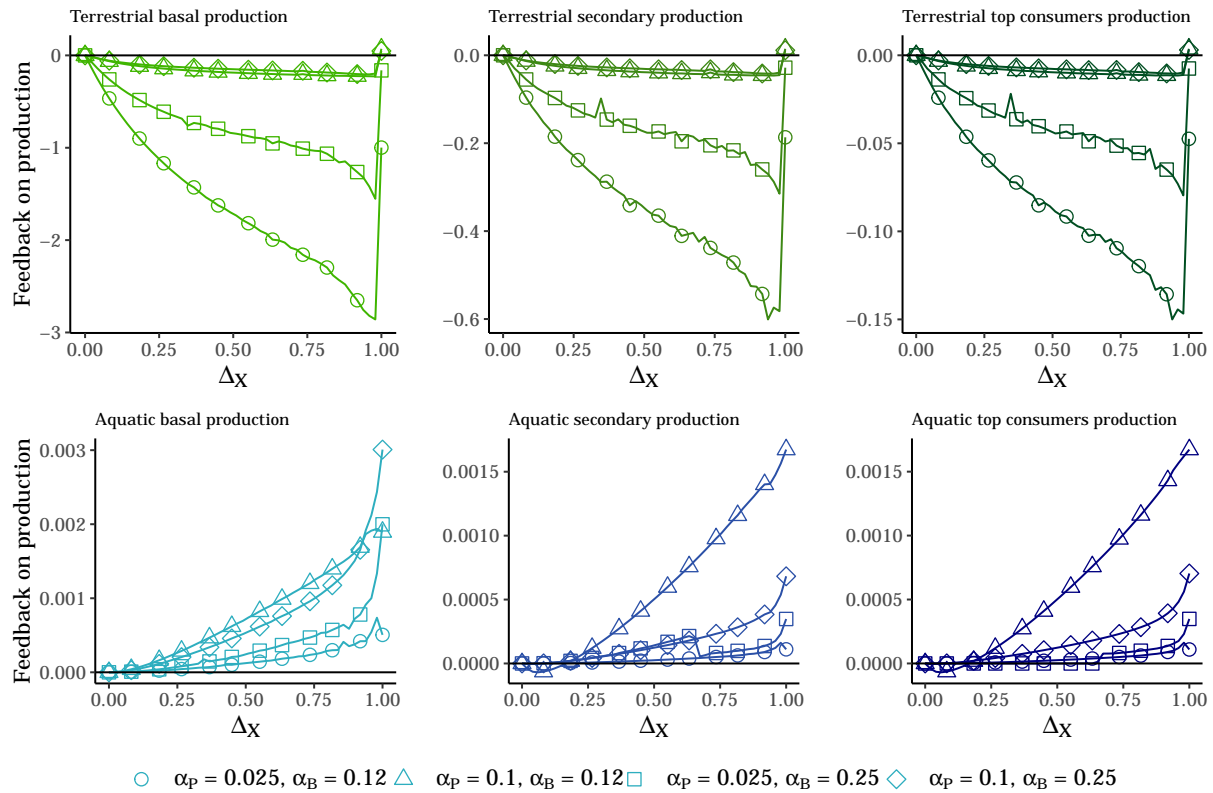


Figure S4.4: **Sensitivity analysis of the food-web structure: feedbacks under N-limited decomposers..**

We computed the feedback as shown in Fig. S1.1 and Eq. 4. The feedback is computed for each trophic level (columns) in both ecosystems (rows). Here decomposers are limited by nitrogen.

872 S5 Co-limitation of decomposers

873 In the main text, we restricted the analysis to the case where a strict limitation of carbon
874 or nitrogen was observed in decomposer populations. Here we relax this hypothesis by
875 assuming that decomposers are co-limited by nitrogen and carbon. In fact, co-limitation is
876 expected to be selected at the community scale due to competitive exclusion that favors
877 the most competitive species for nitrogen (plants or decomposers). Co-limitation has
878 been experimentally observed (Danger et al., 2008; Daufresne et al., 2008) and previously
879 considered in a few non-spatial theoretical models (Cherif & Loreau, 2007; Halvorson
880 et al., 2017). Here we investigate the impact of co-limitation in a meta-ecosystem context.
881 We considered independent co-limitation which assumes a synergy between two limiting
882 resources (Harpole et al., 2011; Sperfeld et al., 2016). When decomposers are co-limited,
883 the decomposition flux is defined as $\phi_D = e_B a_{BD} D_{C_A} a_{BN} N_A B_{C_A}$ and immobilization flux
884 as $\phi_I = \frac{\alpha_B - \alpha_D}{\alpha_B} \phi_D$ so that decomposers are held at a constant stoichiometry (Sperfeld
885 et al., 2012; Wirtz & Kerimoglu, 2016). Under the co-limitation scenario for decomposers,
886 we chose to represent the primary production with ϕ_D .

887 The parameters were the same as in the C-limited scenario (see Table S3.3).

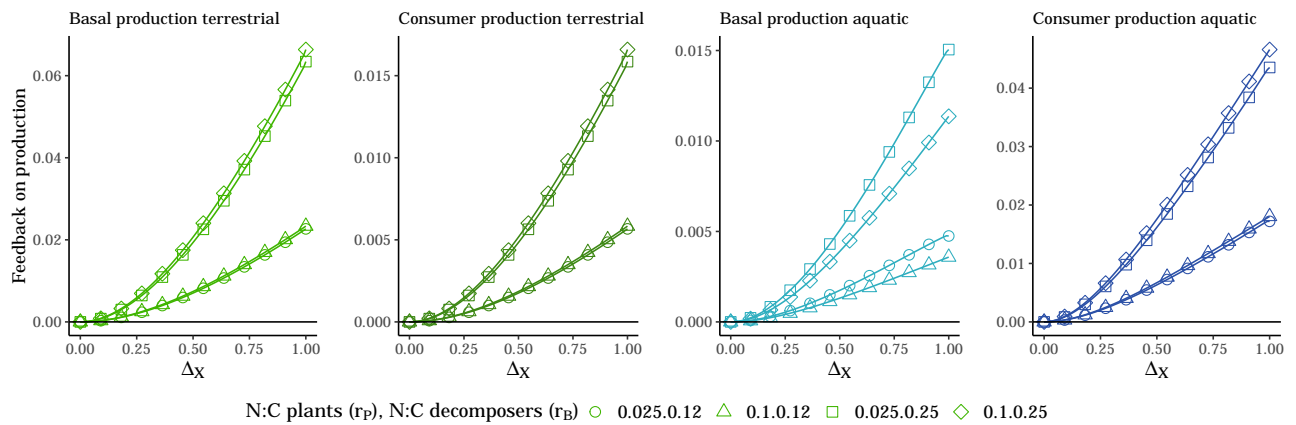


Figure S5.1: Feedback at the landscape extent under co-limitation of decomposers. We computed the feedback as shown in Fig. S1.1 and Eq. 4. The feedback was computed for each of the trophic levels in both ecosystems (columns) under the co-limitation of decomposers.

888 **S6 Donor-Control functional responses**

889 In this section, we performed a sensitivity analysis on the functional responses used in
890 the main text by using donor-control functional responses for each trophic interaction. In
891 this case, the flow only depends on the size of the donor pool (*e.g.*, $f_P = a_P N_T$ for plants).
892 Parameters are the same as in Table S3.3. We set $l_{N_A} = 2$ in the N-limited scenario so
893 that decomposers stayed in nitrogen limitation for the range of stoichiometric parameters
894 explored. The results with donor-control functional responses are qualitatively similar to
895 the ones in the main text (see Figs. S6.1, S6.2, S6.3).

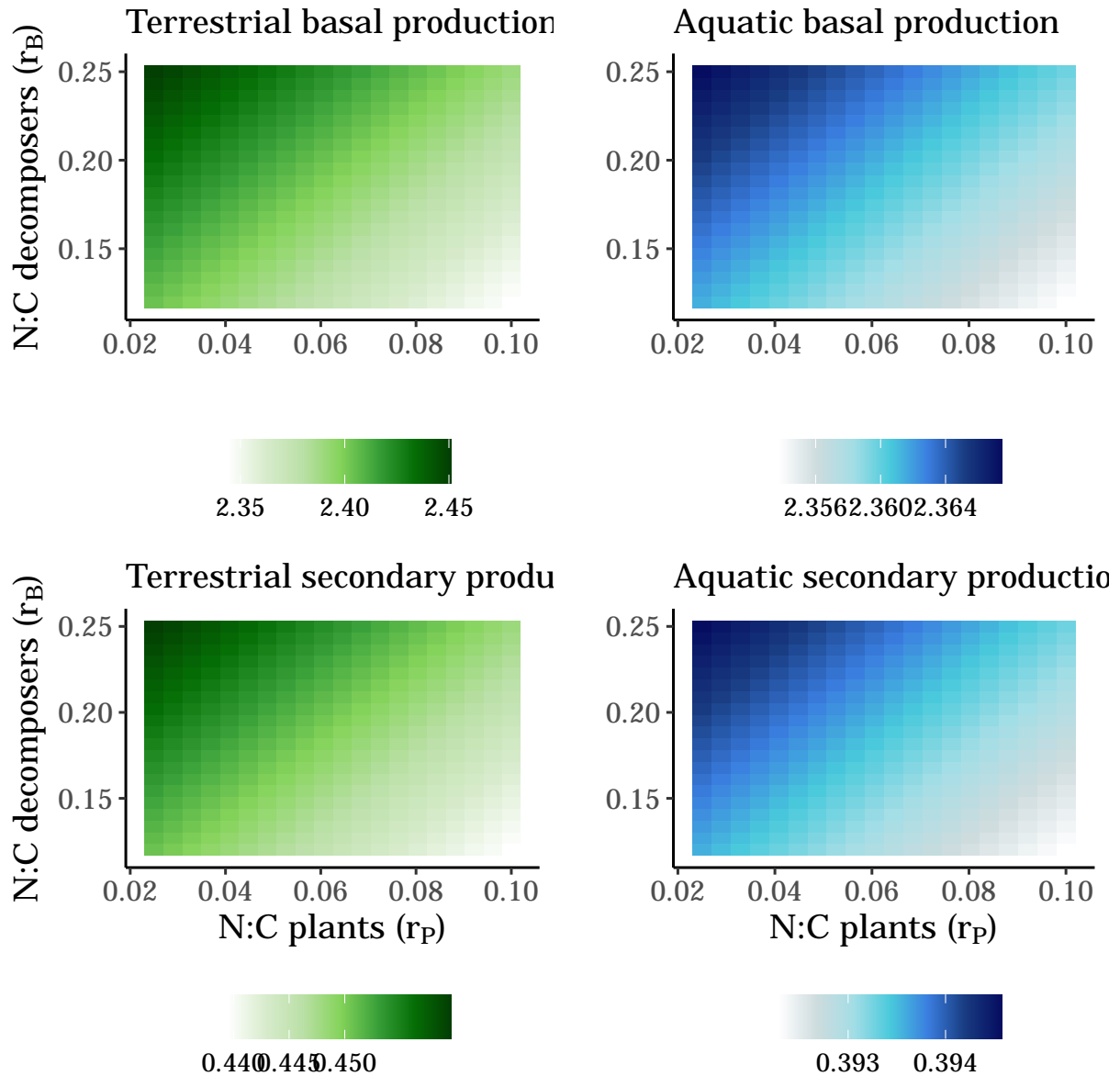


Figure S6.1: **Main conclusions are robust to donor-control functional responses under the carbon limitation of decomposers.**

The legend is the same as in Fig. 3 but we also show the secondary production of both terrestrial and aquatic ecosystems (bottom figures). Here, decomposers are carbon limited.

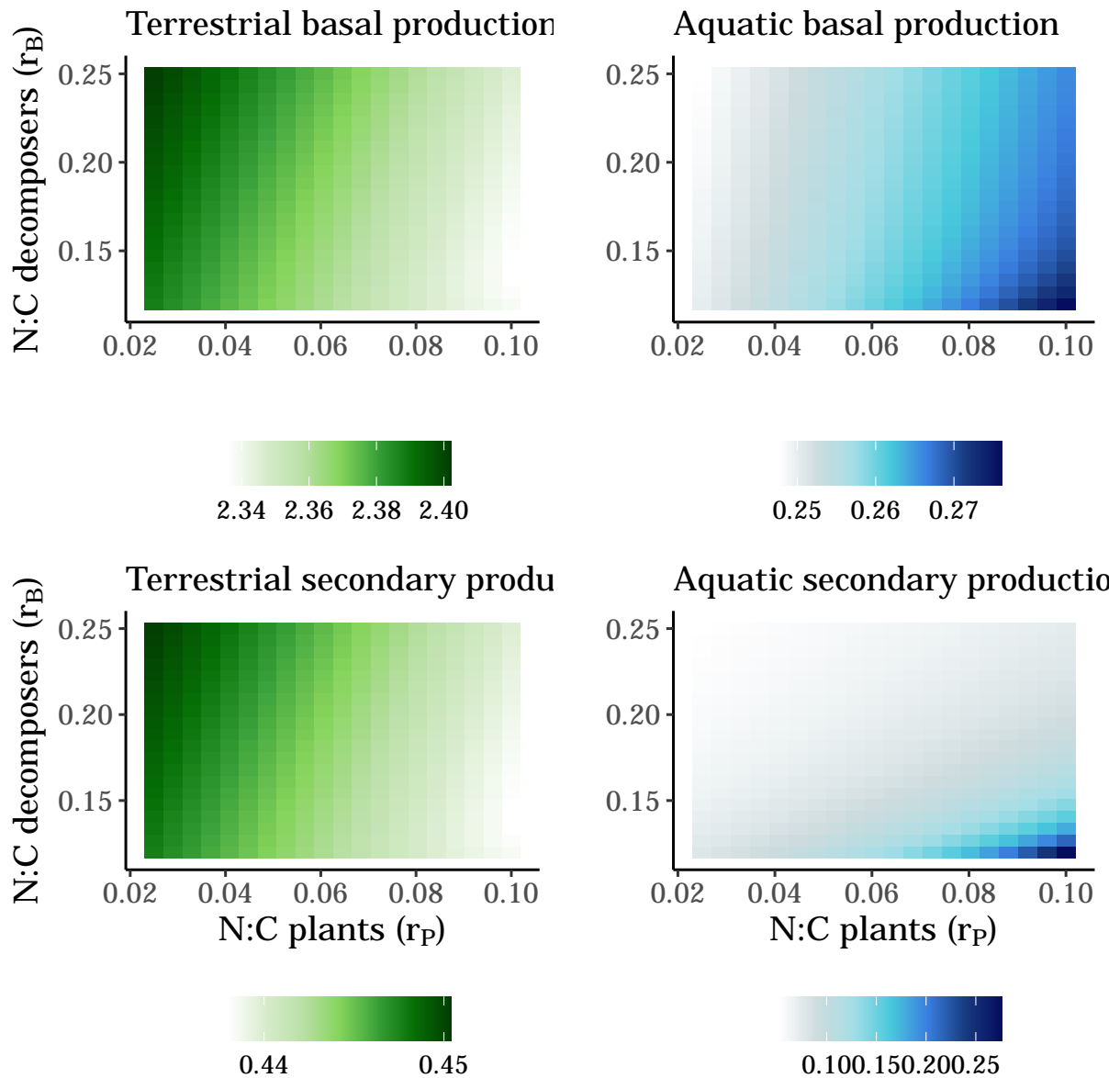


Figure S6.2: **Main conclusions are robust to donor-control functional responses under nitrogen limitation of decomposers.**
 The legend is the same as in Fig. S6.1 except that here, decomposers are nitrogen-limited.

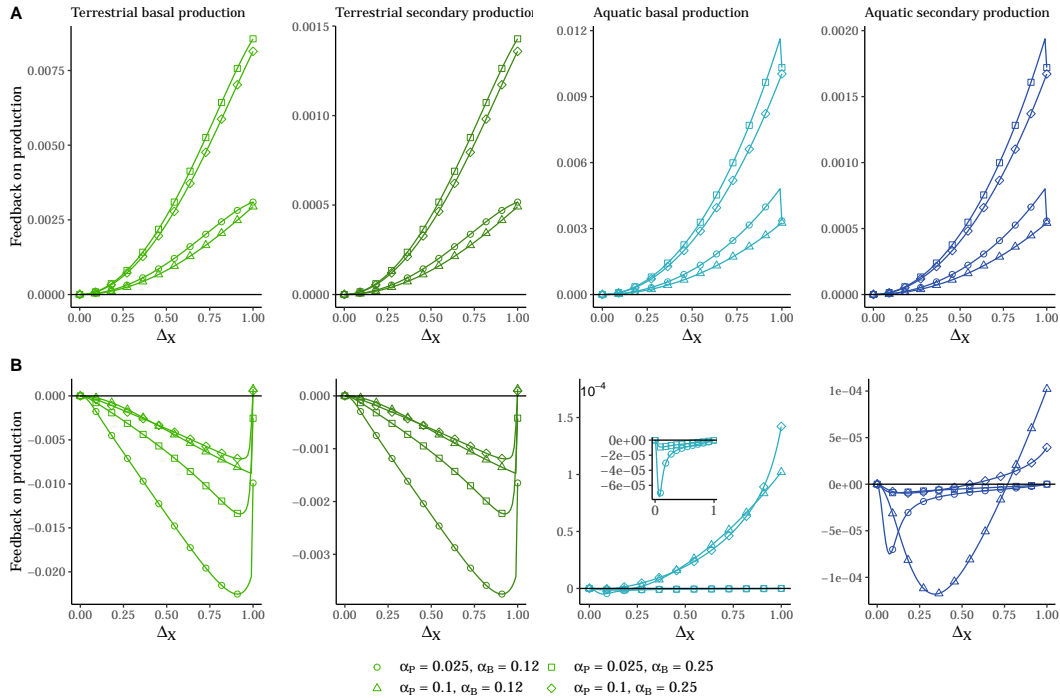


Figure S6.3: Feedback under both N-limited and C-limited decomposers with donor control functional responses.

We computed the feedback as shown in Fig. S1.1 and Eq. 4. The feedback is computed for each of the trophic levels in both ecosystems (columns) and under C-limited (A) and N-limited (B) decomposers. The insert shows the sign of the feedback on secondary production for $\alpha_P = 0.1, \alpha_B = 0.25$ (diamond shape) and $\alpha_P = 0.025, \alpha_B = 0.25$ (square shape).

896 **S7 Sensitivity analysis on the parameter values**

897 In this section, we aim to perform a sensitivity analysis on the parameter value. As the
898 model contains many parameters, we first determined which model parameters were the
899 most sensitive and we further explored for these parameters, whether they qualitatively
900 changed the patterns found in Fig. 3. We performed a sensitivity analysis on the parameter
901 values by varying each parameter independently (see Table. S7.1). For the first step, we
902 varied independently each parameter independently. The range of each parameter under
903 carbon or nitrogen limitation was determined so that (i) the simulations remained in the
904 same resource limitation and that (ii) the two trophic levels in both ecosystems coexisted
905 (Table S7.1). We measured under the two resource limitations (nitrogen and carbon) the
906 average change in the production of each ecosystem defined as the range of variation of
907 production divided by the range of variation of the parameter value (Fig. S7.1). In both
908 nitrogen- and carbon-limitation, a_P , a_H , d_H and e_H were the most sensitive parameters
909 (Fig. S7.1B-C). Therefore, for these parameters, we display how the production in both
910 the aquatic and terrestrial ecosystem change with variations of these parameters. Overall,
911 the patterns shown in Fig. 3 are robust to the quantitative variations in parameter values.
912 Finally, we varied the strength of coupling of ecosystems Δ and observed similar patterns
913 as found in the case $\Delta = 1$ in Fig. 3.

Table S7.1: **Range of parameter variation in the sensitivity analysis.**

Note that for I_{N_A} and I_{D_A} the range under C-limitation (left range) and N-limitation (right range) is different.

Class	Parameter	Range varied
Terrestrial ecosystem	I_{N_T}	1-15
	I_{D_T}	1-15
	l_{D_T}	0.5-5
	l_{N_T}	0.5-5
	m_T	0-1
	e_G	0.2-1
	a_{PN}	0.1-0.7
	a_{GP}	0.1-2
	d_G	0.05-1
	d_P	0.01-1
	Aquatic ecosystem	I_{N_A}
I_{D_A}		2-20, 12-18
l_{D_A}		0.5-1
l_{N_A}		1-2
m_A		0-1
e_C		0.3-1
e_B		0.5-1
a_{BD}		0.83-2
a_C		0.3-1
d_B		0.01-0.5
d_C		0.01-0.15

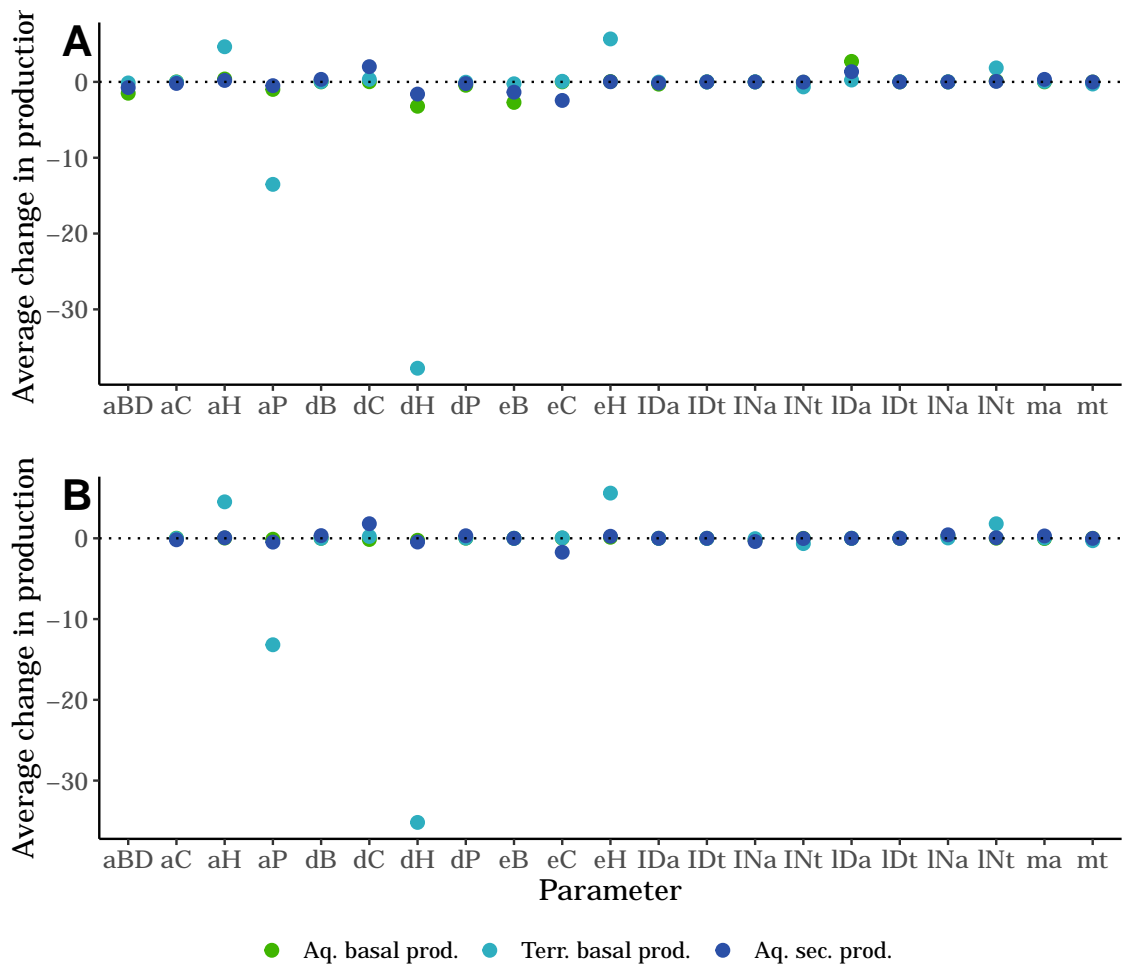


Figure S7.1: Quantitative sensitivity of ecosystem production to change in parameter values.

(A & B) We show the average change in the ecosystem production computed as the range of variation of the production divided by the range of variation of each parameter. Each point corresponds to the mean across the 4 values of primary producer stoichiometries. The analyses were performed for (A) C-limited decomposers and (B) N-limited decomposers. Note that we excluded the secondary production in the terrestrial ecosystem as it is qualitatively similar to the primary production. terr. = terrestrial, aq. = aquatic and prod. = production. Some parameters such as d_H under carbon and nitrogen limitation, have a strong quantitative influence on the ecosystem production.

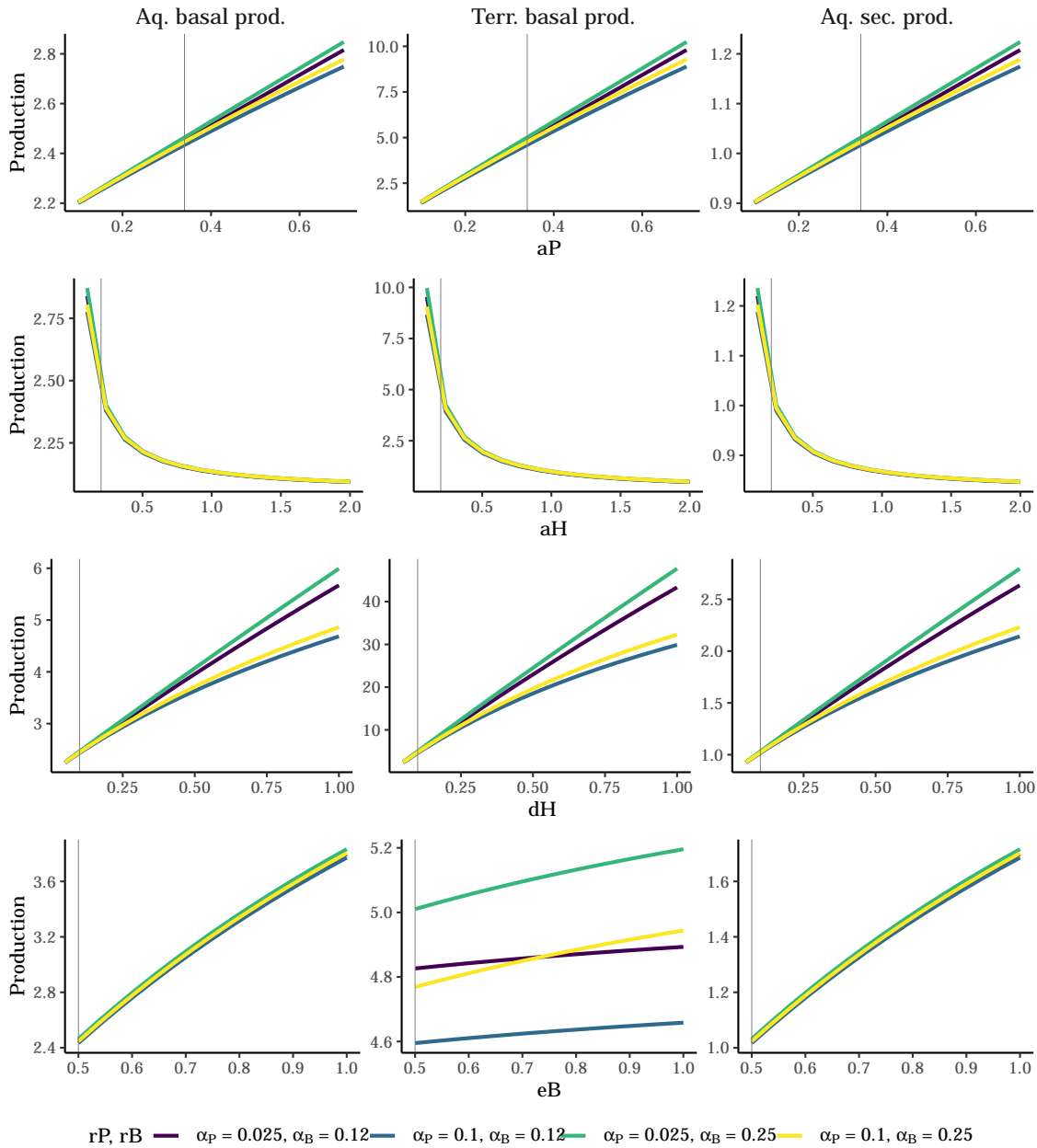


Figure S7.2: Results are qualitatively robust to parameter variation in C-limitation. While the most sensitive parameters change quantitatively the production of ecosystems, they do not change the patterns observed in Fig. 3 (*i.e.*, as seen by the relative position of the lines). Here decomposers are carbon-limited.

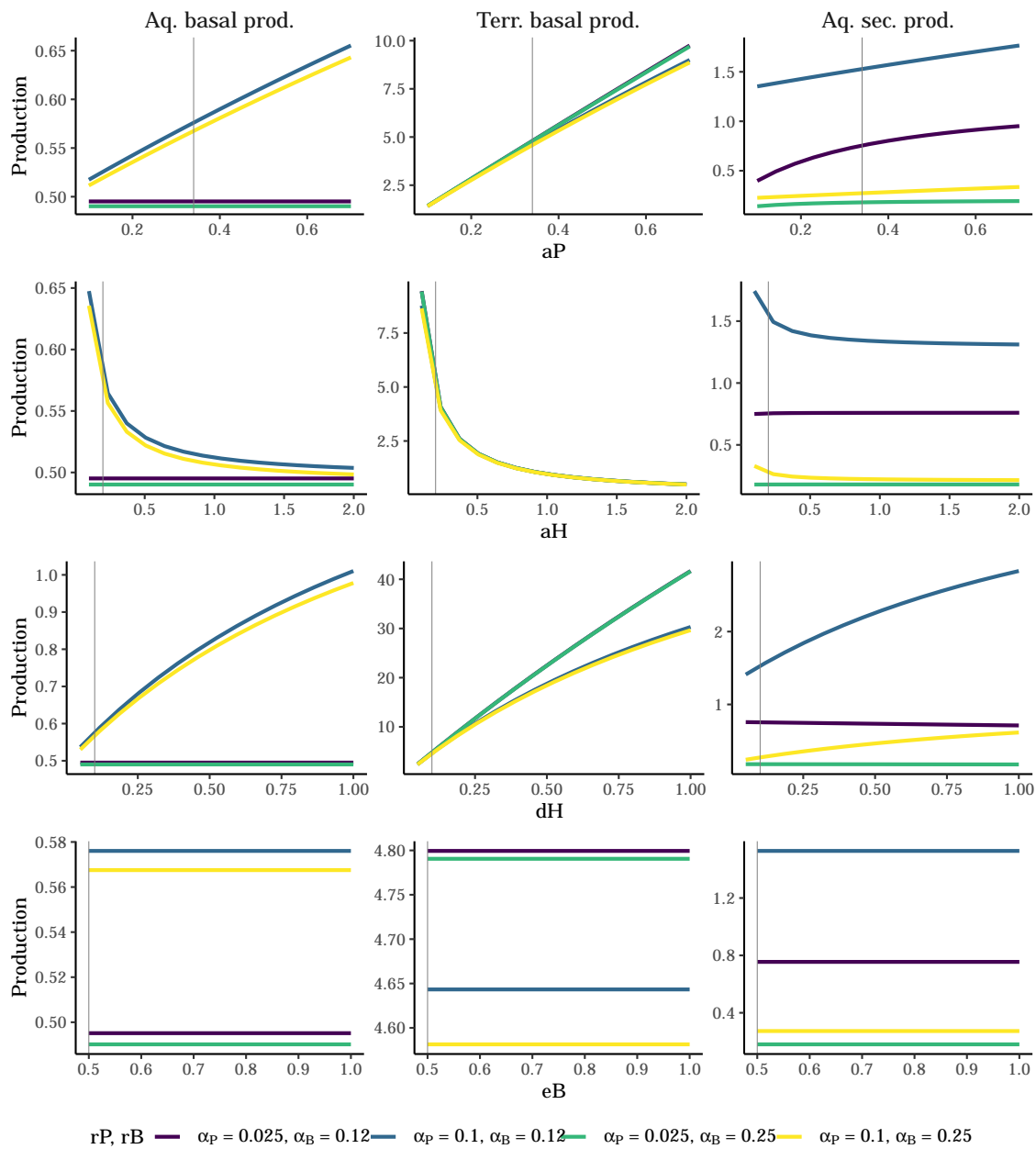


Figure S7.3: Results are qualitatively robust to parameter variation in N-limitation. While the most sensitive parameters change quantitatively the production of ecosystems, they do not change the patterns observed in Fig. 3 (*i.e.*, as seen by the relative position of the lines). Here decomposers are nitrogen-limited.

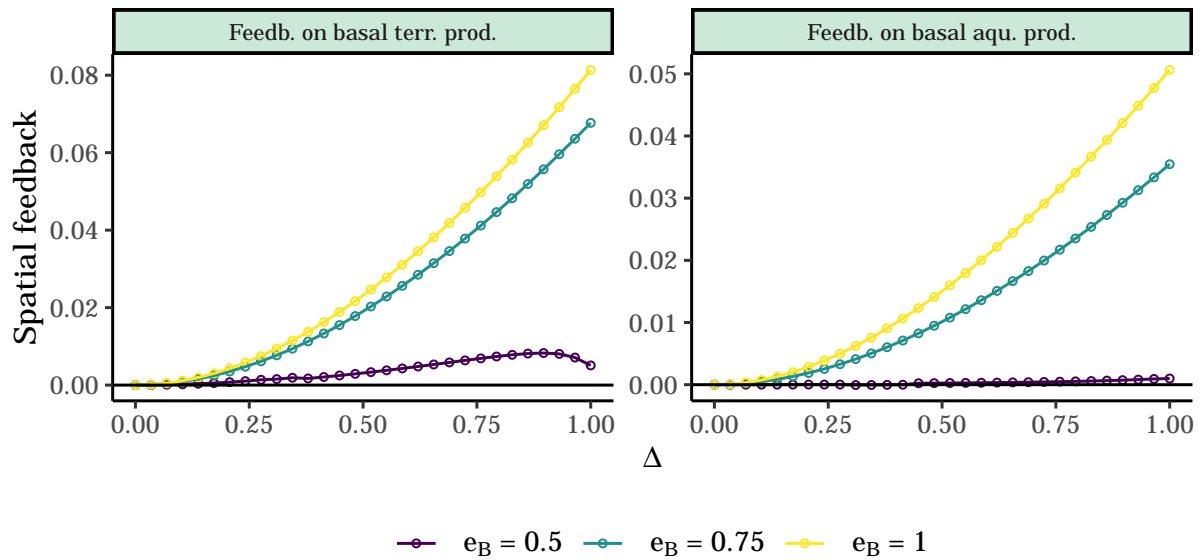


Figure S7.4: **Influence of the growth efficient on the spatial feedback in C-limited aquatic ecosystems.**

We show how the growth efficiency of the decomposers modulates the spatial feedbacks on the basal production of both ecosystems. We only show the results for the basal production as qualitatively similar results are obtained for secondary production. When the growth efficiency of decomposers decreases, the strength of the positive feedbacks on both ecosystems decreases. Other parameters = $\alpha_P = 0.1, \alpha_B = 0.25$.

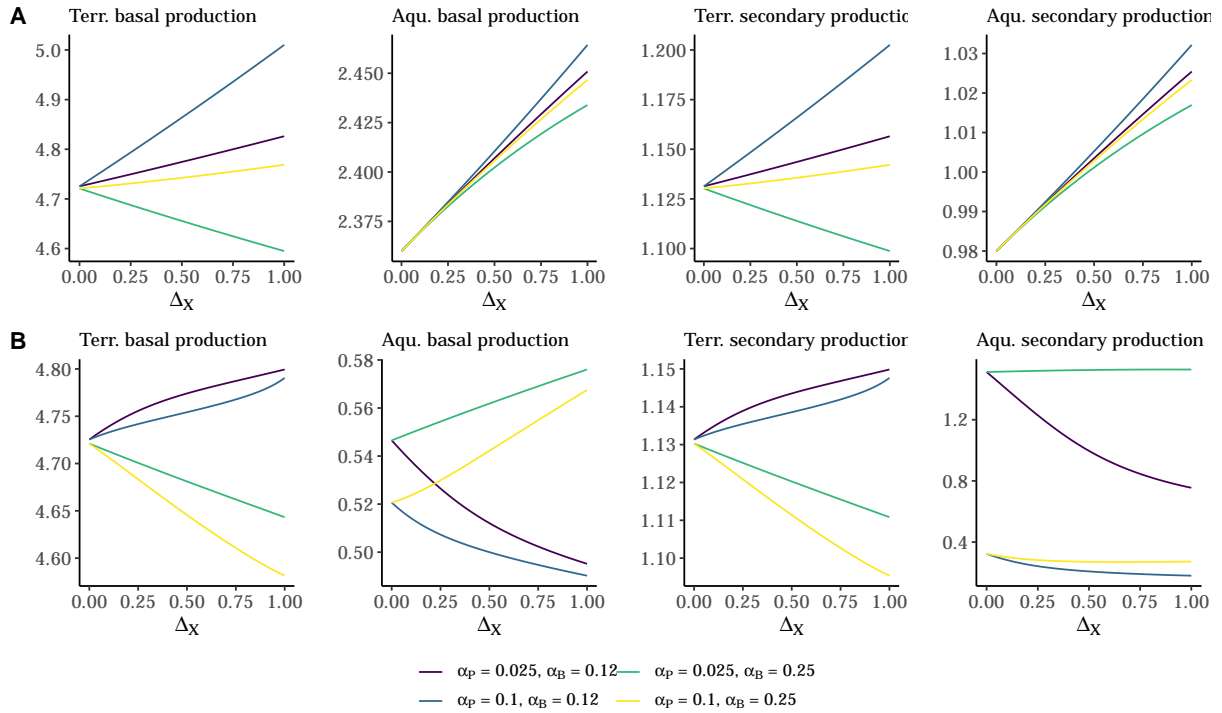


Figure S7.5: Influence of the strength of ecosystem coupling on the patterns presented in Fig. 3.

We show the changes in basal and secondary production along the strength of coupling between ecosystems (Δ) for 2 values of plant stoichiometry ($\alpha_P \in [0.025, 0.1]$) and 2 values of decomposers stoichiometry ($\alpha_B \in [0.12, 0.25]$). These cases correspond to the corners of Fig. 3A (top) and Fig. 3B (bottom) along the gradient of coupling between ecosystems. Panel A = C-limited decomposers. Panel B = N-limited decomposers.

S8 Sensitivity analysis on the asymmetry of flows

We performed a sensitivity analysis to investigate the role of the asymmetry of flows. While in the main text we assumed all Δ to be equal for each trophic level, here, we relax this hypothesis by adding a subscript to the parameter Δ to account for heterogeneous fraction of detritus transferred across ecotone depending on the trophic level: Δ_X , where $X \in \{P, B, G, C\}$. We focus on the asymmetry of subsidy flow between terrestrial and aquatic ecosystems ($\Delta_{\mathcal{T}} = \{\Delta_P, \Delta_H\}$ versus $\Delta_{\mathcal{A}} = \{\Delta_B, \Delta_C\}$). We investigated how differences between $\Delta_{\mathcal{T}}$ and $\Delta_{\mathcal{A}}$ modulate the basal and second production of both ecosystems. The results are displayed in Fig. S8.1. Under the scenario of C-limitation of decomposers, the aquatic ecosystem benefits from higher exports from the terrestrial ecosystem as it relaxes the carbon limitation and fuels the detritus stock (Fig. S8.1A-right). Interestingly for the terrestrial ecosystem, production does not change when detritus from plants and grazers are locally instead of regionally recycled: plants only benefit from nitrogen-rich subsidies exported from the aquatic ecosystem (Fig. S8.1A-left). When decomposers are limited by nitrogen, we see that production in the aquatic ecosystem decreases with increasing subsidies from the terrestrial ecosystem (due to the stoichiometric mismatch mechanism, see main text). Production in the aquatic ecosystem increases when nitrogen-rich detritus from both decomposers and their consumers are locally recycled (Fig. S8.1B-right).

Moreover, we explored how the feedbacks changed depending on the asymmetry of flows by varying $\Delta_{\mathcal{T}}$ (resp. $\Delta_{\mathcal{A}}$) for $\Delta_{\mathcal{A}} \in \{0, 0.25, 0.75\}$ (resp. $\Delta_{\mathcal{T}} \in \{0.25, 0.75\}$) with the stoichiometric parameters taken in Fig. 5. The results are displayed in Fig. S8.2. To simplify the reading, we only display the feedback on the basal production of both ecosystems. Under C-limitation, we observe similar qualitative behavior than when the flows are symmetric (*i.e.*, $\Delta_{\mathcal{T}} = \Delta_{\mathcal{A}}$ in the main text): the feedback is positive and increases with increasing connectivity of ecosystems (Fig. S8.2Aa, Ba colored lines versus red line). Interestingly the feedback strength increases when ecosystems are more spatially coupled (higher values of $\Delta_{\mathcal{A}}$ in Fig. S8.2Aa or $\Delta_{\mathcal{T}}$ in Fig. S8.2Ba). This is similar for N-limited

941 decomposers (Fig. S8.2Ab, Bb). To relate to the mechanisms explained in the main text
942 for the N-limitation scenario, we observe that feedbacks are more important when the
943 coupling between ecosystems is more important (as mass-effect increases relatively to
944 stoichiometric mismatch).

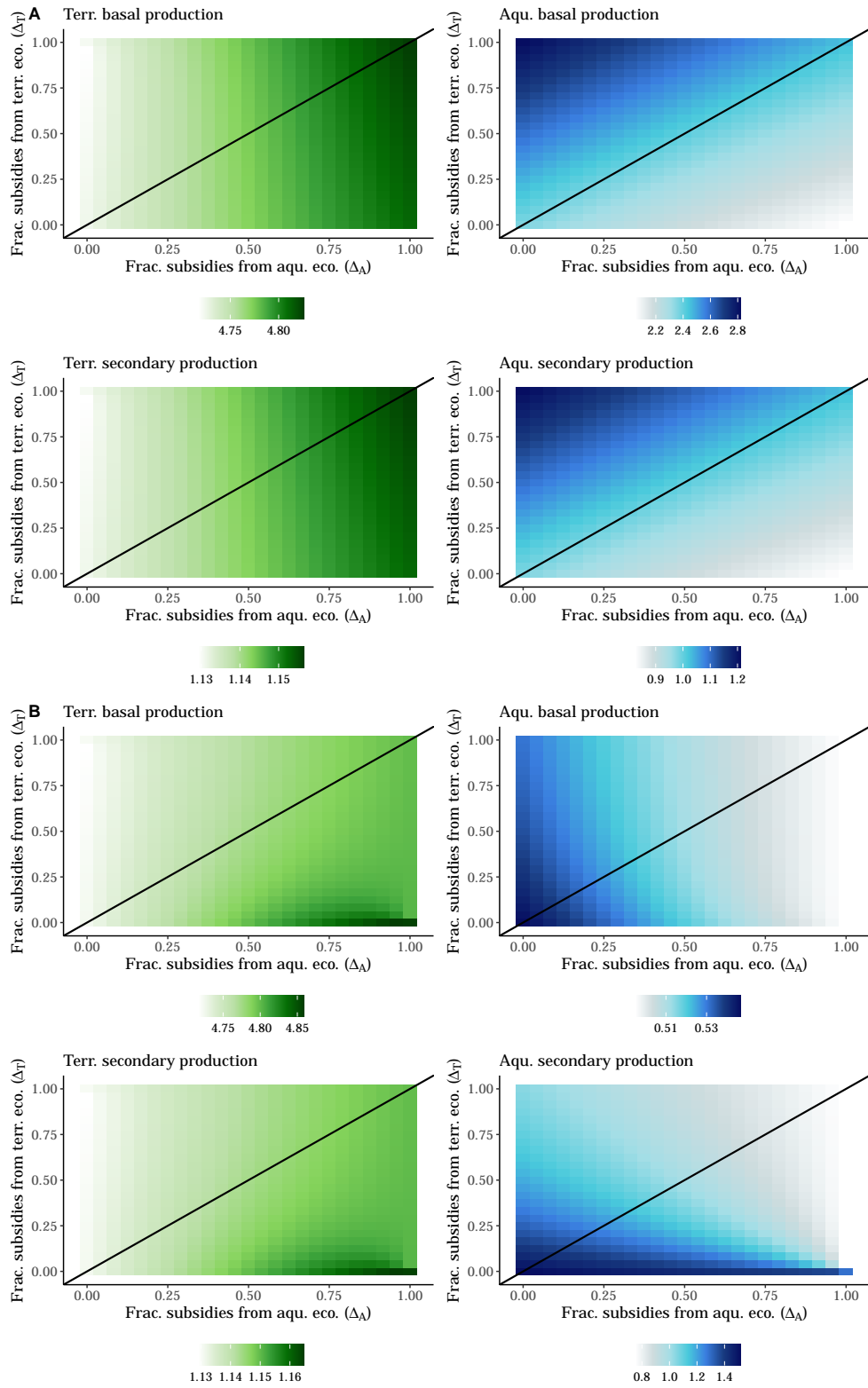


Figure S8.1: Caption is on next page

945 **Fig. S8.1 Sensitivity analysis on the asymmetry of flows on ecosystem production.**
946 We show how basal and secondary productions in both ecosystems are modulated by
947 the asymmetry of subsidies being exchanged at the terrestrial-aquatic ecotone. The black
948 line describes the scenario where the coupling is symmetrical $\Delta_{\mathcal{T}} = \Delta_{\mathcal{A}}$, while below
949 this line (*resp.* above) relatively more subsidies are exported from the aquatic (*resp.*
950 terrestrial) ecosystem. (A) C-limited decomposers. (B) N-limited decomposers. Other
951 parameters: $\alpha_P = 0.025, \alpha_B = 0.12$. Qualitatively similar behaviour is obtained for different
952 combinations of stoichiometries of decomposers and plants. Frac. = Fraction, aqu.= aquatic,
953 terr. = terrestrial, eco. = ecosystem.

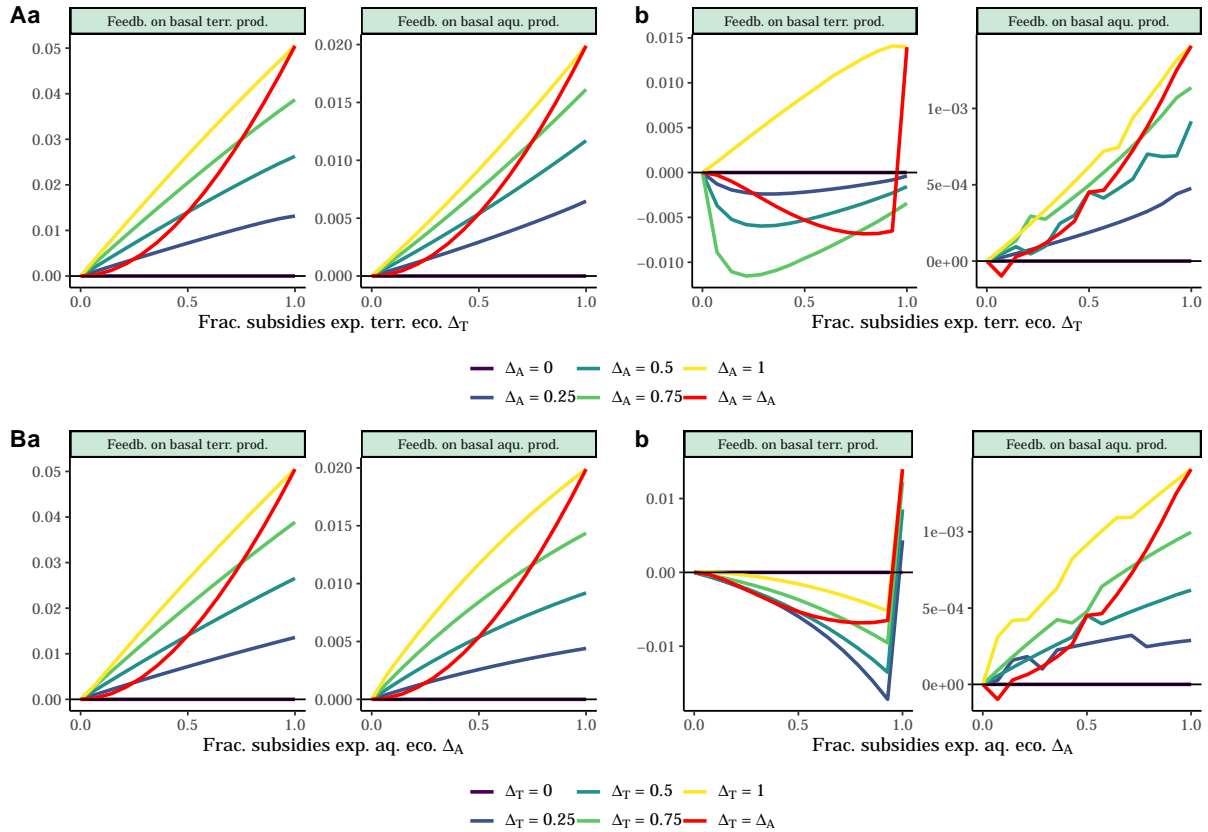


Figure S8.2: Sensitivity analysis on the asymmetry of flows on spatial feedbacks.

We show how the spatial feedbacks on the basal ecosystem productions are modulated by the asymmetry of subsidies being exchanged at the terrestrial-aquatic ecotone. The black line delimits the negative from the positive feedbacks. (A) We varied the fraction of subsidies exported from the terrestrial ecosystem ($\Delta_{\mathcal{T}}$, x-axis) under different symmetry/asymmetry of flows (colors, red line shows the case of symmetrical coupling as in Fig. 5), and two scenarios of decomposer limitation: C-limited on the left (a) and N-limited on the right (b). Panel B = Similar to (A) but we varied the fraction of subsidies exported from the aquatic ecosystem. Feedb. on basal terr. prod. = Feedback on basal terrestrial production. Feedb. on basal aqu. prod. = Feedback on basal aquatic production.

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