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Supplementary information

Quantifying Earth system interactions for sustainable food production via expert elicitation

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Supplementary materials for

Quantifying Earth system interactions for sustainable food production via expert elicitation

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Supplementary materials

S.1 Elicitation control variables status and elicitation details

By subdividing biosphere integrity into the land, freshwater, and ocean components and surface water into blue (high and low flow) and green water, we achieved a matrix of 8x8 and a total of 54 potential interactions for the selected set of control variables (abbreviated further as X-->Y). Participants were advised and encouraged to respond only for the interactions that they assumed most relevant for their expertise. Due to the local nature of our assessment, in comparison to the planetary boundaries framework, we used different sets of control variables for many of the Earth system processes explored and we thus, provided values that are very likely to fall within a safe range, according to available literature. Table S1 describes the control variables, the safe ranges, and the status of them in the hypothetical area (100 km^2) participants had to assess.

*Table S1.1. Control variables used in the elicitation, safe range, initial condition of each variable at the hypothetical area, within the safe operating space, and the change (ΔX) in each control variable given to experts to assess its impact on other control variables. Control variables indicated with * are the same as defined in Steffen et al. (2015).*

Adapted planetary boundaries representing Earth system processes relevant to food production	Control variable	Safe range (boundary if available)	Status in hypothetical area (100 km^2)	ΔX given to assess interaction
Land Biosphere integrity	Biodiversity Intactness Index (BII) *	BII>= 90% is considered within safe limits	95% BII	From 95% to 90% BII
Freshwater Biosphere integrity	Keystone fish biomass	Biomass >= 0.5 of carrying capacity (K) is within safe biological limits	0.8K	From 0.8K to 0.6K
Ocean Biosphere integrity	Keystone fish biomass	Biomass >= 0.5 of K is within safe biological limits	0.8K	From 0.8K to 0.6K
Land system change	Forest cover relative to potential forest cover *	Biome scale safe limits: Tropical & Boreal: 85% Temperate: 50% Global safe limit: 75%	90%	From 90% to 80% forest cover
Biogeochemical flows	N concentration in runoff	N concentration in runoff < 1 N mg/L is within safe limits	0.5 N mg/L	From 0.5 to 0.8 N mg/L
Blue water – High flow season	River discharge relative to environmental flow requirement (EFR)	River discharge >EFR is within safe limits EFR: 15-45% of pre-industrial flows	65% pre-industrial	From 65% to 60% river discharge
Blue water – Low flow season	River discharge relative to EFR	River discharge >EFR is within safe limits EFR: 45-75% of pre-industrial flows	95% pre-industrial	From 95% to 90% river discharge
Green water	Growing season root-zone soil moisture		95% pre-industrial	From 95% to 90% soil moisture

S1.1. Elicitation process

The project planning started in early 2020 and the web-application development in March 2020. The elicitation questions were developed in parallel. Before releasing the web application to experts, an early version of the web application and questions were pilot tested by four members of the research group who were not involved in the project. The application and question format were updated based on their feedback. After the revisions, the pre-elicitation, IDEA elicitation protocol stages, and post-elicitation phases took place as described in Table S1.2. During the pre-elicitation phase, experts were encouraged to read the instructions and example questions provided in the web application and to explore the web application to practice providing their estimates in a probabilistic format. For example, the web application instructed the experts to *"…provide the lowest and highest values you think plausible, your best estimate as well as your credible intervals. For example, if you provide a certainty level of, say, 70%, for 10 similar events, then the truth should lie within your credible intervals 7 out of 10 times."* Combined, the pre-elicitation and the first elicitation round spanned eight weeks, which gave the experts the opportunity to spend time understanding the questions and the ways to respond to them. Participants who had difficulties or questions about the process or the elicitation questions were asked to contact the first author for assistance. Of the 37 participants that completed the elicitation, 28 actively participated in the discussion phase by commenting in the discussion threads. Some participants that did not actively participate in the discussion mentioned in personal communication with the first author that there was no more for them to add to the existing discussion threads. Any potential ambiguity related to the elicitation questions or questions that arose during the discussion phase was resolved between the participants and moderators from the research team. During the second elicitation round, 17 experts updated their responses, which reduced the responses' coefficient of variation between the two elicitation rounds (Table S1.5).

Table S1.2. Expert elicitation timeline.

Phase	Duration	Tasks
Pre-elicitation	2 weeks	Planetary boundaries literature was reviewed and author background was checked (see Supplementary materials S1.3 for details). Once a list of 200 potential participants were reached, literature-based search was concluded. Potential participants, with fitting background, received invitations to join the elicitation via personalized emails from the project primer investigator. The snowballing method (participants inviting more potential participants) was used to expand the pool of potential participants. Participants that wanted to participate in the elicitation, filled the consent form for participating in the elicitation. Participants were given time to explore the web application, were given detailed instructions, an example of the elicitation questions and background information. They were encouraged to contact the first author should they have any questions regarding the entire process. No special training on providing responses in probabilistic format was given as this knowledge was assumed given the participants' academic backgrounds.
1st elicitation round	6 weeks	Experts anonymously provided their first assessment on the interactions (to which their expertise fitted) through the web-application. One-to-one assistance was provided by request during the process. Reminders were sent after the initial deadline of submitting the first elicitation round responses and a further 2 week extension was given.
Data analysis	4 weeks	The first-round results were cleaned and checked for potential mistakes in the responses. Experts were contacted and asked to double-check and clarify their responses when potential mistakes were found. Common mistakes were related to blank estimates, wrong units, responses given as proportions rather than percentages, and out-of-range numbers (Hemming et al., 2018). The 1st round results were analyzed and aggregated (see Methods) to be provided to elicitation participants. Graphical outputs of the single expert and aggregate responses for each interaction were made (see Figure S1.1). Causal diagrams of the mechanisms involved in the interactions were drawn based on expert provided explanations
Discussion round	3 weeks	Feedback and aggregated 1st elicitation round assessments were shared with experts. Expert discussion using the Slack software was initiated with 2-3 questions, and supervised by moderators consisting of core research team members. Feedback on the elicitation process was asked as a part of the discussion round, and based on this, questions detailed in Supplementary material S1.2 were added to the web app. Update emails summarising the progress of discussions were sent every few days.
Data share & info-session	1 week	Discussion data was compiled and shared with participants. Info-session on new web-app features was held and a demonstration video was circulated via email.
2nd elicitation round	4 weeks	Experts had the chance to update their initial assessment through the web-application.
Post-elicitation		2nd elicitation round results were checked for potential mistakes. Experts were contacted and asked to double-check and clarify their responses when potential mistakes were found. Final expert elicitation results were shared with all participants. Article collaborative drafting.

S1.2. Questions' format

The questions asked during the first elicitation round to the participants had the following general format for any given interaction X-->Y:

How would a decrease/increase in X from A level to B level alter Y in nearby areas (currently at C level)?

Realistically, what do you think is the lowest plausible value?

Realistically, what do you think is the upper plausible value?

Realistically, what is your best estimate?

How confident are you that your interval, from lowest to highest, could capture the true value (50-100%)?

Elaborate your reasoning for the values you provided above.

What X level would change this interaction to non-linear?

Realistically, what is your best estimate?

Elaborate your reasoning for the tipping point you provided above.

Did you have a specific region in mind during the process?

After the discussion round and the feedback, three additional questions were added for the second elicitation round:

The identified mechanisms for this interaction are: A, B, C, D

Please rank the above mechanism(s) in descending order of importance. Elaborate if the mechanism ranking varies based on context or if you think some mechanisms are missing.

Could any of the above mechanisms cause cascading effects on a scale larger than our hypothetical area? If yes, how and at which scale(s)?

For interactions involving biogeochemical flows, a specific question was added for the second elicitation round:

If you think that the interaction is first positive and then turns to negative, a) at what level of leached N concentration in runoff (mg N/L) would you expect it to turn to negative and in which context? b) Please provide your estimate of the change in Y (ΔY) relative to a ΔX=0.3 mg N/L change in N concentration above this level.

All questions and explanations/background information provided to the elicitation participants can be explored in the web-application https://chrysafi1.shinyapps.io/shiny_exp_elic/.

S1.3. Expert elicitation recruitment and participants' information

For the recruitment process, relevant literature on planetary boundaries was searched including most cited, earliest and more recent publications. Then the background of all authors was investigated through their academic/institutional profiles and if it fitted any of the Earth system processes of interest, they were added in the list of potential participants. Once the list reached a number of 200 potential participants, the literature-based recruitment was concluded. Invitation emails were sent to all potential participants and additionally, the "snowball method" was used when potential participants were first contacted, they were asked to suggest further suitable participants. The snowball method yielded 31 additional participants that were also invited to participate in the elicitation. At the beginning of the elicitation, 102 potential participants completed the consent form and 63 experts withdrew from the process before the first elicitation round. Among the voluntarily provided reasons to withdraw, the main reasons were related to time limitations due to over-commitment and other issues as a result of the COVID pandemic as this work took place during the spring of 2020. In total, 39 experts completed the first round of which two more participants did not follow through the discussion and the second elicitation round. All elicitation steps were completed by 37 experts and the results presented in the main text come from these participants. The fields of self-identified expertise and research position of the 37 experts that completed the elicitation is available in Table S1.3. The fact that earlier literature on planetary boundaries has focused mainly on land system change, blue water and land biodiversity, is illustrated also in the representation of different disciplines. Additionally, more than half of the elicitation participants have a senior researcher position and only 3 are at the Ph.D. stage.

It would have been desirable to have an equal representation of disciplines covering the Earth system processes explored in this elicitation. However, our criteria for selecting potential experts leaned towards inviting experts based on field-specific knowledge and knowledge/publications within the planetary boundary framework. As a result, there was greater representation of the well-studied Earth system processes included in the planetary boundaries framework (e.g. Land system change, Blue water and BI land) compared to the newly added or less explored ones (e.g. BI freshwater and BI ocean). Hence, some interactions were estimated by relatively few experts who primarily identify themselves as experts in that field (e.g. marine ecology). Despite this, we received a sufficient number of answers per interaction, as described in S1.4, as experts were instructed to respond to all interactions for which they felt their expertise fit best. For example, while land use was identified as the primary field of expertise by only two experts, the interactions involving Land system change were among the ones receiving the most responses (Table S1.4). To accommodate for the variable response counts reflecting the unequal representation of disciplines, we grouped the interaction strength estimates in three uncertainty zones based on the number of answers received and expert agreement as described in Supplementary materials S5.

Table S1.3. Fields of expertise and academic position of the elicitation participants.

Field of expertise	Count
Agriculture	9
Biodiversity	3
Biogeochemical cycles	1
Climate change	5
Earth science	2
Ecology	3
Ecosystem services	2
Environmental science	6
Geography	1
Hydrology	11
Land use	2
Marine ecology	2
Planetary Boundaries	3
Socio-ecological-systems	3
Water management	9
Position	
PhD candidate	3
Researcher	14
Senior Researcher	20

S1.4. Total expert input & benefits of discussion round

In the elicitation, 37 experts provided their judgment for the Earth system interactions and a total number of 513 responses for all 54 potential interactions were collected. The partition of them per interaction is available in Table S1.4 with responses per interactions ranging 5-19 with the least responses for the newly discussed Earth system processes in the planetary boundaries literature. Despite these discrepancies, empirical evidence related to response counts suggests that only minor improvements are gained when having more than six to twelve participants (Armstrong 2001; Hora, 2004; Cooke and Probst 2006) and thus, we can still trust the elicitation results. However, to be precautionary in the inferences made, we created three uncertainty categories according to the number of responses as described in Table S5.2.

Table S1.4. Total number of expert responses per interaction.

	BI land	BI fresh	BI ocean	Land system change	Biog. flows	Blue water high	Blue water low	Green water
BI land	NA	8	7	10	7	8	8	10
BI fresh	9	NA	8	9	6	10	10	10
BI ocean	8	5	NA	6	5	7	7	8
Land system change	17	8	7	NA	12	19	19	18
Biog. flows	6	6	7	7	NA	8	8	7
Blue water high	9	11	4	11	8	NA	NA	16
Blue water low	9	11	4	11	8	NA	NA	16
Green water	9	6	5	13	9	19	19	NA

The discussion round was held in the Slack discussion software and a separate channel for each interaction was created. The round moderators (from the core team) initiated the discussion with 2-3 questions per channel. Additionally, all the results from the first elicitation round were provided in each channel in a figure of individual and aggregated responses for the lower, best and upper values standardized at 80 CI and a causal diagram created based on the text responses of the participants (Figure S1.1). The discussion was fruitful and many issues related to the interactions were discussed between the participants which led to higher agreement in the second elicitation round as seen in Table S1.5.

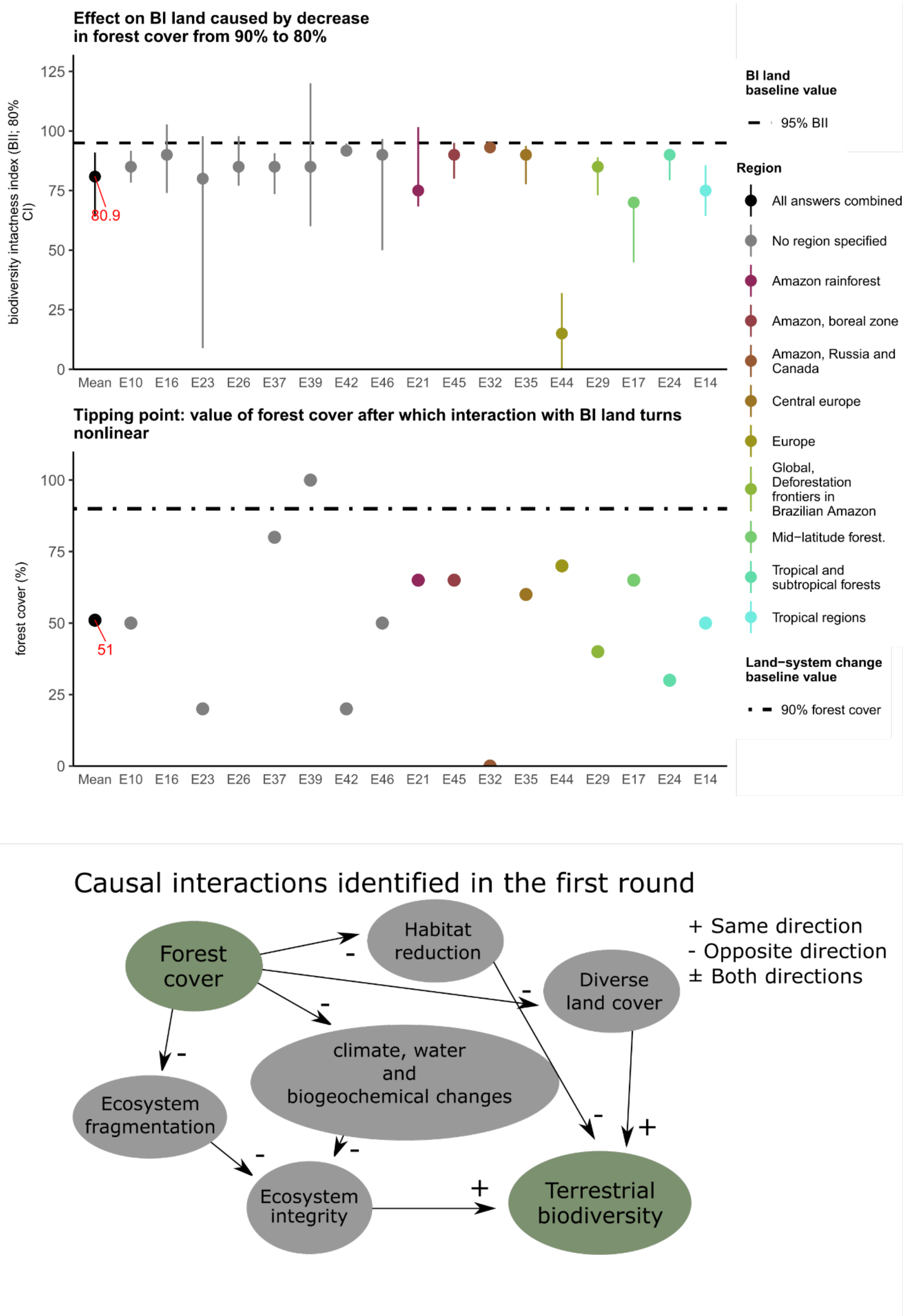

Figure S1.1. Example of the graphical output of the first elicitation round given to expert during the discussion round.

Table S1.5. Agreement between experts in the two elicitation rounds. Categorization for expert agreement is done according to Gracht et al. (2012) and Scherer et al. (2020) in which high agreement was considered for cv<=0.5, acceptable agreement for 0.5<cv<=0.8 and no agreement for cv>0.8. For the second elicitation round CV is estimated both for all the answers and the answers aggregated for the main results. Cells marked with grey indicate interactions for which CV decreased in the second elicitation round.

	1st elicitation round		2nd elicitation round			
			All answers		Aggregated after divergence metric	
Interaction	**CV in best estimate**	**No of responses**	**CV in best estimate**	**No of responses**	**CV in best estimate**	**No or responses**
Biland_Bifresh	0.138	8	0.210	8	0.224	7
Biland_Biocean	0.047	7	0.048	7	0.048	7
Biland_LSC	0.160	11	0.048	10	0.048	10
Biland_Biog	0.316	7	0.186	7	0.186	7
Biland_Blue	0.162	8	0.062	8	0.062	8
Biland_Blue	0.010	8	0.023	8	0.023	8
Biland_Green	0.022	10	0.022	10	0.022	10
Bifresh_Biland	0.349	10	0.096	9	0.095	8
Bifresh_Biocean	0.089	8	0.090	8	0.090	8
Bifresh_LSC	0.076	9	0.028	9	0.028	9
Bifresh_Biog	0.207	6	0.097	6	0.097	6
Bifresh_Blue	0.016	10	0.027	10	0.027	10
Bifresh_Blue	0.021	10	0.026	10	0.026	10
Bifresh_Green	0.013	10	0.013	10	0.013	10
Biocean_Biland	0.386	8	0.070	8	0.070	8
Biocean_Bifresh	0.085	5	0.085	5	0.095	4
Biocean_LSC	0.045	6	0.046	6	0.046	6
Biocean_Biog	0.026	5	0.027	5	0.030	4
Biocean_Blue	0.011	7	0.012	7	0.012	7
Biocean_Blue	0.007	7	0.008	7	0.008	7
Biocean_Green	0.011	8	0.011	8	0.011	8
LSC_Biland	0.224	17	0.224	17	0.227	16
LSC_Bifresh	0.214	8	0.210	8	0.210	8
LSC_Biocean	0.256	7	0.256	7	0.256	7
LSC_Biog	0.795	12	0.782	12	0.780	11

LSC_Blue	0.157	18	0.148	19	0.148	19
LSC_Blue	0.127	18	0.256	19	0.082	18
LSC_Green	0.098	18	0.098	18	0.098	18
Biog_Biland	0.459	6	0.089	6	0.098	5
Biog_Bifresh	0.212	6	0.108	6	0.112	3
Biog_Biocean	0.150	7	0.151	7	0.149	5
Biog_LSC	0.035	7	0.034	7	0.034	7
Biog_Blue	0.028	8	0.028	8	0.028	8
Biog_Blue	0.022	8	0.022	8	0.022	8
Biog_Green	0.026	7	0.023	7	0.023	7
Blue_Biland	0.062	9	0.063	9	0.063	9
Blue_Biland	0.034	9	0.034	9	0.034	9
Blue_Bifresh	0.123	12	0.115	11	0.115	11
Blue_Bifresh	0.151	12	0.058	11	0.058	11
Blue_Biocean	0.459	4	0.063	4	0.063	4
Blue_Biocean	0.559	4	0.034	4	0.034	4
Blue_LSC	0.026	3	0.138	11	0.138	11
Blue_LSC	0.119	11	0.082	11	0.082	11
Blue_Biog	0.153	8	0.000	8	0.000	8
Blue_Biog	0.205	8	0.000	8	0.000	8
Blue_Green	0.045	16	0.043	16	0.043	16
Blue_Green	0.058	16	0.102	16	0.102	16
Green_Biland	0.034	9	0.120	9	0.151	6
Green_Bifresh	0.113	6	0.112	6	0.112	6
Green_Biocean	0.028	5	0.028	5	0.028	5
Green_LSC	0.040	13	0.041	13	0.041	12
Green_Biog	0.141	9	0.123	9	0.123	9
Green_Blue	0.136	18	0.091	19	0.091	19
Green_Blue	0.097	18	0.064	19	0.064	19

S2. Control variables

S2.1. Land biosphere integrity (BI land)

The control variable we use for land biosphere integrity is biodiversity intactness index (BII), which was also used by Steffen et al. (2015) as an interim proxy variable for functional diversity. Functional diversity represents the value, range, distribution, and relative abundance of the functional traits of the organisms present in an ecosystem. As functional diversity decreases in the face of environmental change, key ecosystem functions and processes could be at risk. BII assesses population abundance across a range of taxa and functional groups at a biome or ecosystem level, relative to pre-industrial era abundance. Steffen et al. (2015) set the boundary at 90% BII, but there is considerable uncertainty due to lack of evidence on the relationship between BII and Earth System responses (hence a very large uncertainty range of 90% to 30%).

S2.2. Freshwater and ocean biosphere integrity (BI fresh and BI ocean)

Lade et al. (2020) assigned two new components for the biosphere integrity planetary boundary, freshwater and ocean biosphere integrity, as interactions involving aquatic and terrestrial biospheres differ considerably. The authors used global fisheries, represented as a metric of ecosystem functioning within freshwater and ocean systems to assess the interactions between these two components and others. Here, we use the same control variable, fish biomass, but rather than focusing on global fisheries, we target keystone fish species biomass relative to carrying capacity K specifically.

The reasons for this choice are twofold: 1) one of the greatest challenges global fisheries face is a lack of sufficient data to assess the status of exploited populations (Salas et al. 2007; Espinoza-Tenorio et al. 2011; Costello et al. 2012; Lorenzen et al. 2016) and 2) keystone species can act as a robust indicator of ecosystem functioning, as they play a critical role in determining community structure and their removal can cause drastic changes in species composition and other ecosystem attributes (Pain 1966; Zhao-Hua et al. 2001; Heip et al. 2009; Pedersen et al. 2017). Therefore, to assess ecosystem functioning for the entire globe, it is more reasonable to prioritize and invest in the monitoring and assessment of keystone species rather than all exploited fish populations. Because using the biomass of keystone fish species as a control variable is a new approach for assessing freshwater and ocean biosphere integrity, we recommend further research to test its suitability. However, to elicit expert knowledge on the matter, a measurable and clearly defined control variable was required. Fish population dynamics have been studied extensively, thus, a comprehensive understanding already exists about what population sizes should be to remain within safe biological limits and what thresholds should not be crossed. Based on knowledge about population dynamics and the biomass reference points used in fisheries management (Maunder 2008; Lorenzen et al. 2016; ICES 2017; 2018; Cortés and Brooks 2018), we propose that the biomass of keystone fish species should not fall below 50% of carrying capacity, K.

S2.3 Land system change

The control variable we use for land system change is forested land area relative to potential forest cover (i.e. assuming no human land-cover change), as defined by Steffen et al. (2015). Steffen et al. set boundaries for three distinct forest biomes: tropical, boreal, and temperate forests (85%, 85% and 50% of potential forest cover, respectively). The boundaries are set based on the potential of land cover change to:

1) impact the climate system beyond the region where change occurs (through climate-regulating processes such as exchange of energy and water)

and

2) transgress biome-specific thresholds beyond which self-reinforcing feedbacks of change are activated (e.g. forest to savanna transition in tropical forests due to deforestation leading to reduced moisture recycling).

S2.4 Biogeochemical flows

Planetary boundaries of biogeochemical flows were originally proposed for nitrogen (N) and phosphorus (P) cycles, although Steffen et al. (2015) note that there may be need to develop boundaries also for other elements and ratios between elements, due to their impacts on biodiversity. In this study, we focus on flows of N, due to limitations of our modelling framework. The control variable for biogeochemical flows in this study is leached inorganic N concentration in runoff to surface waters, which was recently used by Gerten et al. (2020) as a proxy for leached inorganic N concentration in surface waters. To prevent eutrophication or acidification in surface waters, leached N concentration shouldn't exceed 1 mg N/L (lower end of uncertainty range of 1-2.5 mg N/L), as suggested by DeVries et al. (2013). As a precautionary measure, and to ensure N concentrations in tributary rivers are captured, we consider the safe local limit for leached inorganic N concentrations in runoff to be the same as in surface waters, 1 mg N/L.

S.2.5 Blue water (Blue high and Blue low for the two different flow seasons)

The control variable for blue water in this study is river discharge (after human activity) relative to pre-industrial seasonal average. This control variable is similar to the one of Steffen et al. (2015), in that it is based on the concept of environmental flow requirements (EFRs), which refer to the minimum discharge needed to maintain fair ecological status in the river. The main distinction in our approach is that we focus on the flow remaining in rivers after human activity, relative to EFRs, as opposed to allowable water withdrawals as in Steffen et al. (2015). Reasoning for this is that human activity alters river flows in several direct and indirect ways, not only through water withdrawals. As most river ecosystems depend on seasonal variation in flows, EFRs are usually different for high and low flow seasons and thus, we also consider both seasons in our assessment.

S2.6. Green water

The control variable for green water in this study is growing season root zone soil moisture relative to pre-industrial growing season average. In other words, we are interested in how much growing season soil moisture (average over the season) deviates from average pre-industrial conditions and how the deviation affects the other control variables considered in this study. A planetary boundary for green water has previously not been defined. However, recent research by Gleeson et al. (2020a, 2020b) proposes that focusing only on blue water and environmental flows does not capture all the crucial Earth System functions of freshwater or the full extent and nature of anthropogenic modifications of the water cycle. First attempts to define the planetary boundary for green water (or several boundaries for different green water stores and fluxes) have only recently started. While critical global or local limits or even relevant control variables have not yet been defined, we still wanted to include a simple green water metric in this study. Soil moisture connects the two green water flows, precipitation and evaporation, and is determined by their balance as well as soil properties affecting infiltration. Root-zone soil moisture can be used to measure water available for plants (and soil organisms), thus linking it to e.g. biodiversity and ecosystem health, land cover and carbon storage. We do not propose a critical value for soil moisture but assume here that both the baseline soil moisture (95% of mean seasonal pre-industrial root zone soil moisture) and the change that was asked to consider (from 95 to 90%) fall within the safe range.

S.3. Aggregation of expert opinions

Table S.3.1. Expert responses that were not included in the aggregation due to high divergence in the resulting individual distribution relative to the non-region aggregated distribution. The values (Lower, Upper, Best) show the change in ΔY caused by ΔX for each interaction X→Y as described in Table S1.

Interaction	Expert	Season	Lower	Upper	Best	CI	Region
BI land->BI fresh	Exp16	no	0.8	0.82	0.8	100	Bears hunting salmon from a river
BI fresh->BI land	Exp14	no	85	95	95	100	Possibly north America, but unlikely in northern Europe where landscapes are already heavily transformed
BI ocean->BI fresh	Exp23	no	0.76	0.86	0.8	100	May be relevant for Nordic regions
BI ocean->Biog. flows	Exp24	no	0.47	0.5	0.5	100	Coastal ecosystems of British Columbia
Land system change->Biland	Exp17	no	38.57	72.85	70	100	probably a mid-latitude forest.
Land system change->Biog.flows	Exp24	no	0.49	0.61	0.53	100	Hubbard brook experiment, referenced paper from Amazon, etc.
Biog.flows->BI land	Exp25	no	95	95	95	100	European rivers
Biog.flows ->BI fresh	Exp14	no	0.66	0.93	0.8	100	Europe
Biog.flows->BI fresh	Exp23	no	0.4	1.2	0.8	100	mainly lakes and ponds. Characteristics in river are differently nutrient river runoff can create anoxic zones in coastal areas and separated ocean regions e.g. Baltic Sea
Biog.flows->BI fresh	Exp25	no	0.8	0.8	0.8	100	European rivers
Biog.flows->BI ocean	Exp21	no	0.45	0.88	0.6	100	Gulf of Mexico and Great Barrier Reef
Biog.flows->BI ocean	Exp25	no	0.8	0.8	0.8	100	European rivers
Green water->BI land	Exp14	no	84	90.66	88	100	Tropical rainforest
Green water->BI land	Exp21	no	63.33	96.66	90	100	Amazon and Australia
Green water->BI land	Exp35	no	49.28	92.14	85	100	Sahel, Amazon, Australia (wild fires)
Green water->Land system change	Exp45	no	86.25	90	90	100	rainforest vs. summergreen forest in particular (Amazon, Sahel...)

S4. Normalization of control variables & estimation of interaction strengths

The control variables were normalized as shown in Table S4.1 and the 80% CI range of the expert assessed ΔY for all identified direct interactions are available in Table S4.2. In addition, for some of the interactions, experts assessed solely or partially indirect interactions, which were excluded from the analysis to avoid double counting. In the latter case, we extracted the indirect portion of the interaction and kept only the direct portion as described below for the interaction that was necessary and possible.

<u>BI land</u> <u>--></u> **<u>BI fresh interaction</u>**

Experts mentioned that except for direct interactions, there are also indirect interactions via changes in biogeochemical flows. Thus, we can remove the indirect portion as follows:

BI land --> BI fresh: 1

BI land --> Biog.flows: -0.4

Biog.flows --> Bi fresh: -0.84

Product of BI land --> Biog.flows --> BI fresh: 0.336

Then the direct portion BI land --> BI fresh: 0.664

<u>BI land</u> <u>--></u> **<u>Green water interaction</u>**

Experts mentioned both direct mechanisms but also indirect via land system change:

BI land --> Green water:0.15

BI land --> Land system change : 0.20

Land system chance --> Green water: 0.50

Product of BI land --> Land system change --> Green water: 0.1

Then the direct portion is BI land --> Green water 0.05

<u>BI fresh</u> <u>--></u> **<u>Land system change interaction</u>**

Experts mentioned direct via seedling dispersion but also indirect via nutrient transport (e.g. salmon returning to rivers and carcasses spreading nutrients in the forest). With the existing input it was not possible to quantify either portion, but we at least know that in certain areas they can interact via these mechanisms.

<u>Land system change</u> <u>--></u> **<u>BI fresh interaction</u>**

Article cited by one expert mention fish feed on fruit/seeds and structural changes but people mention mainly the indirect via changes in biogeochemical flows (mainly) and maybe river discharge so then it is Land system change --> Biog.flows/ Blue --> BI fresh and partially direct via changes in habitat structure and food availability.

Land system change --> BI fresh: 0.35

Land system change --> Biog.flows:-0.44

Biog.flows --> BI fresh: -0.83

Land system change --> Biog.flows --> BI fresh: 0.365

In that case, we can assume 0 direct (as negative is not logical) so it was not possible to quantify this direct (weak) link.

<u>Land system change</u> <u>--></u> **<u>Biog.flows interaction</u>**

Experts mention the obvious direct interaction (erosion, runoff) but also indirect via green water:

Land system change --> Biog.flows: -0.4

Land system change --> Green water: 0.5

Green water --> Biog.flows: 0.08

Land system change --> Green water --> Biog.flows: 0.04

Then the direct portion is Land system change --> Biog.flows: -0.44

<u>Land system change</u> <u>--></u> **<u>Blue water interaction</u>**

Experts mention mechanisms via green water:

Land system change --> Blue water (High): -0.5

Land system change --> Blue water (Low): -0.0024

Land system change --> Green water: 0.5

Green water --> Blue water (High):0.6

Land system change --> Green water --> Blue water (High): 0.30

Green water --> Blue water (Low):1

Land system change --> Green water --> Blue water (Low): 0.5

Then the direct portion becomes Land system change --> Blue water (High): -0.8

and Land system change --> Blue water (Low): -0.50021

<u>Blue water</u> <u>--></u> **<u>BI land interaction</u>**

Experts mention indirect via trophic interactions with BI fresh:

Blue water --> BI land: 0.6

Blue water (High) --> BI fresh: 0.6

Blue water (Low) --> BI fresh: 0.8

BI fresh --> BI land: 0.43

Blue water (High) --> BI fresh --> BI land: 0.258

Blue water (Low) --> BI fresh --> BI land: 0.344

Blue water (High) --> BI land: 0.342

Blue water (Low) --> BI land: 0.256

Blue water --> Land system change interaction

Experts mention indirect mechanisms via green water:

Blue water (High) --> Land system change: 0.20

Blue water (Low) --> Land system change: 0.4

Blue water (High) --> Green water: 0.2

Blue water (Low) --> Green water: 0.000006

Green water --> Land system change: 0.4

Blue water (High) --> Green water --> Land system change: 0.08

Blue water (Low) --> Green water --> Land system change:0.0000024

Then the direct portion is Blue water (High) --> Land system change: 0.12 and Blue water (High) --> Land system change: ~0.4

Green water --> BI land interaction:

Experts also mentioned indirect mechanisms via Land system change:

Green water --> BI land: 1

Green water --> Land system change: 0.4

Land system change --> BI land: 1

Green water --> Land system change --> BI land: 0.4

Then the direct portion is Green water --> BI land: 0.6

Table S4.1. Selected values to normalize control variables for each of the Earth system processes with the normalized safe range of each control variable and the normalized ΔX in the hypothetical area experts assessed.

Earth system process	Control variable	Value for normalization	Normalized safe range	Normalized ΔX
Land Biosphere integrity	Biodiversity Intactness Index (BII)	100 %	0.9-1	0.05
Freshwater Biosphere integrity	Keystone fish biomass (K)	1	0.5-1	0.2
Ocean Biosphere integrity	Keystone fish biomass (K)	1	0.5-1	0.2
Land system change	Forest cover relative to potential forest cover	100%	Boreal & tropical :0.85-1 Temperate: 0.5-1 Global: 0.75-1	0.1
Biogeochemical flows	N concentration in runoff (N mg/L)	2.5	0-0.4	0.12
Blue water – High flow season	River discharge relative to environmental flow requirement (EFR)	100%	(0.15-0.45) -1	0.05
Blue water – Low flow season	River discharge relative to EFR	100%	(0.45-0.75)-1	0.05
Green water	Growing season root-zone soil moisture	100%	0.8-1	0.05

Table S4.2. Assessed normalized Δy best estimate and 80% CI for each normalized Δx for all the direct interactions identified before indirect portions removed.

Interaction	Season	ΔX	Best estimate ΔY	10th percentile ΔY	90th percentile ΔY
BI land->BI fresh		-0.05	-0.05	-0.101	0.001
BI land->Land system change		-0.05	-0.01	-0.049	0.000
BI land->Biog.flows		-0.05	0.02	0.004	0.077
BI land->Green water		-0.05	-0.0075	-0.033	-0.003
BI fresh->BI land		-0.2	-0.085	-0.186	-0.026
BI fresh->BI ocean		-0.2	-0.085	-0.143	-0.021
BI fresh->Land system change		-0.2	0	-0.034	0.000
BI fresh->Blue water	High	-0.2	0	-0.002	0.000
BI fresh->Blue water	Low	-0.2	0	-0.007	0.000
BI ocean->BI land		-0.2	-0.05	-0.169	-0.006
BI ocean->BI fresh		-0.2	-0.01	-0.119	-0.002
BI ocean->Land system change		-0.2	0	-0.029	0.000
Land system change->BI land		-0.1	-0.1	-0.160	-0.024
Land system change->BI fresh		-0.1	-0.035	-0.083	-0.001
Land system change->Biog.flows		-0.1	0.04	0.013	0.115
Land system change->Blue water	High	-0.1	0.05	-0.001	0.143
Land system change->Blue water	Low	-0.1	0	-0.101	0.023
Land system change->Green water		-0.1	-0.05	-0.123	0.006
Biog.flows->Biland		0.12	0	-0.211	0.000
Biog.flows->BI fresh		0.12	-0.1	-0.287	0.008
Biog.flows->Biocean		0.12	-0.05	-0.244	0.018
Biog.flows-> Land system change		0.12	0.01	0.000	0.036
Blue water->BI land	High	-0.05	-0.03	-0.085	-0.010
Blue water->BI land	Low	-0.05	-0.03	-0.051	-0.003
Blue water->BI fresh	High	-0.05	-0.03	-0.089	-0.006
Blue water->BI fresh	Low	-0.05	-0.04	-0.098	-0.017
Blue water->BI ocean	High	-0.05	-0.025	-0.069	-0.004
Blue water->BI ocean	Low	-0.05	-0.02	-0.047	0.000
Blue water->Land system change	High	-0.05	-0.01	-0.053	-0.004
Blue water->Land system change	Low	-0.05	-0.02	-0.053	-0.003
Blue water->Green water	High	-0.05	-0.01	-0.047	-0.001
Blue water->Green water	Low	-0.05	0	-0.014	0.000
Green water->BI land		-0.05	-0.05	-0.092	-0.004
Green water->Land system change		-0.05	-0.02	-0.058	-0.004
Green water->Biog.flows		-0.05	-0.004	-0.018	0.001
Green water->Blue water	High	-0.05	-0.03	-0.064	-0.001
Green water->Blue water	Low	-0.05	-0.05	-0.101	-0.007

S5. Identified interactions, uncertainty categorization and network analysis

The direct interactions identified with the expert knowledge elicitation can be seen in Table S5.1 in a matrix form. The interactions identified with the help of expert knowledge are sensitive to potential biases in the assessment. To accommodate for this, we separated them into three different uncertainty zones based on expert agreement and the number of inputs per interactions (Table S5.2). Expert agreement was very high for all interactions but one, so that shows that for all cases, despite the number of responses per interactions, experts agreed on the level of impact.

Some of these interactions are extremely weak, however this could be because they are present in very special environments. In that case, even though here they seem insignificant, in these specific environments they potentially could be very central. These interactions are the following:

BI fresh --> Land system change links: Seed dispersal and excess nutrient absorption by fish in e.g. Amazon and nutrient enrichment from dead migratory fish (e.g. salmon) e.g. in Alaska.

BI fresh --> Blue water potential link: changes in freshwater ecosystem functioning could alter vegetation and growth of macrophytes could affect river discharge and sediment turbidity.

BI ocean --> Land system change links: Seed dispersal and fertilization by fish in e.g. mangrove forests and nutrient enrichment from dead migratory fish (e.g. salmon) e.g. in Alaska.

Biogeochemical flows --> BI land links: It could potentially boost productivity, but it could also be toxic to specific species at high levels. No parameterization between nitrogen bleaching and BII exists thus, difficult to assess.

Biogeochemical flows --> Land system change links: In N limited systems, e.g. Taiga, the increased nutrients could boost plan productivity.

The above interactions but the last (interaction strengths <0.005), were excluded in the network analysis and the metrics are presented in Table S5.1.

Table S5.1. Absolute normalized biophysical interaction strengths identified with expert knowledge elicitation. We shaded the cells where a direct interaction was identified. Interactions with strength in the range of -0.005≤s≤0.005 were excluded from the analysis and were set to NA as well.

	BI land	BI fresh	BI ocean	Land system change	Biog. flows	Blue water High	Blue water Low	Green water
BI land	NA	0.664	NA	0.2	-0.4	NA	NA	0.05
BI fresh	0.43	NA	0.43	NA	NA	NA	NA	NA
BI ocean	0.25	0.05	NA	NA	NA	NA	NA	NA
Land system change	1	NA	NA	NA	-0.44	-0.8	-0.5	0.5
Biog.flows	NA	-0.83	-0.42	0.08	NA	NA	NA	NA
Blue water High	0.342	0.6	0.5	0.12	NA	NA	NA	0.2
Blue water Low	0.256	0.8	0.4	0.4	NA	NA	NA	NA
Green water	0.6	NA	NA	0.4	0.08	0.6	1	NA

The uncertainty categories based on expert agreement and responses per interaction are available in Table S5.2. Categorization for expert agreement is done according to Gracht et al. (2012) and Scherer et al. (2020) in which high agreement was considered for cv<=0.5, acceptable agreement for 0.5<cv<=0.8 and no agreement for cv>0.8. For the number of responses per interactions according to the literature, a minimum of four to six experts should be included in an elicitation (Cooke & Goossens 2004; Cooke and Probst 2006), with empirical evidence suggesting that only minor improvements are gained when having more than six to twelve participants (Armstrong 2001; Hora, 2004; Cooke and Probst 2006). This suggests that even for the interactions that we had the least responses, it should be sufficient to make inference. However, to be more precautionary in our assessment, we created 3 categories to represent our certainty in the assessment. High certainty for >=10 responses, medium certainty for 6-9 responses and low certainty for <=5 responses. Color coding is according to the above two metrics and their combination leads to six different uncertainty categories (green-green, green-yellow, green-red, yellow-red, red-red). The assessed interaction uncertainty fell in only three of the total six categories as seen below by the number of interactions per combined categories.

Table S5.2. Uncertainty categorization criteria for each interaction based on agreement of expert opinions (coefficient of variation-CV in best estimates) and the number of expert inputs per interaction. Categorizations based on CV: a) green (cv<=0.5), b) yellow (0.5<cv<=0.8), c) red (cv>0.8). Categorizations based on number of responses: a) green (>=10), b) yellow (6-9), c) red (<=5).

CV of best estimates	Anwers per interaction	Combined Categories
<=0.5	>=10	14
<=0.5	6-9	10
<=0.5	<=5	5
0.5-0.8	>=10	1
0.5-0.8	6-9	0
0.5-0.8	<=5	0
>0.8	>=10	0
>0.8	6-9	0
>0.8	<=5	0

Table S5.3. Network analysis metrics. Network analysis was performed with the igraph R package (Csardi & Nepusz 2006). The three PBs with higher importance for each metric are presented in bold.

Metric	**BI land**	**BI fresh**	**BI ocean**	**Land system change**	**Biog. flows**	**Blue water high**	**Blue water low**	**Green water**
Strength								
Receiving	**2.898**	**2.944**	**1.75**	1.2	0.92	1.4	1.5	0.75
Originating	1.314	0.86	0.3	**3.24**	1.33	1.78	**1.858**	**2.68**
Total	**4.212**	**3.804**	2.05	**4.44**	2.25	3.18	3.358	3.43
Eigen vector [1]	**0.95**	0.772	0.425	**1**	0.507	0.736	0.781	**0.83**
Node degree [2]	**10**	7	6	**10**	6	7	6	**8**

[1] influence of a node in a network

[2] connections with other nodes

S6. Commonly identified interactions in this work and in Lade et al. (2020).

Related to the impacts of *Land system change* on *BI Land*, when we recalculated the Lade et al. (2020) estimate with our definition for interaction strength, their estimate of the strengths becomes moderate while ours is very strong. A recent study by De Palma et al. (2021) finds that the reduction of Biodiversity Intactness Index (BII) is half of the relative reduction in forest cover, which is closer to

Lade et al.’s (2020) findings than ours. An earlier empirical approach, which estimates species loss relative to habitat disturbance for tropical forests (Alroy 2017), finds that the relationship for certain taxonomic groups can be above the 1:1 ratio, consistent with our assessment. In addition, a more recent estimate of BII by Sanchez-Ortiz et al. (2019) places BII at around 71-73% in response to *Land system change*, in comparison to Newbold et al. (2016) that places BII at 84.6%. Recalculating the interaction strength from Lade et al. (2020) with the updated BII by Sanchez-Ortiz et al. (2019), and not the Newbold et al. (2016) the authors use (See Supplementary materials Table S6.1 for details), the interaction between *Land system change* and *BI Land* becomes stronger. Therefore, our estimate of a strong interaction is in fair agreement with recent literature, which indicates a moderate to strong interaction.

Our estimate on the attenuating interaction from *Land system change* to *Blue water* was stronger than in Lade et al. (2020). However, our local-scale interaction was assumed to occur strictly within a river basin without teleconnections to regional or continental scales. As this is relatively different from the global interaction estimated in Lade et al. (2020), and as this interaction is highly sensitive to spatial scale (see Section 3.1), a direct comparison is difficult. In more comparable scales, Zhang et al. (2017) find a higher than 2:1 relationship between forest loss and increase in river discharge (for both large and small watersheds). In addition, Horton et al. (2021) also find in Mexican tropical forests a close to 2:1 relationship between forest loss and mean monthly discharge for both the low and high-flow season, respectively. When this interaction was estimated with the above local-scale values (See Table S6.1 for details), our results of moderate to strong interaction are in agreement.

Table S6.1: Comparison of the commonly identified interactions in this work and in Lade et al. (2020). Shaded the cells where the magnitude of the interactions is at similar levels. Biogeochemical flows related interactions identified in this work are amplifying when negative and attenuating when positive.

Interaction	This work	Lade et al. (2020)	Comparison based on our normalization scheme
Land system change --> **BI land**	1	0.8	Based on the current value for Land system change and BII as described in Lade et al. (2020) ΔX=-38% and ΔY=-15.4%. If we apply our approach for estimating the interaction strength, this leads to s=0.4*0.8=0.32 because Campbell et al. (2017) suggested that Land system change is responsible for 80% of the current status of the BI land status. This indicates that we estimated a stronger relationship than the above as for example in our estimates, a 10% decrease in forest cover would lead to a 10% decrease in BII. At the same time Alkemade et al. (2009) estimated that current mean species abundance (MSA) was at 0.7 at 2000 thus, if the forest cover was then as currently as 62% globally, then the interaction between forest cover and MSA is s=0.79*0.8=0.632. According to De Palma et al. (2021), the reduction of BII is half of the reduction in forest cover and thus this means s=0.5. However, Alroy (2017) estimated that this relationship can be as close to 1:1 for specific taxonomic groups thus s=1. A more recent evaluation of BII by Sanchez-Ortiz et al. (2019) placed it at 71-73% and therefore s=0.74*0.8=0.6. Our estimate is on the higher end of the above estimates but still within the literature range.
Land system change --> **BI freshwater**	0	0.08	Lade et al. (2020) estimated this interaction being very weak, as decrease in forest cover is found to affect fisheries catch per unit of effort (CPUE) only close to the river (Castello et al. 2018). Even though it is not easy to compare CPUE to fish biomass, that is the control variable used here, halving of CPUE could also indicate halving of biomass, though without knowing what the initial biomass level was. In our elicitation, the mechanisms identified were mainly indirect, via biogeochemical flows and river discharge, and direct interactions via altered habitat and trophic interactions were considered extremely weak (and therefore set to 0) thus, we can conclude that despite the different control variables, the conclusion is the same for a very weak interaction.
Land system change --> **Freshwater use (Blue water)**	-0.8 (high) -0.6 (low)	-0.11	In both cases, the interaction is identified as attenuating but we estimate it to be stronger than the one estimated in Lade et al. (2020). If we again apply the normalization and parameterization we used here, then the change in land system change ΔX=-38% and an increase in river discharge globally of ΔY=6.6% as identified in Rost et al. (2008) would lead to an estimation of s=-0.17. The difference could be due to the fact that we removed the indirect portion of the interaction with Green water and that might have been done in a more roughly way that appropriate. In addition, in Rost et al. (2008) river discharge is estimated as the total volume of water whereas here we assess river discharge relative to the pre-industrial average. Zhang et al. (2017) found a larger than 2:1 ratio in the relationship between Land system change and water discharge, which brings the estimated interaction to s>=0.5, which is closer to our estimate. Additionally, Horton et al. (2021) found a decrease of water discharge by 27% and 30% for the low and high flow season, respectively, when forest cover decreased to 42%. This leads to an estimate for the interaction of s=0.46 for low-flow season and s=0.52 for the high-flow season. Our estimates are higher than the above calculation but still within the same range of moderate to high interaction strength.
Biog. flows --> **BI land**	-0.0008	0.02	In both cases a very weak interaction between added nutrients and impacts on BI Land were observed. In our case, an even weaker relationship is found because at the low levels of nitrogen we assessed the interaction, some experts considered the productivity boosting. Note, that our interaction estimate is negative due to the parameterization we used even though it is amplifying as an increase in nitrogen concentration leads to a decrease in BII thus, they are both moving towards outside the safe range.
Biog. flows --> **BI fresh**	-0.83	1	Lade et al (2020) estimated this interaction such as once the nutrient boundary is reached so has also the BI freshwater. If we follow the same logic with the current parameterization and nitrogen concentration increases from to 1 N mg/L and assuming fish biomass was initially at 1K, then the fish biomass would decrease to 0.67K with our estimate, which

			brings fish biomass closer to the lower safe limit of 0.5K. Thus, we can see that in both cases the interaction strength is quite close. Note, that our interaction estimate is negative due to the parameterization we used even though it is amplifying as an increase in nitrogen concentration leads to a decrease in keystone fish biomass thus, they are both moving towards outside the safe range.
Biog. flows --> **BI ocean**	-0.42	0.05	The interaction strength is notably different and not even comparable as Lade et al. (2020) assessed it relative to phosphorus and the probability of a widespread ocean hypoxic event. Here we assessed the coastal areas and thus, as in the Biogeochemical flows□BI freshwater BI relationship, the main mediating mechanism is eutrophication and a half magnitude interaction relative to the freshwater BI seems reasonable. Note, that our interaction estimate is negative due to the parameterization we used even though it is amplifying as an increase in nitrogen concentration leads to a decrease in keystone fish biomass thus, they are both moving towards outside the safe range
freshwater use (Blue) --> **BI fresh**	0.6 (high) 0.8 (low)	1	Lade et al. (2020) estimated this interaction such that once the freshwater use boundary is reached then the BI freshwater is also reaching its boundary. In that case, if we assume that for river discharge the boundary is at 45% mean pre-industrial, then a decrease of ΔX=-55% in river discharge and a ΔY=-0.5K decrease in fish biomass lead to s=0.9 which is quite close to our estimate as well.

S7. Mediating mechanism of Earth system processes interactions

Details on the mechanisms identified by the experts and relevant literature are available in the Excel supplementary file. Additionally, in the excel file are available all the elicitation results after the second round updates standardized to 100% CI. Individual results are not discussed in the main text as the purpose was to illustrate the general picture related to the identified interactions. However, individual results may be of interest for further studies. Figure S7.1 describes all identified mechanisms including context-specific ones.

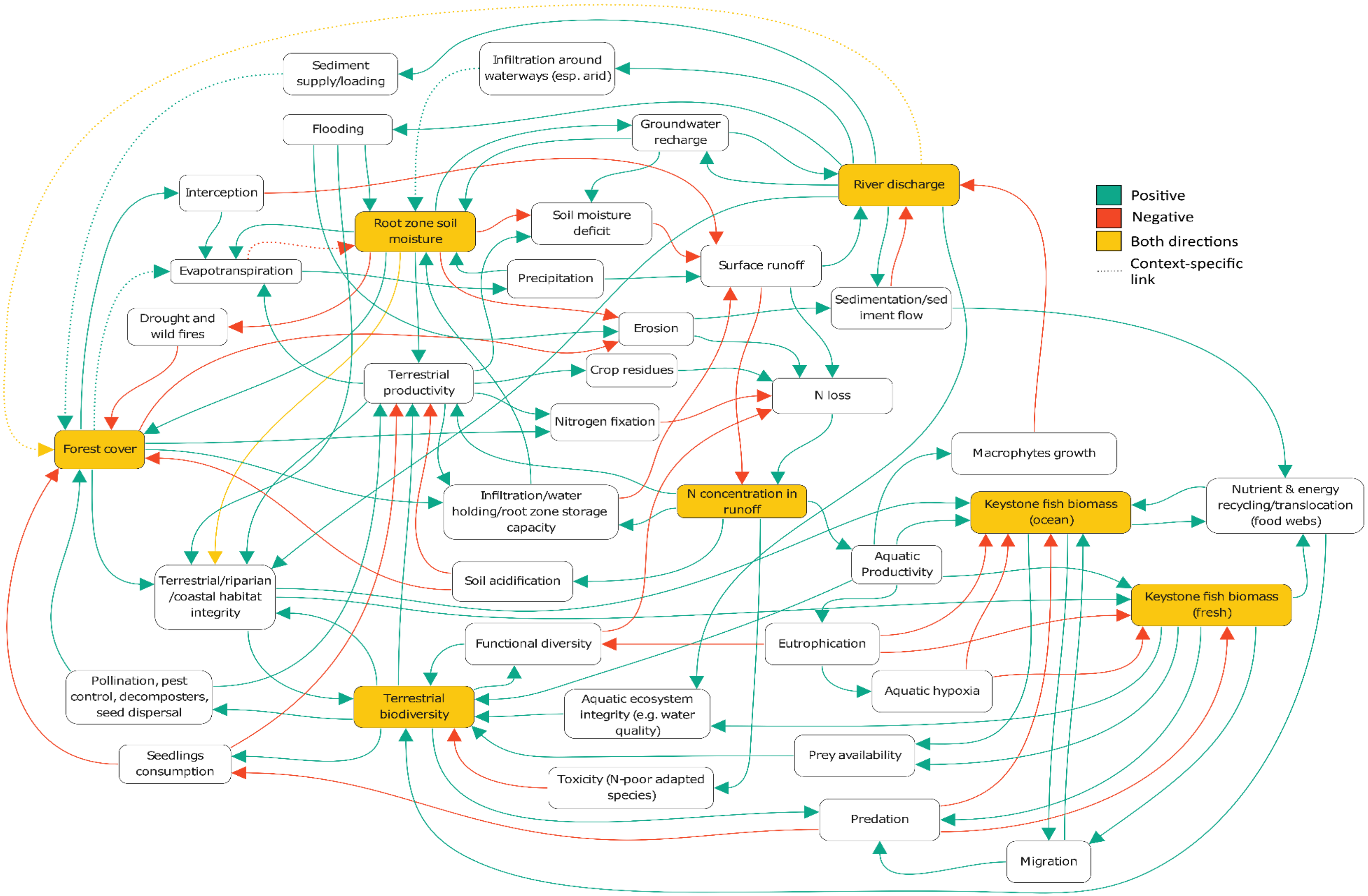

Figure S7.1: Mediating mechanisms of interactions among Earth system processes relevant to food production identified by expert knowledge elicitation. Positive links indicate that an increase/decrease in one variable leads to an increase/decrease in another variable, respectively. Negative links indicate that an increase/decrease in one variable leads to a decrease/increase in another variable, respectively. Both direction links indicate that an increase/decrease in one variable can lead to both increase and decrease in another variable, depending on specific contexts. Dotted links indicate highly context-specific relationships, which may exist only in certain environments.

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