Quantifying Earth system interactions for sustainable food production: an expert elicitation

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Article

Keywords: Safe Operating Space, Earth system processes, interactions, food production, expert elicitation

Posted Date: December 3rd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-1085622/v1

Version of Record: A version of this preprint was published at Nature Sustainability on August 15th, 2022. See the published version at https://doi.org/10.1038/s41893-022-00940-6.

Quantifying Earth system interactions for sustainable food production: an expert elicitation

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Abstract

Several safe boundaries of critical Earth system processes have already been crossed by human perturbations. Recent research indicates that not accounting for the interactions between these processes may further narrow the safe operating space for humanity. Yet existing work accounts only for transgression of single boundaries and only a few studies take some of the boundary interactions into account. For future sustainability assessments, it is essential to understand boundary transgressions and their interactions more comprehensively. Here, we explore quantitatively how strongly seven variables, representing Earth system processes relevant to food production, interact with each other, using a structured expert knowledge elicitation. We identify *Green water* and *Land system change* as crucial interactive processes through their impacts on multiple relevant processes, while *Biosphere integrity-land, freshwater* and *ocean* components appear to be most affected by other Earth system processes, most notably *Blue water* and *Biogeochemical flows*. The elicitation also enabled us to map the complex network of mechanisms mediating interactions, to support integrated Earth system and planetary boundaries modelling and assessments. Finally, we created a prioritisation scheme for future research according to the interaction strengths and existing knowledge gaps. Our analysis improves our understanding of Earth system interactions, with clear implications for sustainable use of natural resources such as the biophysical limits for food production.

Keywords: Safe Operating Space, Earth system processes, interactions, food production, expert elicitation

1. Introduction

Food production is exerting unprecedented pressure on ecosystems across the globe. Terrestrially, agriculture is responsible for about 80% of global deforestation (Campbell et al. 2017) and is the main driver for land biodiversity loss (Newbold et al. 2016; Leclère et al. 2020). About 70% of freshwater withdrawn from rivers, lakes, and aquifers is used for irrigation annually (AQUASTAT). At the same time, freshwater systems are increasingly polluted and eutrophied through pesticide and fertiliser use, with serious implications on aquatic species (Conijn et al. 2018). Moreover, the increasing demand for blue foods (seafood from fisheries and aquaculture) has led to growing numbers of unsustainable fisheries - rising from 10% in 1974 to 34.2% in 2017 (FAO 2020).

Current human pressures on the environment – to a large extent caused by agriculture (Campbell 2017) – are so extensive that they have already been pushing the Earth system beyond the safe operating space for humanity, as demarcated by the planetary boundaries (Rockström et al. 2009; Steffen et al. 2015). The planetary boundaries framework identifies nine critical Earth system processes and proposes boundaries to their anthropogenic modification. Beyond these boundaries, the risk of abrupt or irreversible global environmental change increases, with the potential to push the Earth system out of its stable Holocene condition, thus threatening the capacity of humanity to develop and thrive (Hughes et al. 2013; Steffen et al. 2015).

The first quantitative estimates of an array of interactions among the Earth system processes, represented by the planetary boundaries, suggest that the cascades and feedbacks of their interactions are amplifying human impacts on the Earth system, but at the same time offer scope for potential synergies; decreasing impacts on one Earth system may decrease impacts to others as well (Lade et al. 2020). Accounting for these interactions may narrow the estimated global safe operating space for human activities. Given that many agriculture-related interactions are not quantified by Lade et al. (2020), and marine processes have received less attention within the planetary boundaries literature (Nash et al. 2017), achieving sustainable food futures would potentially require even more drastic measures than suggested by past work.

However, Earth system interactions are challenging to account for in food system analyses and spatially disaggregated models. These challenges are multifaceted, as interactions and interaction strengths are still largely unknown, can be context specific, and not all variables are suitable for spatial models. For these reasons, future research should not focus only on respecting the global safe operating space, but should also explore how to stay within critical limits of ecosystems at smaller scales (Zipper et al. 2020) – i.e. the limits that could cause an ecosystem regime shift if exceeded. Such effects can be easily detected at the ecosystem level, as the impacts and the interactions of key Earth system processes are mostly manifested locally (Newbold et al. 2016; Heck et al. 2018; Zipper et al., 2020; Li et al. 2021). Furthermore, ongoing advances in climate, ocean and terrestrial modelling capacities (Christensen & Walters 2004; Schipper et al. 2020; Drüke et al. 2021) open up possibilities to including such complex interactions and feedbacks to better understand their roles in climate and sustainability outcomes (Gerten & Kummu 2021).

Our research advances the field in two major ways. First, our exploration mapped a wider array of Earth system processes linked to food production and particularly agriculture, compared to previous attempts and quantified the interaction strengths among them. This is an important step towards understanding the safe operating space for food production, as currently only a limited number of these interactions are quantified based on the available literature (Lade et al. 2020). Second, we identified the mechanisms mediating these interactions, and thus provide unprecedented information to better understand the processes driving them, which is also important for Earth system modelling among other fields. A significant difference between ours and Lade et al.'s (2020) attempt to quantify interactions among Earth system processes is that we explored them with variables that can be quantified and used in spatially disaggregated models, whereas Lade et al.'s (2020) global approach – while retaining the planetary boundaries framework control variables – precludes the inclusion of their quantifications from such models.

We concentrated on four key Earth system processes relevant for food production (Gerten and Kummu 2021) that are all likely already transgressed (Campbell et al. 2017), namely *Biogeochemical flows*, *Biosphere integrity* (BI), *Freshwater use* and *Land-system change.* We divided *Biosphere integrity* (BI) into *land*, *freshwater* and *ocean* components and *Freshwater use* into *Blue* and *Green* water, as justified in Methods (see also Figure 1, Figure 2A). We therefore evaluated interactions among seven terrestrial and aquatic control variables – i.e. functional indicators of the underlying Earth system processes as listed and introduced in Figure 2A. All included Earth system processes are bottom-up in nature, as opposed to, for example, climate change, which is a top-down process.

The identification and quantification of the interactions between the selected control variables was conducted through an expert knowledge elicitation, following the IDEA (Investigate, Discuss, Estimate, Aggregate) structured elicitation protocol (Hemming et al. 2018; see Methods). This approach was chosen as we are very early in the process of quantifying such interactions and expert knowledge is therefore an excellent first source of available information accumulated through training and experience. The elicitation was done for a hypothetical study area (Figure 2B; Methods), and the achieved results provided valuable information on the strength of the interactions, the role of each control variable at a local scale in mediating these interactions, and the mechanisms involved (Figure

1). We envision that our results will be useful for modelling of Earth system processes, for ecosystem managers and for future planetary boundaries framework development.

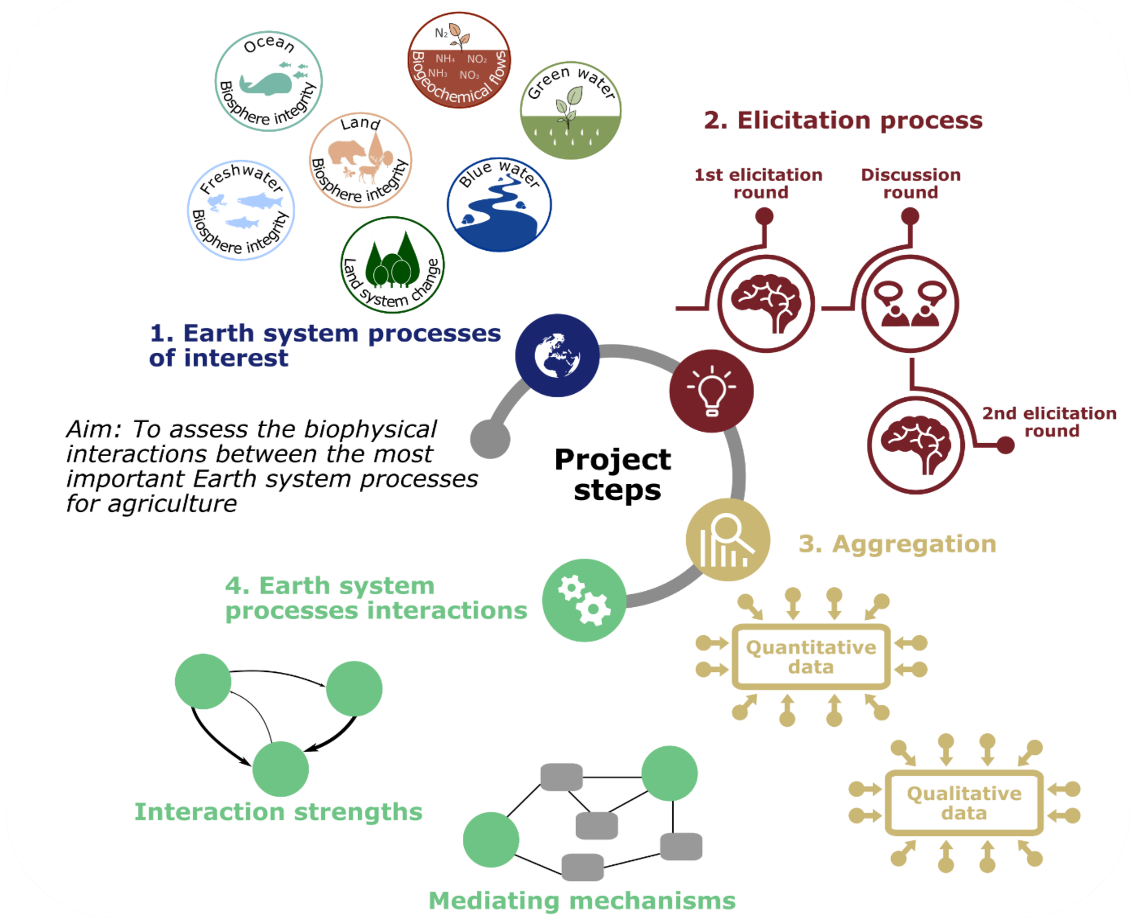
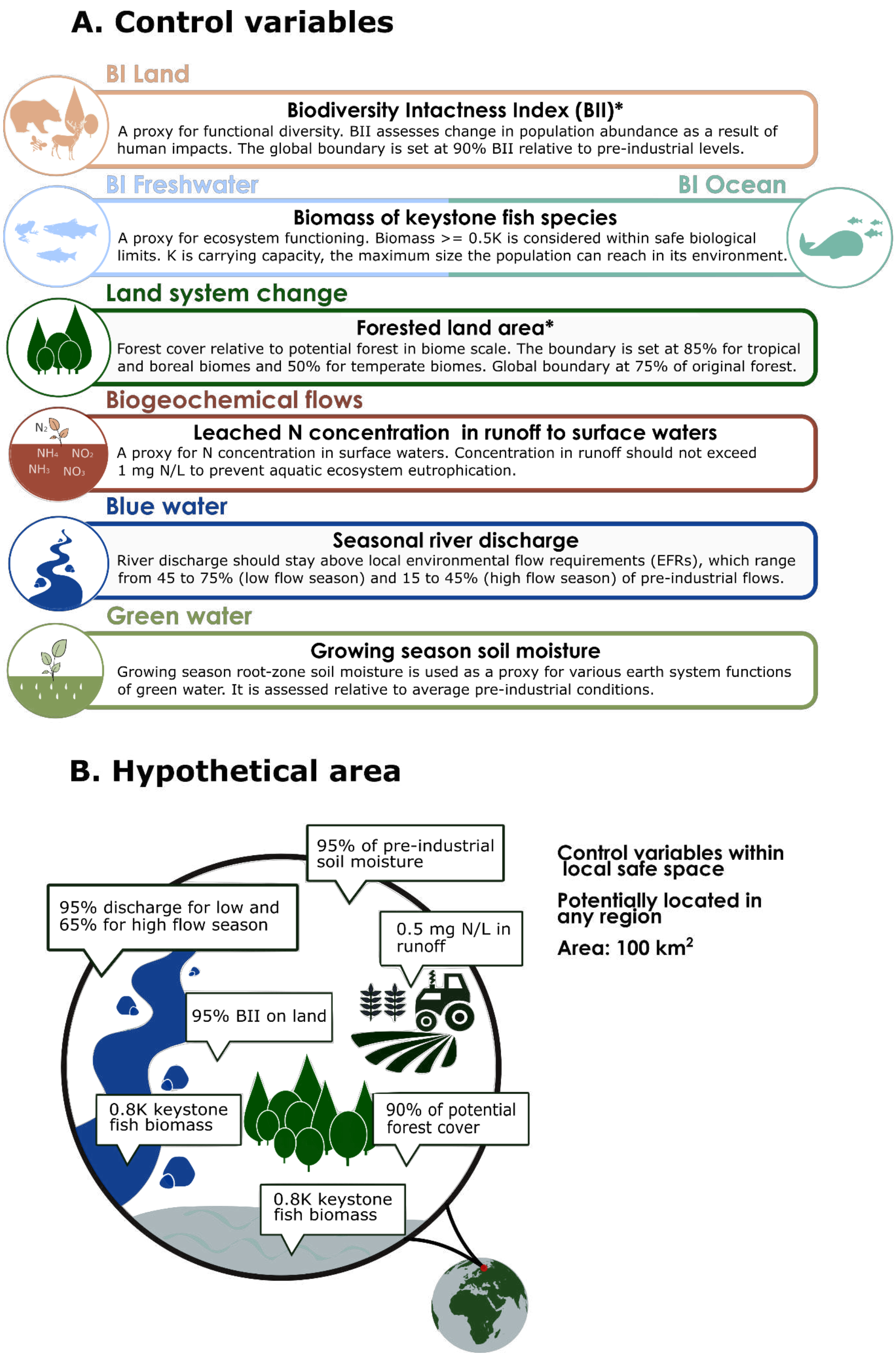


Figure 1: Schematic representation of the project steps. 1: The Earth system processes closely linked with agriculture were selected as the focus of this work. 2: The expert elicitation was conducted following a structured protocol. 3: Individual expert assessments were aggregated to derive the final elicitation results. 4: The aggregated data were used to estimate the interaction strengths and build the network of mediating mechanisms.



Biodiversity Intactness Index (BII)*
A proxy for functional diversity. BII assesses change in population abundance as a result of human impacts. The global boundary is set at 90% BII relative to pre-industrial levels.

Biomass of keystone fish species
A proxy for ecosystem functioning. Biomass >= 0.5K is considered within safe biological limits. K is carrying capacity, the maximum size the population can reach in its environment.

Forested land area*
Forest cover relative to potential forest in biome scale. The boundary is set at 85% for tropical and boreal biomes and 50% for temperate biomes. Global boundary at 75% of original forest.

Leached N concentration in runoff to surface waters
A proxy for N concentration in surface waters. Concentration in runoff should not exceed 1 mg N/L to prevent aquatic ecosystem eutrophication.

Seasonal river discharge
River discharge should stay above local environmental flow requirements (EFRs), which range from 45 to 75% (low flow season) and 15 to 45% (high flow season) of pre-industrial flows.

Growing season soil moisture
Growing season root-zone soil moisture is used as a proxy for various earth system functions of green water. It is assessed relative to average pre-industrial conditions.

Figure 2: Control variables and hypothetical study area. ***A****: The control variables for each of the Earth system processes used for the elicitation purposes. Control variables indicated with * are the same as defined in Steffen et al. (2015). For control variables without existing boundary values, safe ranges were developed and set instead (see SM).* ***B****: The hypothetical area of 100 km^2 with the control variables within safe ranges was used to assess the interactions among the agriculture- impacted Earth system processes by experts in this scenario-based elicitation.*

2. Results & interpretations

2.1. Identified interactions and their roles

Experts identified 37 direct biophysical interactions out of a total of 54 possible ones, considering all components of the agriculture-impacted Earth system processes and the selected control variables (Figure 3). The findings suggest considerable local interconnections of Earth system processes. Some of these interactions, such as the impacts of *Land system change* on *BI Land*, are well known and documented in the Earth system literature (for example, see Newbold et al. 2016; Heck et al. 2018), but the majority of them, such as the interactions between the aquatic (*BI Freshwater* and *BI Ocean*) and *BI Land* components (both directions), are not quantified in the literature (Figure 3 and Table S5.1). Our results reveal that experts estimate strong impacts on aquatic biodiversity (*BI Freshwater* and *BI Ocean*) by changes in other Earth system processes. For example, *BI Freshwater* is seen to be especially impacted by changes in *Blue water*, *Biogeochemical flows* and *BI Land*. Larger negative impacts on *BI Freshwater* can be caused by increased nitrogen concentration in surface waters and decreased water flow. At the same time, a decrease in *BI Freshwater* can substantially impact *BI Land* and *BI Ocean*, which reflects the importance of considering all three components in future *Biosphere integrity* assessments. *Green water* and *Land system change* are also involved in many strong interactions. (Figure 3 and Table S5.1) – for example, a decrease in soil moisture can directly impact *Blue water*, *BI Land* and *Land system change*. At the same time, soil moisture can be reduced when forest cover decreases. *Land system change*, as expected, seems to be a major cause of changes in other Earth system processes, notably *BI Land* and *Blue water*.

Very few interactions were found to be attenuating; the interaction from *Land system change* to *Blue water* was the only one that experts identified as strongly attenuating, whereby a decrease in forest cover leads to increased river discharge at both high and low-flows (Figure 3). However, this might hold only at the local scale, as larger-scale decreases in forest cover tend to cause regionally drier conditions (Lawrence and Vandecar 2015). Experts also identified a weak attenuating interaction from *Biogeochemical flows* to *Land system change*, as increased nitrogen in runoff can boost plant productivity up to some limit. Another weak attenuating interaction was from *Green water* to *Biogeochemical flows*, as decreased soil moisture can lead to smaller concentration of nitrogen in runoff. Relevant literature for the identified interactions (not limited to those provided by the elicitation participants) is available in Supplementary materials S7.

For seven of the identified direct interactions, the resulting strength was extremely weak (s<0.005), so these were excluded from further analysis. This weak relationship could be attributed to the fact that these interactions are indeed very weak, that they are present only in specific environments with potentially high local importance, or that they are more complex than the others and do not follow simplified linearity assumptions, and therefore have not been well-characterised in past work (See Supplementary materials S5 for details on these interactions).

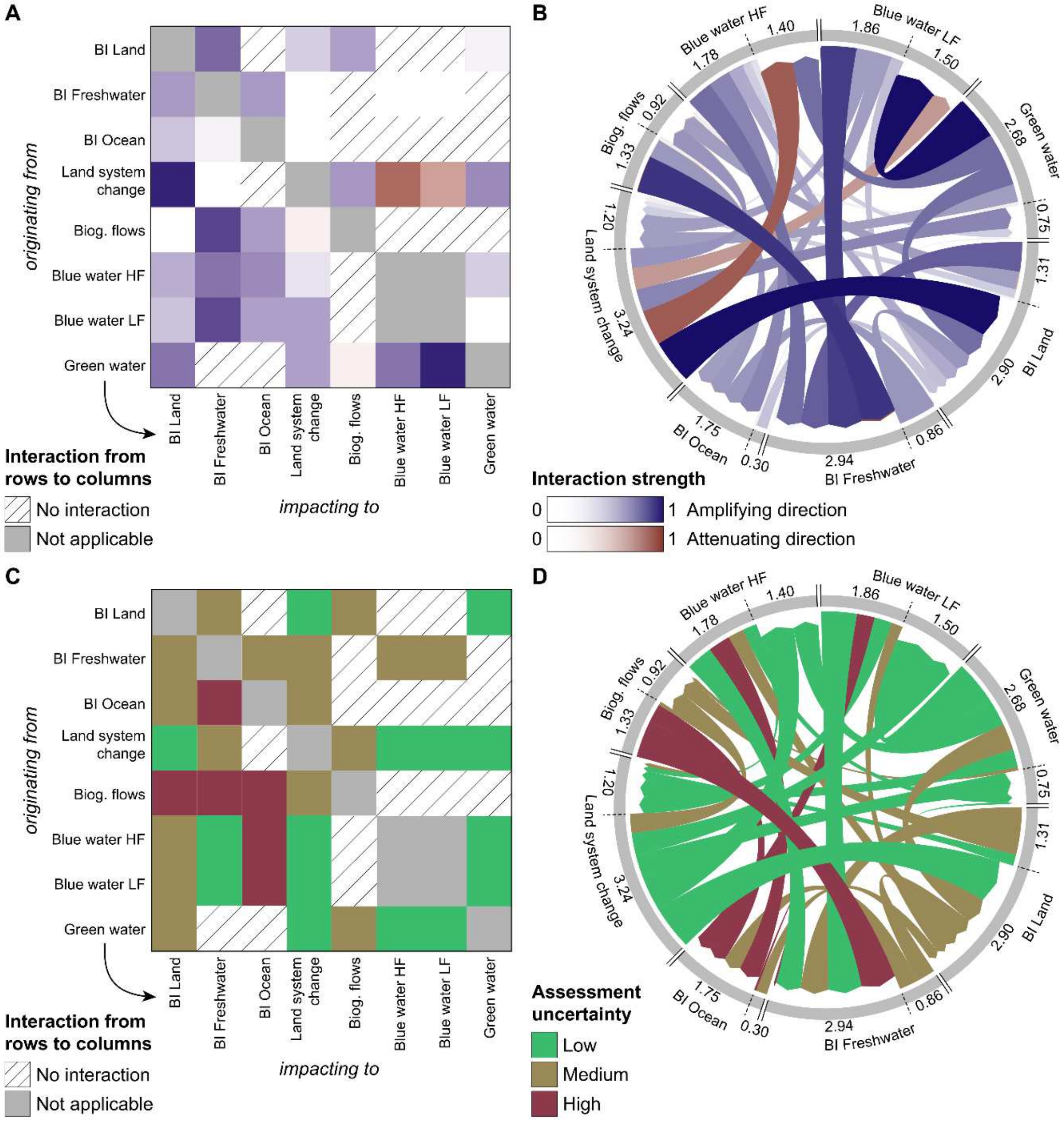


Figure 3: Absolute normalized biophysical interaction strengths and associated uncertainty identified with expert knowledge elicitation. BI stands for biosphere integrity, HF for high-flow season, and LF for low-flow season. ***A****: Identified interactions and interaction strengths between the selected control variables, ranging from the weakest (0) to the strongest (1).* ***B****: Net originating and receiving interaction strengths for each control variable.* ***C-D****: Uncertainty related to assessing the interactions. The uncertainty is evaluated based on expert agreement and the number of responses per interaction (See Supplementary materials Table S5.2. for uncertainty criteria and categorisation).*

2.2. Identified interaction strengths in line with literature

From the total 37 biophysical interactions we identified (Figure 3), only seven are quantified at the global scale by Lade et al. (2020) who synthesised the interactions in existing literature. When comparing these same interactions identified here and in Lade et al. (2020), in both instances they are of the same direction, though with some differences in strength. A direct comparison between all interactions identified here and in Lade et al. (2020) is not possible due to differences in the normalisation, the chosen control variables and the scale considered; relative comparisons are shown in Supplementary Materials Table S6.1. For five out of seven interactions that both studies assess, the interaction strengths are at similar levels (from low to high interaction strength range in both cases), which shows that the use of expert elicitation captured the variation that individual studies in the literature have identified. For the remaining two interactions (*Land system change->Blue water* and *Biogeochemical flows->BI Ocean*), there is a considerable difference that could be attributed to the different control variables and spatial scale used.

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 Supplementary materials Table S6.1 for details), our results of moderate to strong interaction are in agreement.

2.3. Receiving and originating Earth system processes

A simple network of the expert-identified interactions and their strengths (Figure 4) sheds light on the role of different Earth system processes in local-scale interactions of the control variables. The three Earth system processes with the greatest total influence in the network are *BI Land*, *Land system change* and *Green water,* as they have the most connections with other Earth system processes (Table S5.3). We can separate the Earth system processes explored into three main categories according to their role in mediating the identified interactions: a) the ones that are mainly on the receiving end, meaning that they are affected by others; b) the ones that are mainly on the originating end, meaning that they affect others; and c) the ones that are both receiving and originating at similar levels. All three *Biosphere integrity* components clearly belong in the first group, as they receive the strongest interactions (Figure 3 & 4, Table S5.3). Steffen et al. (2015) and Lade et al. (2020) identify *Biosphere integrity* as one of the two core Earth system processes, which are regulated by other Earth system processes considered in the planetary boundaries framework, and our results thus further support this.

Land system change and *Green water* processes exemplify the second category, as they contain the highest sums of originating interaction strengths (Figure 3 & 4, Table S5.3), consistent with findings by Lade et al. (2020), who identify *Land system change* as a major mediator of interactions among Earth system processes. Gleeson et al. (2020a, b) suggest that focusing only on *Blue water* and environmental flows does not capture all the crucial Earth system functions of freshwater, and work to define a separate *Green water* component is underway (Wang-Erlandsson et al., under revision); our results support the need for these efforts by highlighting the critical role of *Green water* in mediating interactions among Earth system processes. Finally, in the third category, *Biogeochemical flows* and *Blue water* have an intermediate role in mediating the identified interactions, as the receiving and originating interaction strengths are more balanced (Figure 3 & 4, Table S5.3).

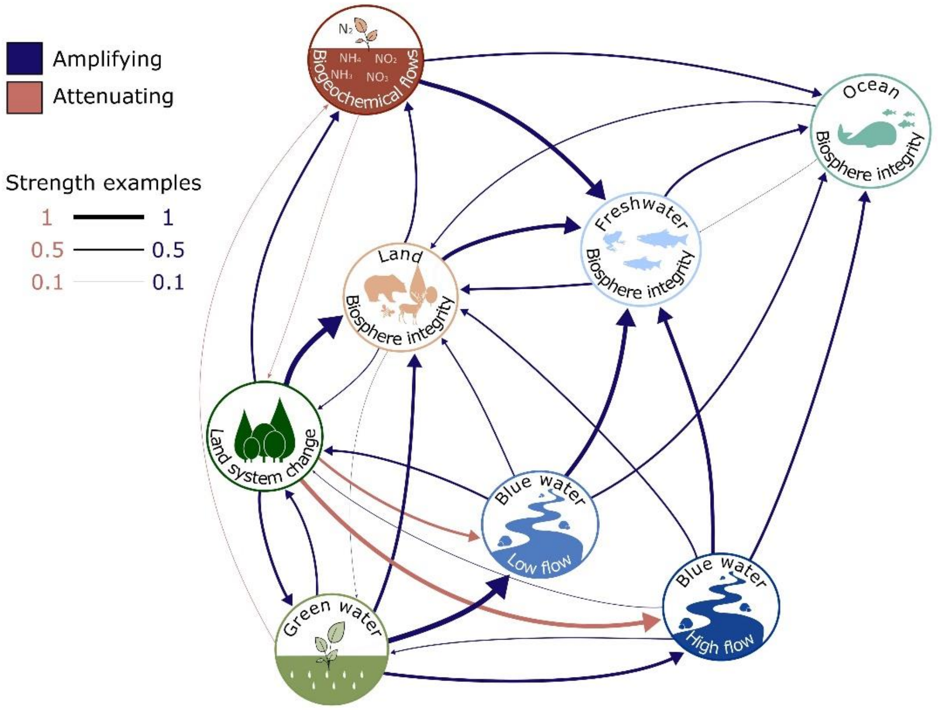


Figure 4: A network diagram of the identified interactions with a force-directed layout. Nodes are arranged according to the normalised interaction strengths, with the stronger connections being closer together. Interactions with strength in the range of -0.005≤s≤0.005 were excluded from this figure.

2.4. Mediating mechanisms

During the elicitation, the experts identified an array of primary and case-specific mechanisms that mediate the interactions between the selected control variables at the local scale (Supplementary materials S7 and Figure S1). The main mechanisms involved in these interactions are shown in Figure 5, which illustrates that Earth system processes are complex and interconnected, even when only considering those closely linked to agriculture, and that different processes can have counteracting effects on the selected control variables. For example, forest cover is negatively impacted by wildfires and drought but is benefited by pollinators, seed dispersal and decomposers. Terrestrial productivity and habitat integrity can play central roles mediating the Earth system interactions because of their high number of connections and importance in ecosystem functioning (Figure 5). During the second elicitation round, we aimed to explore the relative importance of the different mediating mechanisms; however, this endeavor was challenging, and we were unable to make inferences on the matter. The limited data collected to rank mechanisms and details on the identified mechanisms and relevant literature are available in Supplementary materials S7.

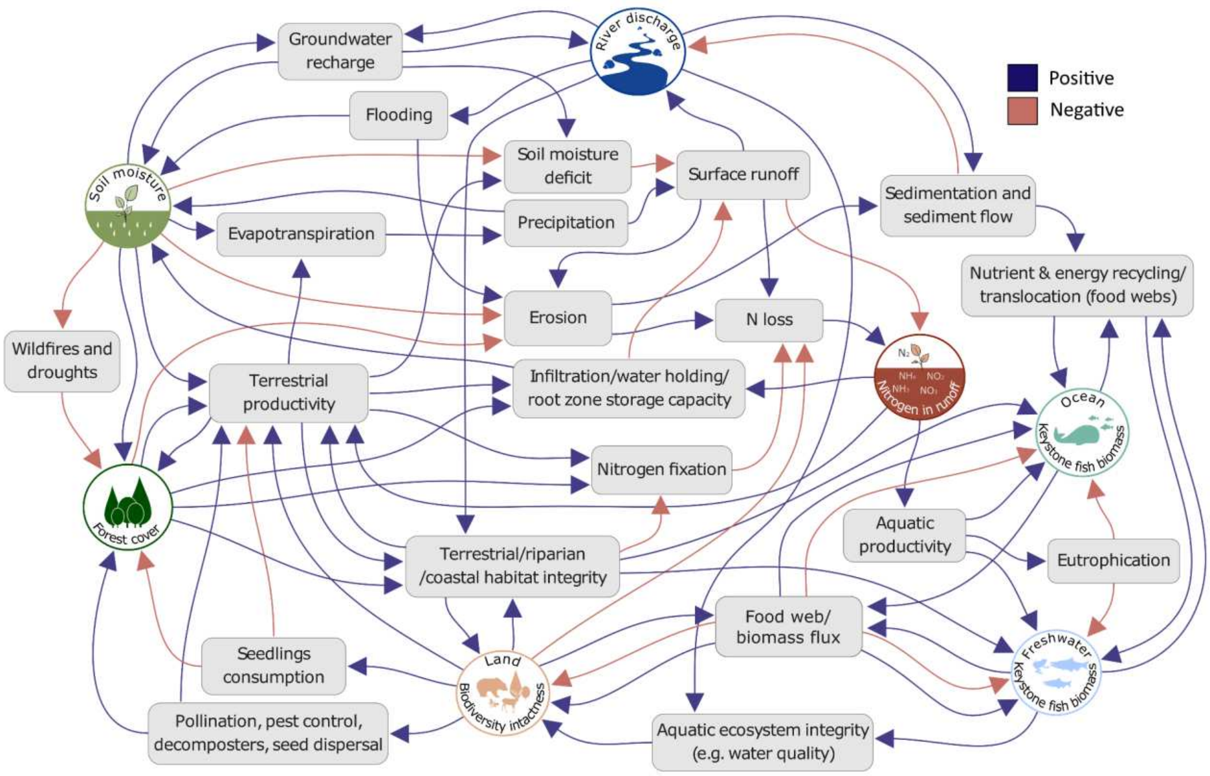


Figure 5 Main mechanisms mediating agriculture-impacted interactions among Earth system processes at the local scale as described by elicitation participants. Positive links indicate that an increase/decrease in one variable leads to an increase/decrease in another variable, respectively. Negative links indicate that an increase/decrease in one variable leads to a decrease/increase in another variable, respectively. Some links are uncertain (see Fig 6) and dependent on impact level, spatial scale, temporal dynamics, and Earth system processes beyond the scope of this study.

2.5. Prioritisation of interactions

This expert elicitation identified many interactions between the selected control variables for agriculture-impacted Earth system processes that have not been quantified in the Earth system literature before. Thus, we show that the network of interactions of Earth system processes is even richer than previously thought. However, even though expert agreement regarding interaction magnitude was very high (coefficient of variation in best estimate <0.2) in all but one interaction (Table S5.2), the number of answers per interaction varied significantly, increasing the uncertainty related to the assessment. Due to this inherent limitation of the expert elicitation process, we created an interaction prioritisation scheme for future research based on interaction strength and the level of uncertainty in our assessment estimates (see Methods and Supplementary materials Table S5.2). In addition, we prioritised interactions with discrepancies in expert opinions, whether they were amplifying or attenuating. This may have occurred either because experts were considering different temporal scales, different regional contexts, or different mechanisms during their assessment.

One example of discrepancies between expert opinions was the high-uncertainty zone and the interactions from *biogeochemical flows* to *BI freshwater* and *BI ocean* (see Figure 6); some experts considered the positive impacts on primary productivity and ecosystem functioning from added nutrients (before a critical limit is passed and impact becomes negative), while others believed added nutrients cause immediate negative impacts. This critical limit is very context-specific, including factors such as the denitrification potential of riparian wetlands (Billen et al. 2018). An appropriate critical limit for nitrogen concentration might substantially differ among environments – thus, this interaction needs more case-by-case examination. In addition, the inclusion of other elements such as phosphorus (Carpenter & Bennett 2011) could substantially modify the strength of nitrogen interactions on *BI freshwater* and *BI ocean* (Garnier et al. 2021). Other uncertainties of note include the interaction from *Blue water* to *BI Ocean,* which was established but could potentially be higher or lower than identified, suggesting the need for additional exploration of this relationship.

In the medium-uncertainty zone, the interactions related to the BI components deserve further attention due to their central role in Earth system functioning and stability. This applies in particular to interactions with aquatic BI components of the Earth system, as they are yet to be explored or quantified. Most interactions related to *Land system change*, *Blue water* and *Green water* are included in the low-uncertainty zone (Figure 6), since these Earth system processes and their relationships have already been widely explored (See Supplementary materials S7 for relevant literature). However, a larger number of the interactions with a greater expert input show discrepancies related to the nature of the interactions (amplifying or attenuating) (Figure 6), even though agreement on the magnitude of the interaction strength is very high (Figure 3C, D). Again, this could be attributed to context-specific mechanisms, time-scale differences or different contexts, which highlight that case-by-case approaches are required for operationalising our findings. Despite the discrepancies, we can assume it is more likely that the interaction direction present in most environments is the aggregated result presented in Figure 3, due to the larger number of expert input in such cases. This prioritisation scheme highlighted that higher uncertainty or discrepancies require future research to be directed primarily towards the interactions with these characteristics.

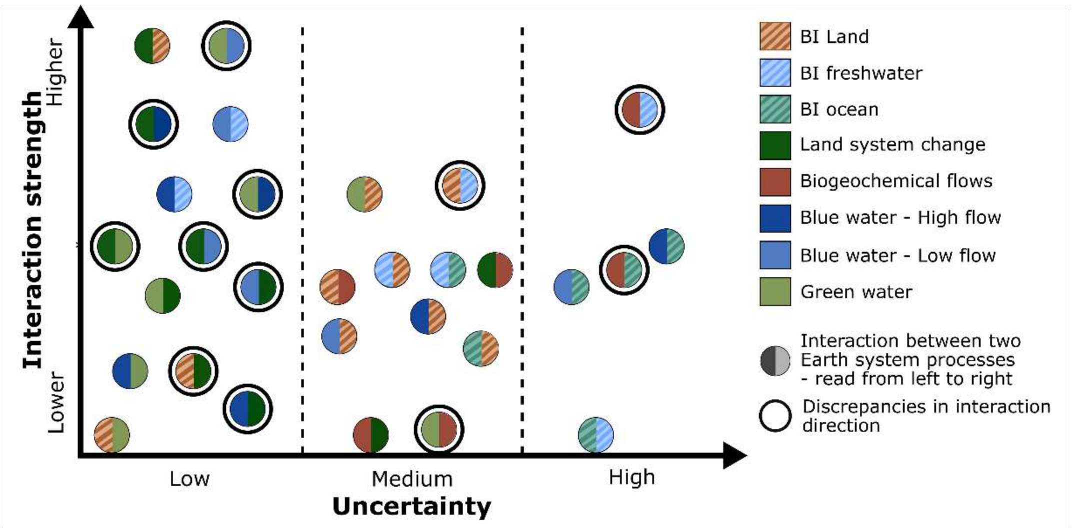


Figure 6: Interactions identified in the expert elicitation grouped by uncertainty and positioned relative to their strength. Uncertainty in the assessment is evaluated based on expert agreement and the number of responses per interaction (See supplementary Table S5.1. for uncertainty criteria and categorisation). The specific location of an interaction within an uncertainty zone is not significant, as uncertainty within each category is considered equal. The uncertainty is evaluated based on expert agreement and the number of responses per interaction (See Supplementary materials Table S5.2. for uncertainty criteria and categorization). Interactions with strength in the range of -0.005 ≤ s ≤ 0.005 were excluded from this analysis.

3. Discussion

This study represents the first attempt to quantify interaction strengths between Earth system processes linked to food production, and particularly agriculture at the local scale, using expert knowledge elicitation. We identified 37 out of 54 potential interactions between the selected control variables and constructed a network of the mechanisms mediating them. The elicitation participants identified the newly introduced components of *BI Freshwater*, *BI Ocean* and *Green water* as ones with crucial roles in the interactions of agriculture-impacted Earth system processes locally. In addition, our results highlight the importance of the low-flow season for certain *Blue water*–related interactions, the major role of *Land system change* in impacting other Earth system processes, and the high impact of *Biogeochemical flows* on *BI freshwater* and *BI ocean* (Figures 3 & 4). These findings will be useful for further assessments related to agricultural impacts on critical Earth system processes. Our identified local-scale interactions – which can potentially cascade to the Earth system scale – could also be incorporated in future developments of the planetary boundary framework. Our study is the first to map the mechanisms involved in interactions among Earth system processes in such detail, revealing a complex and interconnected network of variables and processes. Finally, our categorisation of the interactions based on their strengths and associated uncertainty can guide future research.

3.1. Bridging the local and global scales

The complex interactions between the Earth system processes important to food production highlight the need for a systemic approach to environmentally sustainable food production, and suggest potential future developments of the planetary boundaries framework. The planetary boundaries were developed to understand the limits of the Earth system within which humanity can thrive (Rockström et al. 2009: Steffen et al. 2015), and the framework has often been seen as a connector between Earth system and sustainability sciences (Downing et al. 2019). At the same time, the framework has been criticised for being a strictly top-down concept, while many of the relevant processes and stresses occur locally – although with global importance (Lewis 2012; Montoya et al. 2018; Biermann & Kim 2020); thus, interactions between many of the Earth system processes also mostly take place on a local-to-regional scale. Without understanding these important relationships, governance that aims to keep us within safe global boundaries could go critically wrong and defeat its purpose.

Our findings reveal, for the first time, the strengths and the direction of many of the interactions between key Earth system processes. Since most interactions identified here were amplifying (Figure 3), approaching and/or transgressing the critical limits of one Earth system process often degrades other Earth system processes, and thereby narrows the safe operating space. However, finding synergies is also possible; alleviating pressures on one Earth system process, such as *Land system change*, can simultaneously reduce pressures on others, such as *Biosphere integrity* and *Biogeochemical flows*, through the complex web of interactions among them (Figures 3 & 4; Lade et al. 2020). By increasing the understanding of these interactions, our results have clear implications for sustainability management in (i) avoiding unintended consequences of actions; (ii) emphasising synergistic solutions to sustainability challenges; and (iii) identifying and prioritising management of the core processes that most impact and are impacted by other Earth system processes. Our study is thus an important step towards enabling more comprehensive consideration of Earth system processes across sectors and disciplines. Further, our work could also help adapt the planetary boundaries framework on the levels at which management of Earth system processes typically occurs. Staying within the planetary boundaries, and thereby keeping humanity within the safe operating space, may require adjusting local safe operating spaces with respect to the related Earth system processes and interactions as shown here. Finally, our findings may also augment local and regional food system models and assessments, as incorporating our results in models could enable quantifying aspects beyond the use of resources only – such as the substantial impacts on *Biosphere integrity*.

At the same time, it should be noted that the revealed mechanisms, their strengths, and even the directions of interactions might vary in different contexts, and the results presented here show only their aggregate outcomes. Further, a better understanding of local-scale mechanisms potentially cascading to planetary-scale feedbacks (Rocha et al. 2018) is needed for prioritising management actions. Data sets for many of the control variables are already available for more local-level assessments to be carried out while maintaining global consistency. (e.g. Hansen et al. 2013; Sexton et al. 2013; Newbold et al. 2016; Frieler et al. 2017; Lin et al. 2019; Gerten et al. 2020). Quantitative, multi-scale modelling of the interactions could help in evaluating how well the aggregated interaction strengths hold in different contexts, and also show where the largest uncertainties prevail.

3.2. Importance of expert knowledge

Nonetheless, will modelling become the prevalent method of assessing Earth system processes and their interactions? Even an overarching modelling approach to understanding these connections does not replace the need for expert knowledge. Process dynamics should be represented in mathematical terms, and in most cases, an exact representation of the Earth system is beyond our modelling capabilities and will necessarily be based on simplified process descriptions. Deciding which subprocesses to model, what assumptions can be made, and how to represent interactions between the processes when all mediating mechanisms cannot be fully modelled, are all expert decisions (Van der Sluijs 2006). Furthermore, the mediating mechanisms may not be the same in different regions, or even in different locations within the same region. This is also reflected in an expert elicitation; the experts have their own backgrounds that affect their views and decisions (Hoekstra 2000) – such as different fields of study or familiarity with different natural environments – which may lead to apparent discrepancies.

In this elicitation process, not all experts agreed on the direction of some interactions (Figure 6). Such occurrences should not be written off as a shortcoming of the method or simply as errors; clearly documenting differing views ensures that possible variability in underlying natural processes is sufficiently explored. Even though modelling has traditionally been based on collected quantitative data, the further we increase the complexity of what we aim to model, the higher the data demand. Thus, extracting data from expert knowledge has become more common and used in different fields and for various purposes – for example, in ecosystem modeling (Reside et al. 2019), risk assessments (Kaikkonen et al. 2021), and even augmenting machine learning models (Gennatas et al. 2020). This illustrates how expert knowledge is extremely valuable and an important way forward to overcome data limitations; our expert elicitation results on Earth system interactions, which is a very complex issue, is a notable step forward in quantifying and better understanding processes that would otherwise remain unknown.

4. Methods

The following section describes the main steps in our methodology as illustrated in Figure 1. We first explain the control variables we used for each of the Earth system processes of interest (Figure 2A) and the hypothetical study area (Figure 2B), and introduce the structured elicitation protocol. We further describe the methods used to aggregate and normalise the elicitation results to quantify the interaction strengths. For further details, we refer to the Supplementary Materials.

4.1. Definitions of Earth system processes control variables

For the *BI land* component, we retained the control variable used by Steffen et al. (2015), the biodiversity intactness index, an interim proxy variable for functional diversity (Figure 2A). Agricultural impacts on *Biosphere integrity* have been demonstrated at a local scale (Newbold et al. 2016) and retaining the existing variable therefore fits our purposes well. The *BI freshwater* and *ocean* components were included in this expert knowledge elicitation, based on recent suggestions of their importance in *Biosphere integrity* assessments (Nash et al. 2017; Lade et al. 2020). For both *BI freshwater* and *ocean*, we used the status of keystone fish species biomass as a control variable. Lade et al. (2020) assign ecosystem functioning as the control variable and use global fisheries status as a proxy for some of the interactions they identify; thus, our control variable is similar as they both assess biomass levels. In aquatic environments, keystone fish species act as a robust indicator of ecosystem functioning and play a critical role in determining community structure (Pain 1966; Zhao-Hua et al. 2001; Heip et al. 2009; Pedersen et al. 2017). In addition, freshwater habitats in particular have experienced a substantial decline in biodiversity due to human activities and environmental change (WWF 2020; Barbarossa et al. 2021). Therefore, keystone fish biomass can act as a control variable to assess the aquatic components of *Biosphere integrity*.

The control variable for *Land system change* is forested land area relative to potential forest cover (i.e. assuming no human land-cover change; Figure 2A) – a variable retained from Steffen et al. (2015). For *Biogeochemical flows*, we assessed nitrogen, using leached inorganic N concentration in runoff to surface waters as the control variable (De Vries et al. 2013). For *Blue water*, the control variable used is river discharge, relative to the pre-industrial average. In addition, to account for seasonal variation in river flows, we separated the *Blue water* interactions into effects during high and low-flow periods.

While Steffen et al. (2015) propose maximum allowable water withdrawals, we focused on the flow remaining in rivers after any discharge alteration. Extending the control variable beyond withdrawals captures discharge alteration due to both direct human impacts, such as water extraction (Huang et al. 2021), and indirect human impacts, such as climate change (Gudmundsson et al. 2021) and changes in atmospheric moisture recycling (Wang-Erlandsson et al. 2018). For *Green water*, the control variable we used is root-zone soil moisture, during the growing season, relative to the pre-industrial growing season average (Figure 2A), similar to the control variable Wang-Erlandsson et al. (In revision) suggest. Though *Green water* is not identified as a separate control variable within the freshwater use boundary of the original planetary boundaries framework, recent research by Gleeson et al. (2020a, b) proposes that focusing only on *Blue water* does not capture all crucial Earth system functions of freshwater (notably groundwater), and thus, we considered it to be indispensable. For more details on the control variables used, see the Supplementary Materials S2.

The elicitation was scenario-based: experts assessed the interactions for a hypothetical area of 100 km^2 with an assumed baseline status of each control variable within the local safe operating space (Figure 6A, Supplementary material Table S1.1.). This spatial scale was selected for future modeling purposes of the interactions among the control variables of selected Earth system processes.

4.2. Elicitation process

Expert knowledge elicitation has been applied within various fields of environmental sustainability-focused research (e.g. Uusitalo et al. 2005; Lenton et al. 2008; Roman et al. 2008; Zickfeld et al. 2010; Chrysafi et al. 2019), and its suitability for natural resources management has been demonstrated (Hemming et al. 2018). With an elicitation, we can formulate expert knowledge and beliefs about potential uncertainties into a probabilistic form (Garthwaite et al. 2005) that can subsequently be used for modelling purposes. Here, we followed the structured IDEA elicitation protocol (Hemming et al. 2018) for a remote expert knowledge elicitation. This protocol is a structured modified Delphi approach that leads to improved judgments when a diverse group of engaged experts participate (Burgman et al. 2011). It combines the benefits of Delphi (Runge et al. 2011; Adams-Hosking et al. 2016) and four-step elicitation processes (Ban et al. 2014; Firn et al. 2015; Adams-Hoskin et al. 2016), which in combination has been shown to improve judgments (Cooke 1991; Mellers et al. 2014; Hemming et al. 2020). Our elicitation process consisted of two anonymous elicitation rounds and an online discussion round using pseudonyms in between (Figure 1, step 2, Supplementary materials Table S1.2). The discussion round is a critical part of the process, as it decreases linguistic ambiguity, promotes critical thinking, and shares evidence. The IDEA protocol integrates elicitation and discussion because there is evidence that when a discussion stage is included in a standard Delphi process, the response accuracy of the second elicitation increases (Hanea et al. 2016).

Participants were recruited based on their expertise in any of the Earth system processes considered in this study and knowledge of the planetary boundaries framework. For the recruitment process, relevant literature was searched and once a list of potential participants of 200 was reached, the literature-based recruitment was concluded (See supplementary materials S1.3). In addition, the "snowballing method" was used: when potential participants were first contacted, they were asked to suggest further suitable participants. In total, 37 experts completed the elicitation process, resulting in 5–19 answers for each of the identified interactions. Literature suggests that 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). For details on the experts' background, see Table S1.3.

Remote expert elicitations were performed using a web-based application that we developed for this purpose using the 'Shiny' R package (Chang et al. 2021). Although it comes with its own challenges, related especially to usability and user experience, the benefits of a custom-made application are that it minimizes the amount of materials shared with participants and can be fully tailored to a specific task. The web application (accessed in https://chrysafi1.shinyapps.io/shiny_exp_elic/) displayed everything a participant needed to complete the full elicitation process, consisting of a consent form, background information on the elicitation process, the Earth system processes, the control variables to be assessed, a question example, and a dashboard for selecting specific interactions and collecting the inputs.

Experts were asked to evaluate the interactions within the hypothetical area and to elaborate their thinking process behind the provided answers. The questions followed a four-step format, which involved asking first for the lower and upper plausible values and then the best estimate answering the question of how a change ΔX in the control variable (X) would alter the current level of the control variable (Y). Finally, a confidence interval (CI) for the provided estimate was asked and all four inputs were used to estimate the interaction strength. The upper and lower plausible values describe the limits of an expert's CI; for example, assigning a 70% CI means that the expert believes that there is a 70% probability that an interaction strength value would fall within the interval of the upper and lower value, with the best estimate as the most likely value. This format helps experts to construct and convert their knowledge into a quantitative form (Hemming et al. 2018). To illustrate this format, an example of the questions asked is available in Supplementary material S1.2. Participants were encouraged to provide input only for the interactions they felt best fit their expertise. For more details on the elicitation process, see Supplementary materials S1.1. and La Mere et al. (in prep).

4.3. Aggregation of expert opinions

Expert opinions were aggregated with an unweighted median to consider all answers equally while minimising the effect of outliers. Experts could also provide an example region and specific system in their assessment when quantifying an interaction (See Supplementary materials S.1.2). If sufficient regional input became available, region-specific interaction estimates could be feasible. However, there were insufficient regional inputs, and the results for each interaction are therefore a mix of region/non-region–specific answers. To consider differences between the non-region–specific and region-specific answers that could lead to lost information if ignored during aggregation, the following steps were performed for each of the interactions:

1. For each expert, all answers (Best, Lower, Upper, CI) were standardised to 100% CI with linear extrapolation (Adams-Hosking et al. 2016; Bedford & Cooke 2001) from the CI they provided. This standardisation was performed to fit a PERT distribution that takes three parameters: the lower, upper and best (most likely) value.
2. Non-region-specific lower and upper values were aggregated with an unweighted median.
3. A PERT distribution was drawn with the ‘mc2d’ R package (Pouillot et al. 2010) for the non-region-specific aggregated values.
4. A PERT distribution was drawn for each non-region and region-specific set of answers (lower, upper, best).
5. Each non-region–specific distribution was compared to the non-region–specific aggregated distribution with the Kullback-Leibler divergence metric within the ‘LaplacesDemon’ R package (Statisticat, LLC 2020). The 95th percentile of divergence values were used as the limit for aggregation acceptance for the region-specific distributions.
6. Each region-specific distribution was compared to the non-region–specific aggregated distribution with the Kullback-Leibler divergence metric.
7. Region-specific distributions with divergence below the aggregation limit were accepted for aggregation.
8. All non-region–specific and accepted region-specific values were aggregated with an unweighted median.

The final aggregated values were taken to estimate the interaction strengths as described in Section 4.4. The expert opinions that were not aggregated are available in Supplementary Table S3. These single region-specific answers were not sufficient due to the single expert input to make robust inferences, but combined with relevant literature or other available data, they could still be useful for other studies.

4.4. Control variable normalization and interaction estimation

To estimate interaction strengths, we first normalised the control variables relative to the known theoretical natural state for each of the control variables $x=X/X_{tns}$ (Table S1.1. and Table S4.1) and then estimated their interaction strength as $s=\Delta y/\Delta x$ with the above normalisation for every direct interaction between two control variables X->Y, where x is the normalized state, X the current state, X_{tns} is the theoretical natural state for each control variable, Δx is the change in the normalized control variable X, and Δy the normalised change caused in Y by the change in X. Only direct interactions identified were used for the analysis, and the expert-assessed indirect interactions were excluded to remove double counting (See Supplementary Materials S4). With this approach, we quantified and presented the absolute normalised interaction between two control variables. With this estimate, we can better assess the impact of a change in ΔX on Y, and how this could contribute to a more rapid approach to the outer border of its safe range heading to the boundary for Y. The significance of this absolute interaction on how quickly the local safe operating space could be transgressed would depend on local critical limits for each of the variables which are environment-specific– for example, Mace et al. (2015) describe local critical limits for *Biosphere integrity* that are variable in different biomes. Thus, it would require further case-specific investigations to evaluate this, which is outside the scope of this article.

The normalisation of the control variable for *Biogeochemical flows* posed greater challenges compared to others because of the nature of the variable we selected. Based on the nitrogen concentration in surface water EU member states use to define fair ecological status (Poikane et al. 2019) and the upper critical limit De Vries et al. (2013) define, we used a concentration of 2.5 mg L^{-1} of dissolved inorganic N as the theoretical natural state used in the normalisation. In contrast to the other variables that move from the safe range towards zero, nitrogen moves outside the safe range from zero to higher values, as nitrogen concentration increases while the other control variables' states decrease (Table S4.1). As a result, the interaction strength values of amplifying interactions related to nitrogen are negative as the variables move to opposite directions, and values of attenuating interactions are positive as the variables move to the same direction. The contrary is the case for all other control variables and the interactions that do not involve nitrogen. To minimise confusion, for the main results, the sign of the interactions is not highlighted but only their nature of either being amplifying or attenuating. Additionally, in the results section we present the interaction strengths with the aggregated best estimates, while the 80% CI for Δy caused by Δx can be found in Table S4.2.

4.5. Limitations of expert knowledge elicitation

The approach we followed in this study was based on expert knowledge elicitation. However, both lay people and experts are sensitive to subjective biases (Tversky and Kahneman 1974; Kynn 2008). Moreover, the reliability of expert judgments depends on who participates and how questions are posed (Hemming et al. 2018). For this expert elicitation, we invited leading experts within the planetary boundaries framework and whose judgment was supported by authorship of relevant scientific publications. Despite the limitations of such non-model–based approaches, expert opinions are valuable (Gullet 2000), especially in this case where modelling capacity is currently too limited to handle all the complexity of the Earth system (Steffen et al. 2015, Bauer et al. 2021); expert opinions are thus necessary to advise on such critical matters (Burgman et al. 2011; Morgan 2014). Formal structured elicitation protocols, such as the one used here, have been developed to minimise the limitations and associated biases of expert judgments (Cooke 1991; Morgan & Henrion 1990; O'Hagan et al. 2006). Even though a longer elicitation process is associated with declining quantity and quality of information, it appears that the benefits of following a structured protocol outweigh the potential drawbacks (Fraser et al. 2021). Finally, even though our expert-elicited interaction strengths would have benefited from an increased number of responses for certain interactions – as a larger number of responses is generally associated with less bias when aggregating (O'Hagan et al. 2006) – we can still be confident in our assessment. This is due to the high agreement among experts after the second elicitation round (Table S5.2), and the empirical evidence suggesting that only minor improvements are gained by having more than six to twelve participants (Armstrong 2001; Hora 2004; Cooke and Probst 2006).

Acknowledgments

This study was funded by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 819202), Aalto University School of Engineering Doctoral Programme, Maa- ja vesitekniikan tuki ry, and the Academy of Finland –funded project TREFORM (grant no. 339834). BIS is supported by a Royal Commission for the Exhibition of 1851 Research Fellowship. We would like to thank members of the Water and Development group for testing an earlier version of the elicitation web application and Amy Fallon for language checking of the manuscript.

Data availability

All the data produced in this study are available in the supplementary materials and provided with the submission.

Code availability

The analysis was performed using R studio (R version 4.0.5) (R Core Team, 2021). The code is available upon request from the first author.

Author contributions

A.C. and M.K. designed the study with contributions from V.V, M.J., M.P., V.S., J.P., S.L. and K.L.M. A.C. developed the web application with the shiny R package with server deployment support from M.J. A.C. was responsible for the elicitation process while V.V, M.J., V.S., M.P. and J.P supported in the data aggregation and discussion phases. A.C. performed the analysis with help from V.V., M.P, V.S, J.P., M.J. and M.K. All other authors [i.e. L.W-E. - S.Z.; see author list] participated in the expert elicitation. All authors discussed the results and helped shape the research and analysis. A.C. took the lead in writing the manuscript with assistance from M.P, M.K., V.V, V.S, M.J, L.W-E and contributions from all other authors.

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