



Human impacts on planetary boundaries amplified by Earth system interactions

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1 Earth system interactions amplify human impacts on planetary boundaries

2 ABSTRACT

3 The planetary boundary framework presents a ‘planetary dashboard’ of humanity’s globally
4 aggregated performance on a set of environmental issues that endanger the Earth system’s
5 capacity to support humanity. While this framework has been highly influential, a critical
6 shortcoming for its application in sustainability governance is that it currently fails to represent
7 how impacts related to one of the planetary boundaries affect the status of other planetary
8 boundaries. Here, we surveyed and provisionally quantified interactions between the Earth
9 system processes represented by the planetary boundaries and investigated their consequences
10 for sustainability governance. We identified a dense network of interactions between the
11 planetary boundaries. The resulting cascades and feedbacks predominantly amplify human
12 impacts on the Earth system and thereby shrink the safe operating space for future human
13 impacts on the Earth system. Our results show that an integrated understanding of Earth system
14 dynamics is critical to navigating towards a sustainable future.

15 MAIN

16 The planetary boundary framework assesses humanity’s globally aggregated interference in nine
17 Earth system processes compared to expert-estimated safe boundaries¹. The nine processes are
18 climate change, biogeochemical (nitrogen and phosphorus) flows, land-system change, freshwater
19 use, aerosol loading, ozone depletion, ocean acidification, loss of biosphere integrity such as
20 functional and genetic biodiversity, and introduction of novel entities such as toxic chemicals and
21 plastics. Transgressing these boundaries threatens the capacity of the Earth system to maintain the
22 Holocene-like state that allowed agriculture and complex human societies to develop. Since its
23 inception in 2009², the planetary boundary framework has been widely discussed³, subject to
24 critique^{4,5} (see Methods), refined and updated¹, and applied to policy at national⁶ and international⁷
25 scales.

26 The planetary boundaries interact, in that impacts on one planetary boundary can cause the Earth
27 system to approach another planetary boundary^{1,2}. For example, climate change may reduce the
28 biosphere’s ability to withstand human interference. The boundary for freshwater use is set at a
29 level that should avoid threatening the integrity of freshwater ecosystems. While these interactions
30 are broadly acknowledged, they are in conventional representations of the planetary boundary
31 framework¹. Previous in-depth investigations of planetary boundary interactions have been limited
32 to: (i) model-based studies of subsets of interactions, for example those involving the global carbon
33 cycle^{8,9} or agricultural land-use decisions^{10–12}; and (ii) surveys of which interactions are represented
34 in global models¹³. Interactions between the Sustainable Development Goals, which the planetary
35 boundary framework helped inform⁷, have been qualitatively assessed^{14–17} but a feedback analysis of
36 the consequences of their interactions is also lacking.

37 Here, we surveyed and provisionally quantified interactions between almost the full set of planetary
38 boundaries. We identified both biophysically- and human-mediated interactions, as demanded by a
39 social-ecological view of the Earth system¹⁸. We split the boundary for biosphere integrity into
40 boundaries for land, freshwater and ocean biosphere integrity, since the interactions that we

41 identified frequently involved only one of these biosphere components and in recognition of the
42 under-representation of aquatic dimensions in the current planetary boundary framework¹⁹. We
43 then used a feedback model to calculate the consequences of these interactions for transgression of
44 the planetary boundaries and the “safe operating space” for humanity within the Earth system. Our
45 estimates of interaction strength and the subsequent model are highly simplified and in many cases
46 highly uncertain representations of complex Earth system processes and should not be used to
47 directly inform policy. Our goal is rather to stimulate discussion and research on the magnitude and
48 consequences of planetary boundary interactions.

49 **RESULTS**

50 **A social-ecological survey of planetary boundary interactions**

51 For each Earth system process represented by the planetary boundaries, control variables were
52 selected that indicate the degree to which humans are influencing that Earth system process (Fig 1,
53 vertical arrow). For each control variable, two reference values were identified: the boundary value,
54 which delimits a conservative ‘safe’ range for the control variable (Fig 1, green area); and a ‘zone of
55 uncertainty’, a range of increasing risk beyond the boundary value (Fig 1, yellow area). We use
56 values from the updated version of the framework¹ (Table S1).

57 Two types of interactions between components of the planetary boundary framework can occur (Fig
58 1, arrows on left). First, changes in a control variable can lead to changes in the control variable of
59 another planetary boundary. For example, land-system change can lead to carbon emissions that
60 increase the atmospheric concentration of carbon dioxide, a control variable for the climate change
61 planetary boundary. Here, the boundary value for climate change remains the same. Second, a
62 change in a control variable can change the boundary value for another planetary boundary. For
63 example, climate change may affect the amount of freshwater that can be safely extracted from
64 terrestrial systems. We henceforth use ‘interactions between planetary boundaries’ and ‘changes in
65 a planetary boundary’ to refer to both effects on control variable values and boundary values.

66 We surveyed the literature for evidence on interactions between the planetary boundaries and data
67 on the strength of the interaction (see Methods). Taking a social-ecological system view of the Earth
68 system, we sought interactions mediated by both biophysical and human mechanisms (Box 1). We
69 grouped human-mediated interactions into two subtypes: reactive human-mediated interactions,
70 caused by human behaviour in response to changes in a planetary boundary; and parallel human
71 drivers, where human impact on a planetary boundary is commonly associated with subsequent
72 human impact on another planetary boundary due to shared drivers. While the interactions can be
73 biophysically or human-mediated, all interactions are ultimately caused by direct human impacts on
74 a planetary boundary that then trigger subsequent interactions.

75 The biophysically-mediated interactions that we identified (Supplementary Methods) include:
76 impacts of surface climate warming on land, freshwater and ocean biosphere integrity and
77 stratospheric ozone; impacts of climate change, land-system change and aerosol loading via changed
78 rainfall runoff patterns on freshwater availability and biogeochemical flows; eutrophication in
79 freshwater and ocean systems due to nutrient inputs and freshwater extraction; and climate change
80 and ocean acidification due to carbon emissions from deforestation, changes in uptake by terrestrial,
81 marine and freshwater ecosystems, and radiative forcing from aerosol loading. The parallel human

82 drivers involved carbon emissions that lead to both climate change and ocean acidification, emission
83 of ozone-depleting substances that are also greenhouse gases, and the food-energy-water nexus:
84 clearing of land for agriculture is usually followed by application of fertilisers and freshwater;
85 fertilisers and freshwater use involve carbon emissions from electricity generation; and electricity
86 generation often involves water use. The reactive human-mediated interactions that we identified
87 related to increased agricultural activity in response to loss of protein from freshwater or marine
88 fisheries, and increased carbon emissions to treat or generate water in response to declines in
89 surface water quality.

90 The interactions ranged from well-characterised (such as the effect of atmospheric carbon dioxide
91 on ocean acidification) to highly unconstrained (such as interactions involving biosphere integrity).
92 Our survey and estimates of interaction strengths (summarised quantitatively in Table S2 and
93 graphically in Fig. 2) should be treated as an initial, speculative attempt at characterising these
94 interactions. We welcome further work to identify additional interactions beyond those we listed
95 and to better constrain their interaction strengths.

96 **The planetary boundaries are densely interconnected**

97 Our survey found evidence for over half the possible interactions between different pairs of
98 planetary boundaries (52 out of 90; Table S2). We could quantify a biophysically- or human-
99 mediated interaction for 35 of these interactions (Table S2 and Supplementary Methods). This dense
100 network of interactions between the planetary boundaries is unsurprising, since the Earth system is
101 known to be tightly interconnected^{20,21}. Only six biophysically-mediated interactions are attenuating
102 (negative) interactions (Table S2), where greater disruption of the Earth system process
103 corresponding to one planetary boundary leads to less disruption of the Earth system process
104 corresponding to another planetary boundary; once human-mediated interactions are accounted for
105 only four interactions are net attenuating (Table S2; bordered links in Fig 2A). We expect that
106 interactions between the planetary boundaries therefore mostly amplify human impact on the Earth
107 system, a hypothesis that we test below.

108 The climate change and biosphere integrity planetary boundaries were identified by Steffen *et al.*¹ as
109 the two 'core' planetary boundaries, which are regulated by processes corresponding to the other
110 'non-core' planetary boundaries. Our survey supports their status as core elements within the
111 network of planetary boundary interactions. First, the core boundaries contribute almost half the
112 combined strengths of all originating and receiving ends of the interactions (visualised by climate
113 change and biosphere integrity occupying around half the circumference of Fig 2A). Second, a force-
114 directed network diagram²², which arranges nodes with stronger interactions closer together, places
115 the two core boundaries at the centre of the diagram (Fig 2B). Our survey also found evidence for
116 interactions among non-core boundaries (12 interactions, of which we could quantify 6; Table S2),
117 indicating that the interactions among the planetary boundaries are more complex than a hub-and-
118 spoke pattern between the core and non-core boundaries.

119 **Interactions have amplified human impacts on planetary boundaries**

120 We constructed a simple linear feedback model to illustrate possible consequences of interactions
121 between the planetary boundaries (Methods). Since specific outputs of the model are based on the

122 often highly unconstrained estimates of interaction strengths, we use it only to illustrate possible
123 consequences of the interactions and it should not be used to quantitatively inform policy decisions.

124 We first used our model to estimate how much of the current value of each control variable is due to
125 direct human impacts and how much is due to the propagation of direct impacts via interactions (Fig
126 3). Over all planetary boundaries, biophysically-mediated interactions contributed 34% of the total
127 current values of normalised control variables compared to 37% for direct human impacts, 28% for
128 parallel human drivers and 1% for reactive human-mediated interactions (Methods). Biophysically-
129 mediated interactions have therefore almost doubled direct human impacts on the planetary
130 boundaries (or 50% increase compared to direct human impacts and parallel human drivers
131 combined). Reducing the strengths of biophysically-mediated interactions could therefore
132 significantly reduce future impacts on the planetary boundaries. These interactions, however, reflect
133 basic biophysical mechanisms such as the radiative forcing contributed by atmospheric carbon
134 dioxide emitted by land clearing for agriculture, or nutrient overuse leaching into freshwater
135 systems leading to eutrophication. Modifying these interactions would require costly, difficult to
136 govern²³ and possibly counterproductive^{9,12} geoengineering.

137 Biogeochemical flows were controlled mainly by parallel human drivers (Fig 2A; Table S2);
138 specifically, nutrient application on cropland frequently occurred subsequent to clearing that land
139 from forest²⁴. Freshwater use, ocean acidification and climate change had mixed contributions from
140 biophysical interactions, parallel human drivers, and direct human impacts (Fig 3). Of the planetary
141 boundary interactions that we identified, some of the parallel drivers are perhaps the most
142 amenable to intervention. For example, better nutrient management could break the link between
143 land clearing for agriculture and (in the global aggregate) excessive nutrient application that has led
144 to anthropogenic biogeochemical flows exceeding the planetary boundary.

145 Reactive human-mediated interactions, such as degradation of freshwater biosphere integrity
146 leading to increased carbon emissions from water purification or desalinisation, had relatively small
147 globally-aggregated contributions to interactions in our analysis (Fig 3). Interactions of this type can
148 arise from unintended consequences, such as an increase in agricultural activity in response to the
149 construction of dams that degrade freshwater fisheries²⁵, and therefore difficult to anticipate. Policy
150 instruments could also create new interactions via economic mechanisms²⁶. Some interactions may
151 only manifest after very severe transgressions of planetary boundaries that still have not yet been
152 experienced, for example severe climate change. We encourage future work to better capture
153 human-mediated interactions.

154 **Interactions shrink the safe operating space for future sustainability governance**

155 The planetary boundaries delimit a 'safe operating space' for humanity on planet Earth²⁷. Remaining
156 outside this safe operating space could lead away from a safe Stabilised Earth trajectory to an unsafe
157 Hothouse Earth trajectory for the Earth system²⁸. We characterise the goal of future sustainability
158 governance as navigating back towards the safe operating space and a Holocene-like state of the
159 Earth system.

160 For the analysis of interactions in this paper, we define the safe operating space as those
161 combinations of human impacts on the planetary boundaries that cause no planetary boundary to
162 be transgressed. We include in the category of 'human impacts' both direct human impacts and

163 impacts mediated by human behaviour (of parallel and reactive types). Since most interactions
164 between planetary boundaries are amplifying (Fig 2A), we expect incorporating knowledge about
165 interactions to shrink the safe operating space for human impacts. Such shrinkage would reduce
166 Earth system resilience and further complicate the challenge of Earth system governance in the
167 Anthropocene.

168 For an initial estimate of the safe operating space with interactions taken into account, we set all
169 control variables at their planetary boundaries and used the model to back-calculate the
170 combination of human impacts that would lead to those control variable values (see Methods). We
171 found that along most planetary boundaries, interactions do indeed shrink the safe operating space
172 (Fig. 4). The most significant exception is freshwater use: since climate change will increase
173 precipitation, the safe level of globally aggregated freshwater use could increase, though this result
174 would depend strongly on the location of increased rainfall.

175 This method, however, leads to negative edges of the safe operating space for the ocean and
176 freshwater biosphere integrity planetary boundaries (Fig 4). If all other control variables are at their
177 planetary boundaries, human actions that massively improve ocean and freshwater biosphere
178 integrity would therefore be necessary to stay within the safe operating space. This result occurs
179 because, under the assumptions of the model, either the biogeochemical flows or freshwater use
180 control variables at their planetary boundary pushes the freshwater biosphere integrity control
181 variable to its planetary boundary. Their additive effects plus impacts from climate change and land
182 system change push freshwater biosphere integrity well beyond its planetary boundary. Similar
183 reasoning holds for ocean biosphere integrity, with climate change and ocean acidification causing
184 the greatest impacts. Actions to improve freshwater and ocean biosphere integrity such as
185 transplantation of nursery-grown coral²⁹, ocean plastic removal, freshwater sediment dredging to
186 remove nutrient loading³⁰ or fish restocking³⁰, are conceivable on a small scale but likely
187 prohibitively expensive at the scale demanded by our analysis.

188 **Interactions lead to trade-offs within the safe operating space**

189 We expect that trade-offs between the planetary boundaries, generated by their predominantly
190 amplifying interactions, could be exploited to navigate back to the safe operating space. For
191 example, the interactions described above suggest that massive global action to improve freshwater
192 biosphere integrity could be avoided by reducing freshwater use or anthropogenic contributions to
193 biogeochemical flows, or a combination of both, below their respective boundary values.

194 Here we illustrate trade-offs in the safe operating space between two broad categories of human
195 impacts on the Earth system: agricultural activity and carbon emissions. We represented agricultural
196 activity by applying direct impacts on land-system change (such as land clearing), which via the
197 model's parallel human drivers result in human impacts from agricultural activity on freshwater use
198 and biogeochemical flows. We represented carbon emissions (including emissions from agriculture)
199 by applying direct impacts on climate change, which via the model's biophysically-mediated
200 interactions result in impacts on ocean acidification. We used our model to estimate the
201 consequences of these impacts on the full set of planetary boundaries included in our model. For
202 different combinations of agricultural activity and carbon emissions, we calculated how many
203 planetary boundary values and zones of uncertainty would be transgressed (Fig 5).

204 Without interactions, the safe operating space is bounded by the planetary boundaries for
205 biogeochemical flows and climate change (Fig 5, green dashed line), since agricultural activity and
206 carbon emissions cause these boundaries to be crossed first. With interactions, the size of the safe
207 operating space shrinks substantially (Fig 5, green area). The first planetary boundary to be
208 transgressed as agricultural activity or carbon emissions are increased is freshwater biosphere
209 integrity, though several other planetary boundaries (Fig 5, darker yellow areas) and zones of
210 uncertainty (Fig 5, red areas) are transgressed soon thereafter. These results show that interactions
211 can lead to cascading transgressions of multiple planetary boundaries. Similar cascades were
212 recently suggested to potentially lead to an unsafe Hothouse Earth trajectory for the Earth system²⁸.

213 As well as shrinking in size, the shape of the safe operating space changes substantially in this
214 graphical representation once interactions are taken into account, from square to roughly triangular
215 (Fig 5, green area). The triangular shape leads to trade-offs: if carbon emissions are low then high
216 levels of agricultural activity are safe, and vice versa, but high levels of both agricultural activity and
217 carbon emissions cannot be safely maintained. This shape of the safe operating space is similar to
218 that found previously in a conceptual model³¹. In our model, if agricultural activity is low then the
219 safe level of carbon emissions is even higher than pre-interaction levels, due to the masking effects
220 of aerosol loading.

221 **Interactions affect navigation towards the safe operating space**

222 The current state of the Earth system as represented by the planetary boundaries is well outside the
223 safe operating space for human impacts (Fig 5). Actions that navigate the Earth system back towards
224 the safe operating space are urgently needed. Due to biophysical, economic and other social
225 interactions, however, policies addressing a specific planetary boundary will often lead to impacts on
226 other planetary boundaries²⁶.

227 We investigated two climate mitigation measures that involve changes in agricultural activity: Large-
228 scale bio-energy production with carbon capture and storage (BECCS), where carbon dioxide from
229 the combustion of rapidly growing crops is geologically sequestered, and a global transition to low-
230 meat diets. We used published scenarios to estimate the effects of these measures (Supplementary
231 Methods). They correspond to a small subset of the agricultural practices that could be used to
232 implement BECCS and a small subset of possible food system transitions towards a low-meat diet,
233 and therefore should be considered only as illustrative.

234 The direct impact of BECCS through carbon draw-down could substantially reduce impacts of carbon
235 emissions^{11,32} (Fig 5). The large-scale biomass plantations required for BECCS, however, lead to
236 increased agricultural activity that, via interactions, lead to carbon emissions that counter the
237 reductions achieved by BECCS. The result is, under the assumptions of our model, a trajectory at
238 best parallel to the safe operating space (Fig 5). Some studies even suggest that carbon emissions
239 from land use change (an interaction between the land system change and climate change planetary
240 boundaries) could outweigh carbon draw-down leading to net positive carbon emissions from
241 BECCS^{33,34}. Furthermore, our simple model underestimates impacts on the freshwater use, land
242 biosphere integrity and biogeochemical flows planetary boundaries (Supplementary Methods),
243 because BECCS will likely involve more intensive agriculture than the simple globally and historically
244 aggregated interactions assumed in our model.

245 While the direct impact of low-meat diets on carbon emissions may be smaller than large-scale
246 BECCS, low-meat diets typically lead to reduced agricultural activity and a trajectory moving towards
247 the safe operating space (Fig 5). Reduced agricultural activity triggers interactions that further lower
248 carbon emissions (Fig 2A; Table S2). Our results reinforce that low-meat diets, alongside other
249 transformations of the food system³⁵, are an important strategy for navigating towards the safe
250 operating space for humanity in the Earth system³⁶.

251 **DISCUSSION**

252 Our results offer three key findings for policymakers. First, interactions are crucial to understanding
253 the planetary boundaries and humanity's impacts upon them. For example, we calculated that
254 biophysically-mediated interactions have almost doubled direct human impacts on the planetary
255 boundaries. Second, most interactions we found were amplifying, meaning that impacts on one
256 planetary boundary lead to increased impacts on other planetary boundaries (Fig 2). Cascading of
257 human actions through multiple components of the Earth system complicates governance of the
258 Earth system. On the other hand, these interactions offer substantial scope for synergies: if impacts
259 on one planetary boundary are decreased, impacts on other planetary boundaries may also lessen.
260 Our survey of planetary boundary interactions (Fig 2) offers a roadmap for identifying where these
261 synergies lie. Third, interactions between planetary boundaries lead to trade-offs between the
262 boundaries (Fig 5). For example, interactions between agricultural activity and carbon emissions
263 mean that high levels of both cannot be maintained. On the other hand, these trade-offs offer
264 humanity some freedom in choosing how to navigate to a safe operating space.

265 We caution that while our model can yield insight into consequences of interactions, the interaction
266 strength estimates it uses are often poorly constrained and are globally aggregated. Some planetary
267 boundaries are highly spatially heterogeneous¹, and the distribution of humanity's contributions to
268 globally aggregated boundaries such as climate change is also highly heterogeneous, so we expect
269 that many planetary boundary interactions are also spatially and socio-culturally heterogeneous. Our
270 model in its current form should therefore not be used for policy design, though our methods could
271 be adapted to complement empirical assessments of regional safe operating spaces. The planetary
272 boundary framework only captures limited aspects of changes in the Earth system, and our study of
273 interactions can therefore only capture a limited number of Earth system processes. Our model
274 accounts for feedbacks between planetary boundaries, but does not account for nonlinearities such
275 as interactions that activate after a control variable reaches some threshold, dynamics such as time
276 lags, or interactions of higher order than pairwise such as the multiplicative effects of climate change
277 and land-system change on biodiversity loss³⁷. These shortcomings offer promising avenues for
278 future research towards the challenge of navigating towards a safe operating space. Our approach
279 for stylised modelling of interactions could also be applied to other frameworks that include social as
280 well as biophysical dimensions of global sustainability, such as Raworth's 'doughnut'³⁸ or the
281 Sustainable Development Goals.

282 The original planetary boundary framework² has been used both as a high-level policy reference
283 illustrating humanity's performance on environmental issues of global concern and as an object for
284 scientific and policy-based scrutiny and refinement. We offer our survey of planetary boundary
285 interactions to policymakers and the scientific community in the same spirit: as a summary of

286 current scientific knowledge, a call for future research to better characterise interactions, and as a
287 framework to prompt policy discussions and planning towards a sustainable future.

288 **METHODS**

289 **Planetary boundaries**

290 We included in our analysis of interactions all planetary boundaries except the boundary for
291 introduction of novel entities, which is difficult to systematically assess. As in the previous versions
292 of the framework^{1,2}, the planetary boundaries describe limits that should not be transgressed to
293 maintain the Earth system in a Holocene-like state.

294 We retained the framework presented by Steffen et al.¹ as closely as possible. We found it necessary
295 however to split the planetary boundary for biosphere integrity into planetary boundaries for land,
296 freshwater and ocean biosphere integrity. Interaction mechanisms involving terrestrial and aquatic
297 biospheres differ significantly. While the marine and freshwater biospheres are more similar, some
298 interactions such as the effects of freshwater use and ocean acidification are significantly different in
299 magnitude between these two spheres. We chose not to separate the biogeochemical flow
300 boundary into nitrogen (N) and phosphorous (P) flows since it would involve an increase in model
301 complexity that does not affect model results, for the following reasons. In this de-aggregated
302 model, N and P inputs would occur in direct proportion due to their shared driver (agricultural
303 activity). These direct inputs and increased runoff due to increased precipitation, which we expect
304 affect N and P equally, are the only factors whose strength we estimate that affect N and P flows
305 (Table S2). Furthermore, their current normalised control variables (see below) have almost identical
306 values (Table S1). Therefore, while the mechanisms by which N and P affect other planetary
307 boundaries are different, their normalised control variables could mathematically be interchanged
308 without affecting the result. The relative concentrations of N and P may vary between terrestrial
309 application and those in freshwater and marine ecosystems, but these concentrations do not directly
310 enter our model. Splitting the biogeochemical flows boundary, and the biosphere integrity control
311 variables into more specific features of these biospheres, may be necessary in future work.

312 The planetary boundaries framework has been subject to some critique. Criticisms have included
313 that the global scale of the planetary boundary framework distracts from managing local-scale issues
314 such as biodiversity loss or water overuse and that global tipping points are unlikely for processes
315 that operate mostly at local or regional scales such as loss of biodiversity^{4,5,39,40}. Responses have
316 included that a planetary boundary does not necessarily imply a tipping point and that the
317 framework is a synthesis of anthropogenic impacts significant at the global scale that was never
318 intended to replace local-scale management approaches^{1,41,42}. The purpose of this article is not to
319 contribute to these debates. We note however that our modelling framework (see section 'Control
320 theory framework' below) does not assume any tipping dynamics at or near a planetary boundary.

321 **Normalised control variables**

322 Let X be the planetary boundary control variable, X_0 its pre-industrial values, and X_{PB} its boundary
323 value. The planetary boundaries all represent different Earth system processes with different
324 physical units. To compare the strengths of interactions between planetary boundaries, we first
325 define normalised control variables

$$x = \frac{X - X_0}{X_{PB} - X_0}. \quad (1)$$

326 Lower case symbols hereafter denote normalised control variables and upper case symbols denote
 327 un-normalised control variables. Under Eq. (1), a normalised control variable has value 0 at pre-
 328 industrial conditions and 1 at its boundary value. Values below 0 and above 1 are possible and
 329 correspond to a control value improved beyond pre-industrial and worsened beyond the boundary,
 330 respectively. Changes in the un-normalised control variable (X) or the boundary value (X_{PB}) will cause
 331 a change in the normalised control variable.

332 We calculated the normalised values for the current control variable values and zones of uncertainty
 333 for the planetary boundaries considered here (Table S1). Where there were two or more control
 334 variables for a planetary boundary (such as for climate and biogeochemical flows), we averaged the
 335 normalised values to give a single normalised control variable value. For the biogeochemical flows
 336 planetary boundary we used the two control variables directly subject to human action, “P flow from
 337 fertilisers to erodible soils” and “industrial and intentional biological fixation of N”, omitting the
 338 control variable “P flow from freshwater systems into the ocean” due to its highly uncertain value⁴³.
 339 For the stratospheric ozone planetary boundary we used total column ozone (which is dominated by
 340 stratospheric ozone), averaged over mid-latitudes as defined and assessed by the World
 341 Meteorological Association⁴⁴. This mid-latitude measure is more indicative of global ozone depletion
 342 and would lead to more significant interactions with the Earth system compared to polar ozone
 343 depletion. Since there are no available estimates of control variable values for the here newly
 344 defined freshwater and ocean biosphere integrity boundaries, we estimated their normalised
 345 control variable values using an indirect method (see below).

346 **Literature survey**

347 We surveyed the literature for interactions between the planetary boundaries. For each interaction,
 348 we performed a search on Scopus (last performed 24 June 2019) with search term “[PB1] [PB2]
 349 global*” in Title, where [PB1] and [PB2] were set according to:

- 350 • Climate change: “climate change” OR “radiative forcing” OR “greenhouse gas*” OR “carbon
 351 dioxide”
- 352 • Biosphere integrity (land): biodiversity OR “ecosystem health”
- 353 • Biosphere integrity (freshwater): freshwater OR river* OR lake* OR inland
- 354 • Biosphere integrity (ocean): “biological pump” OR “coral reefs” OR fish* OR “marine
 355 biodiversity”
- 356 • Land-system change: “land-system change” OR “land cover” OR deforestation OR “habitat
 357 loss”
- 358 • Biogeochemical flows: nitrogen OR phosphorus OR fertiliser OR fertilizer
- 359 • Ocean acidification: “ocean acidification”
- 360 • Freshwater use: precipitation OR runoff OR “water cycle” OR “hydrological cycle” OR “water
 361 consumption”
- 362 • Aerosol loading: aerosol*
- 363 • Stratospheric ozone depletion: “stratospheric ozone”

364 We reviewed abstracts and where appropriate read manuscripts to identify those articles that
 365 assessed a globally aggregated strength of the interaction. We sought interactions that operate on
 366 policy-relevant time scales of ~100 years. Where the search yielded no useful results, we expanded
 367 the search by: (a) changing the search to include title, abstract and keywords; (b) changing the
 368 search term to “[PB1] [PB2]” in Title. In all searches, we only examined results from publications
 369 after the year 2000.

370 We sought representative literature for each interaction; exhaustive surveys of each interaction and
 371 analyses of their uncertainties were beyond the scope of this article. We supplemented the search
 372 with our own knowledge of the literature. In a small number of cases, we constructed our own
 373 estimates of interaction strengths using published data.

374 For the freshwater and ocean biosphere integrity planetary boundaries that we introduce in this
 375 article, control variables have not yet been defined. For interactions involving these planetary
 376 boundaries, we relied on assessments of the levels at which various ecosystem functions will be
 377 significantly affected. These ecosystem functions include production of fish biomass, the marine
 378 biological carbon pump (ocean only), depletion of aragonite-forming organisms (ocean only), and
 379 water quality; see the individual interactions in Supplementary Methods for further detail.

380 **Estimation of interaction strengths**

381 For each interaction, we label the originating normalised control variable for the interaction as x and
 382 the receiving normalised control variable for the interaction as y , that is, the interaction is $x \rightarrow y$. For
 383 each interaction, we estimated the normalised interaction strength defined by

$$s = \frac{\Delta y}{\Delta x}, \quad (2)$$

384 where Δx is the change in the normalised control variable x that leads to a change Δy in the
 385 normalised control variable y . The Supplementary Methods describe the interactions we identified
 386 and our estimations of the interaction strengths. Table S2 summarises our estimates of normalised
 387 interaction strengths.

388 Changes in both an un-normalised control variable value and in a boundary value can cause changes
 389 in a normalised control variable value (see Eq. 1). Where data are available on changes in normalised
 390 control variable values, Eq. (2) can be used directly to estimate the normalised interaction strength.
 391 In the list below, Eq. (1) and (2) have been used to derive equivalent expressions to expedite
 392 calculations in cases where only changes in un-normalised control variables or boundary values are
 393 directly available. These equations hold for cases where:

- 394 • A change in un-normalised control variable ΔX causes a change in another un-normalised
 395 control variable ΔY (but X_{PB} and Y_{PB} are fixed),

$$s = \frac{\Delta Y X_{PB} - X_0}{\Delta X Y_{PB} - Y_0}. \quad (3)$$

- 396 • A change in un-normalised control variable ΔX causes a change in the boundary value of
 397 another planetary boundary from Y_{PB} to Y'_{PB} (but X_{PB} and Y are fixed),

$$s = \left(\frac{Y - Y_0}{Y'_{PB} - Y_0} - \frac{Y - Y_0}{Y_{PB} - Y_0} \right) \frac{X_{PB} - X_0}{\Delta X}. \quad (4)$$

398 We expect that this type of interaction would also change the zone of uncertainty but we do
 399 not model this effect here.

- 400 • As for equation (4), but where evidence on the change in the originating control variable is
 401 available in normalised units Δx ,

$$s = \left(\frac{Y - Y_0}{Y'_{PB} - Y_0} - \frac{Y - Y_0}{Y_{PB} - Y_0} \right) \frac{1}{\Delta x}. \quad (5)$$

402
 403 Where the planetary boundary has more than one control variable, we looked for interactions
 404 involving either control variable. For example, for the climate change planetary boundary we looked
 405 for interactions involving either carbon dioxide concentrations or radiative forcing.

406 Some interaction strengths are 1 because some planetary boundaries are defined by the effect of
 407 that boundary's transgression on another planetary boundary. For example, the ocean acidification
 408 planetary boundary is defined as that at which the functioning of marine ecosystems is
 409 compromised, that is, when the marine biosphere integrity planetary boundary is transgressed.

410 We did not assess Earth system feedbacks that involve only one planetary boundary, for example,
 411 the long-wave radiation into space that partially stabilises the Earth's climate against temperature
 412 increases.

413 Control theory framework

414 Control theory studies how feedbacks modify the operation of systems. Engineering commonly uses
 415 control theory to design feedbacks that achieve desired system behaviour⁴⁵. The feedbacks
 416 associated with environmental management, such as fishery quota setting in response to stock
 417 assessments, can also be expressed in a control theory framework⁴⁶. Here, we use a control theory
 418 framework, but without any feedback design, to calculate the effects of interactions between the
 419 planetary boundaries. In the following, bold lower-case symbols denote vectors of the relevant
 420 quantities for the planetary boundaries considered here.

421
 422 The state of the normalised control variables \mathbf{x} without feedbacks is simply given by the direct
 423 human impacts \mathbf{d} (that is, impacts that do not result from changes in another planetary boundary)
 424 (Box 1). With feedbacks active we first calculate the human impacts \mathbf{h} , which are comprised of:
 425 direct human impacts \mathbf{d} ; plus impacts arising from changes in normalised control variables \mathbf{x}
 426 mediated by reactive human mechanisms \mathbf{R} ; plus parallel impacts from reactive interactions and
 427 direct drivers on other planetary boundaries $\mathbf{P}(\mathbf{d} + \mathbf{R} \mathbf{x})$:

$$428 \quad \mathbf{d} + \mathbf{R} \mathbf{x} + \mathbf{P}(\mathbf{d} + \mathbf{R} \mathbf{x}) = \mathbf{h}. \quad (6)$$

429 The values of the normalised control variables \mathbf{x} are comprised of human impacts \mathbf{h} plus impacts
 430 arising from changes in other normalised control variables \mathbf{x} mediated by biophysical mechanisms, \mathbf{B} ,
 431 giving

$$432 \quad \mathbf{h} + \mathbf{B} \mathbf{x} = \mathbf{x}. \quad (7)$$

433 Solving equations (6) and (7) by eliminating \mathbf{h} , we find that interactions have amplified initial direct
 434 impacts according to

$$435 \quad \mathbf{x} = [\mathbf{I} - (\mathbf{B} + \mathbf{R} + \mathbf{P} \mathbf{R})]^{-1} (\mathbf{I} + \mathbf{P}) \mathbf{d}, \quad (8)$$

436 where \mathbf{I} is the identity matrix.

437 This approach assumes that the control variables \mathbf{x} have reached equilibrium in response to the
438 current values of the direct impacts \mathbf{d} . Many components of the Earth system, such as the carbon
439 cycle, contain transient dynamics and time lags that our model cannot capture. Furthermore, our
440 estimations of different interaction strengths (Supplementary Methods) are based on a variety of
441 time periods due to data constraints. The model is also linear and therefore does not account for
442 nonlinear interactions, for example that only activate after a control variable reaches some
443 threshold, nor does the model generate any of the tipping point dynamics that are associated with
444 transgressing some of the planetary boundaries¹.

445 We use this linear, equilibrium model as a first attempt to quantify how interactions between
446 planetary boundaries affect the relationship between direct human impacts and the transgression of
447 planetary boundaries. Incorporating dynamics and non-linearities would better represent the
448 behaviour of the Earth system and potentially be more useful for governance and is a promising
449 avenue for future work. Adding such further detail to the model would however come with the cost
450 of requiring more information to be gathered to characterise each interaction.

451 **Inferring the normalised control variable values for the ocean and freshwater biosphere integrity** 452 **planetary boundaries**

453 Control variables for the ocean and freshwater biosphere integrity boundaries have not previously
454 been empirically estimated. The first step of our analysis was to estimate values for the current
455 normalised values for these boundaries based on their interactions with other boundaries. We
456 assume that these biosphere integrity boundaries only experience human impact through their
457 interactions with other boundaries, that is, their direct human impacts are zero. Even under this
458 conservative assumption, we calculate below that marine and freshwater biosphere integrity is
459 strongly degraded. Future work could incorporate direct human impact on aquatic systems, for
460 example through fisheries or dams.

461 We first outline our logic for calculating these control variable values without mathematical
462 formalism. Since the biosphere integrity boundaries are significantly affected by other boundaries,
463 and we know the control variable values of those planetary boundaries and the strengths of their
464 interactions with the biosphere integrity boundaries, we can therefore estimate the biosphere
465 integrity control variable values. For example, freshwater biosphere integrity experiences impacts
466 from climate change, land system change, biogeochemical flows and freshwater use (Table S2) which
467 have current normalised control variables of 2.0, 1.5, 2.3 and 0.65, respectively (Table S1). For the
468 normalised control variable for freshwater biosphere integrity, this logic gives a value $2.0*0.38 +$
469 $1.5*0.08 + 2.3*1 + 0.65*1 = 3.8$.

470 Formally, we used the following reasoning to ensure consistency with the control theory framework.
471 Let b be the set of the two unknown biosphere integrity planetary boundaries and \bar{b} be the
472 complementary set of the other planetary boundaries. We seek estimates of the control variable
473 values \mathbf{x}_b . Defining

$$474 \quad \mathbf{A} = (\mathbf{I} + \mathbf{P})^{-1}[\mathbf{I} - (\mathbf{B} + \mathbf{R} + \mathbf{P} \mathbf{R})]$$

475 we re-write equation (8) as

$$476 \quad \mathbf{A} \mathbf{x} = \mathbf{d}.$$

477 We pick out the rows b of this vector equation corresponding to the unknown biosphere integrity
478 planetary boundaries (in the ordering given in Table S2, $b = \{3,4\}$):

479
$$\mathbf{A}_{b,*}\mathbf{x} = \mathbf{d}_b = \mathbf{0}.$$

480 Here, $\mathbf{A}_{m,n}$ denotes the submatrix of \mathbf{A} formed by those elements with row numbers in m and
 481 column numbers in n ; the placeholder ‘*’ is understood to refer to all columns. We subtract the
 482 terms on the left-hand side for which \mathbf{x} is known (terms involving $\mathbf{x}_{\bar{b}}$) over to the right-hand side,

483
$$\mathbf{A}_{b,b}\mathbf{x}_b = -\mathbf{A}_{b,\bar{b}}\mathbf{x}_{\bar{b}},$$

484 which we then solve for the unknown values \mathbf{x}_b :

485
$$\mathbf{x}_b = -[\mathbf{A}_{b,b}]^{-1}\mathbf{A}_{b,\bar{b}}\mathbf{x}_{\bar{b}}.$$

486 Using this equation we estimated the following current values for the normalised biosphere integrity
 487 control variables:

- 488 • Freshwater biosphere integrity: 3.8, that is, over three times the planetary boundary. This
 489 value is plausible considering the considerable stress freshwater ecosystems are currently
 490 under⁴⁷ from biogeochemical flows and freshwater extraction.
 491 • Ocean biosphere integrity: 1.4, that is, over the safe planetary boundary at the globally
 492 aggregated scale. This is plausible considering the considerable stress marine ecosystems are
 493 experiencing from ocean acidification and climate change.

494 Using these values ensures consistency when interactions with the other planetary boundaries are
 495 applied. As argued above, they are also plausible values for the boundaries. We do not assign any
 496 upper end to the zones of uncertainty for these two boundaries, in the absence of information to do
 497 so.

498 **Consequences of interactions between the boundaries**

499 Rearranging Eq. (8) gives

500
$$\mathbf{x} = \mathbf{d} + \mathbf{B}\mathbf{x} + \mathbf{R}\mathbf{x} + \mathbf{P}\mathbf{d} + \mathbf{P}\mathbf{R}\mathbf{x}. \quad (9)$$

501 We therefore compared the different contributions to the current values of planetary boundary
 502 control variables, \mathbf{x} , by using: \mathbf{d} for the contributions of direct human impacts; $\mathbf{B}\mathbf{x}$ for the
 503 contributions of biophysically-mediated interactions; $\mathbf{R}\mathbf{x}$ for the contributions of reactive human-
 504 mediated interactions; and $\mathbf{P}\mathbf{d} + \mathbf{P}\mathbf{R}\mathbf{x}$ for the contributions of parallel human drivers. Direct human
 505 impacts, \mathbf{d} , were calculated by rearranging Eq. (8) to give

506
$$\mathbf{d} = (\mathbf{I} + \mathbf{P})^{-1} [\mathbf{I} - (\mathbf{B} + \mathbf{R} + \mathbf{P}\mathbf{R})] \mathbf{x}. \quad (10)$$

507 To estimate the total contribution of each interaction type to the current values of the normalised
 508 control variables, we compared the sums over all elements of $\mathbf{B}\mathbf{x}$, $\mathbf{R}\mathbf{x}$, $\mathbf{P}\mathbf{d} + \mathbf{P}\mathbf{R}\mathbf{x}$ and \mathbf{d} to the sum
 509 over all elements of \mathbf{x} . We re-aggregated the biosphere integrity boundaries by first averaging across
 510 the three biosphere integrity elements for each vector.

511 **Shape of the safe operating space for human impacts on the Earth system**

512 In this paper, we define the safe operating space as those combinations of human impacts on the
 513 planetary boundaries that do not cause any planetary boundary to be transgressed, and therefore
 514 maintain the Earth system within a Holocene-like state.

515 To calculate the initial estimate of the safe operating space for human impacts on the Earth system
 516 in Fig. 4, we set all control variables to their planetary boundaries (all elements of \mathbf{x} to 1). Eq. (9)

517 shows that $\mathbf{x} - \mathbf{B} \mathbf{x}$ back-calculates the corresponding levels of total human impacts (including direct
518 impacts and human-mediated interactions).

519 To the explore trade-offs within the safe operating space for human impacts on the Earth system in
520 Fig. 5, we formed two groups of planetary boundaries: land system change, freshwater use and
521 biogeochemical flows, which all experience large impacts from agricultural activity; and climate
522 change and ocean acidification, impacts on which are driven primarily by carbon emissions.

523 To simulate varying levels of agricultural activity and carbon emissions, we analysed different
524 combinations of values for the *Land-system change* and *Climate change* elements of the direct
525 impacts vector \mathbf{d} . The parallel human drivers built into the model then lead to impacts on the other
526 planetary boundaries within those groups. We fixed the aerosol control variable at its boundary
527 value (normalised value 1), assumed successful rehabilitation of stratospheric ozone by setting its
528 control variable at its preindustrial value (normalised value 0) and assumed no direct human impacts
529 on other planetary boundaries. We set the strength of the parallel human driver *Land-system*
530 *change* \rightarrow *Climate change* to 0 to ensure that fossil fuel emissions of agricultural origin are not
531 double-counted. We applied Eq. (8) for different combinations of \mathbf{d} and counted how many control
532 variables exceeded their boundary values and how many exceeded their zones of uncertainty.

533 We estimated the additional impacts on planetary boundaries resulting from two policy
534 interventions: BECCS and a low-meat diet (see Supplementary Methods for details). For BECCS, we
535 used scenarios from a global modelling study that cast its results in terms of planetary boundaries¹¹.
536 For a low-meat diet, we selected from a systematic review of diet change modelling⁴⁸ the two
537 studies that estimated the effects of a global transition to a vegetarian diet. For further information
538 see Supplementary Methods. We plotted these interventions as deviations from the current direct
539 impacts on Figure 5. Current direct impacts were estimated using Eq. (10), using the modified
540 interaction matrices described earlier in this sub-section.

541
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543 **Data availability.** All data used in the manuscript's analyses are available in the Supplementary
544 Information (Tables S1 and S2).

545 **Code availability.** All computations are fully described in Methods. Implementation in R of these
546 computations is available upon request.

547 **Competing interests.** The authors declare no competing financial interests.

548 **Author contributions.** (Included in cover letter to adhere with double-blind peer review procedure.)

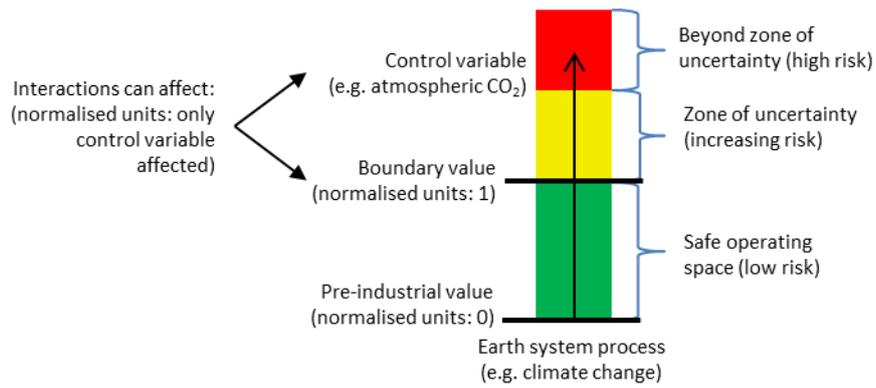
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652

653 **Figure 1: Planetary boundary framework.** A control variable for a planetary boundary quantifies
 654 human interference in the Earth system process represented by that planetary boundary. The
 655 boundary value indicates a conservative 'safe' limit for the control variable, within which the control
 656 variable remains within the 'safe operating space' (green). Beyond the boundary value, the 'zone of
 657 uncertainty' indicates a range of increasing risk (yellow). Beyond the zone of uncertainty indicates an
 658 area of high risk to Earth system functioning (red). In the normalised units introduced in this paper, a
 659 control variable has value 0 under pre-industrial conditions and 1 at the boundary value. Interactions
 660 between planetary boundaries can affect both the boundary value and the control variable; in
 661 normalised units these effects are both captured by changes in the normalised control variable.

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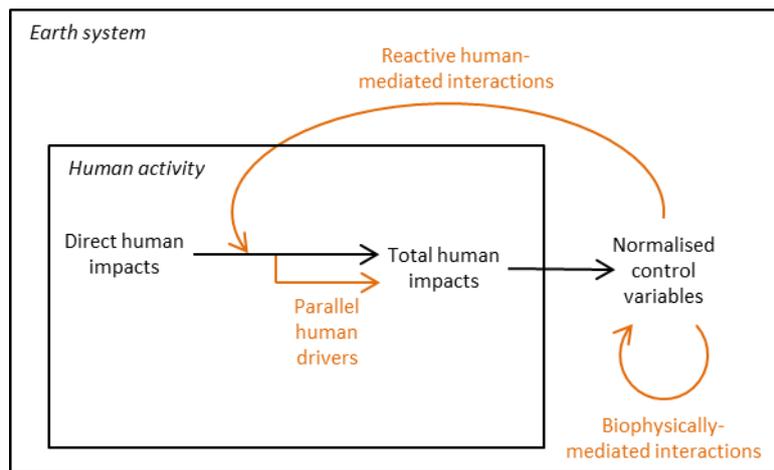
Box 1. Social-ecological framework for interactions between the planetary boundaries

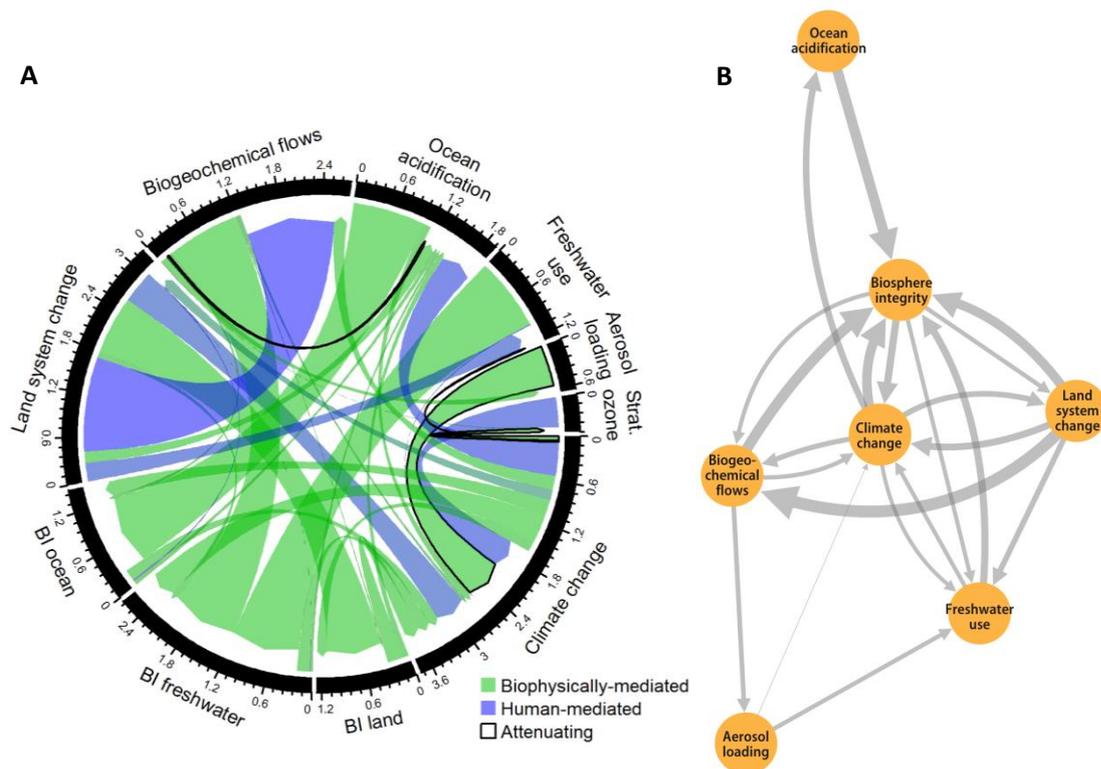
Direct human impacts on one planetary boundary (black arrows in figure) can lead to changes in other planetary boundaries via various mechanisms, which we categorise into three types (orange arrows in figure).

Biophysically-mediated interactions: Changes in a planetary boundary affect another planetary boundary through a biophysical mechanism. For example, land clearing (land system change planetary boundary) leads to carbon emissions (climate change planetary boundary).

Reactive human-mediated interactions: A change in a planetary boundary can lead to a change in human behaviour that affects another planetary boundary. For example, decreased agricultural productivity due to climate change could lead via economic mechanisms to increased land clearing for agriculture (land system change planetary boundary) at the globally aggregated scale.

Parallel human drivers: Human impacts on a planetary boundary are often associated with subsequent impacts on another planetary boundary due to their common drivers. For example, land clearing (land system change planetary boundary) is often followed by increased freshwater use and biogeochemical flows, due to the common driver of agriculture that causes land clearing, freshwater use and biogeochemical flows.

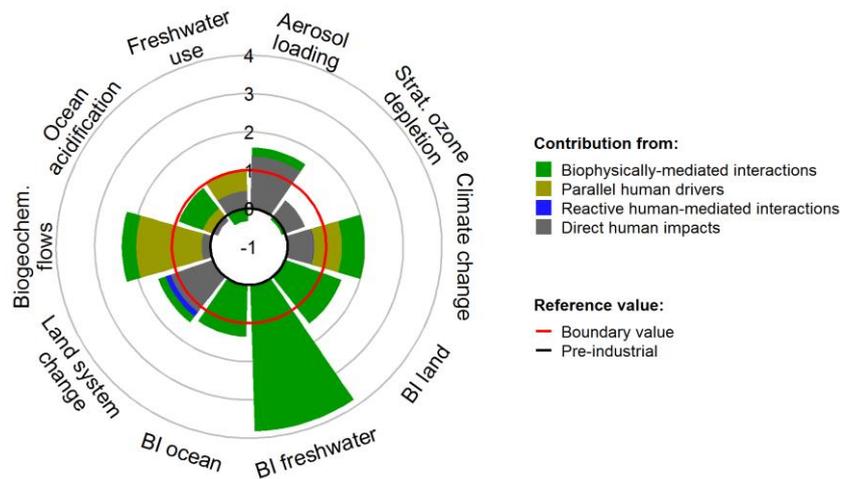




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682 **Figure 2. Interactions between the planetary boundaries.** Net normalised interaction strengths
 683 between the planetary boundaries estimated by our survey. Data are as listed in Table S2. **A**
 684 circular representation of the full interaction matrix using the *circlize* package⁴⁹ (version 0.4.4) in *R*.
 685 The circumference of a circle is filled by originating and receiving ends of each interaction according
 686 to their relative strengths. Interactions where both biophysically-mediated (green) and human-
 687 mediated interactions (blue) are present are coloured a shade between blue and green according to
 688 their relative magnitudes. Black borders indicate a net negative (attenuating) link; all other links are
 689 positive (reinforcing). **B** A force-directed network diagram²², which arranges nodes with stronger
 690 interactions closer together. Here we have re-aggregated the three biosphere integrity boundaries
 691 back into a single node defined by the average of the three separate control variables. We only plot
 692 links whose strength we were able to estimate; for the full set of possible interactions that our
 693 survey identified see Table S2.

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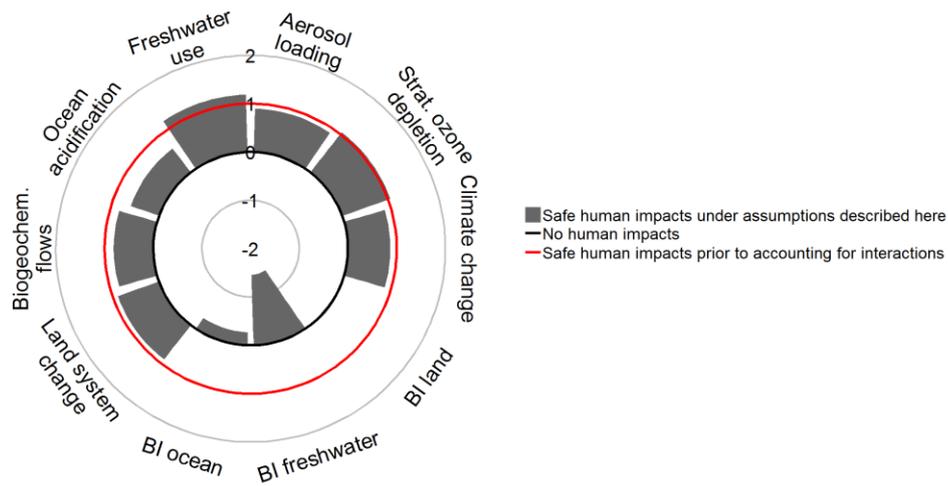
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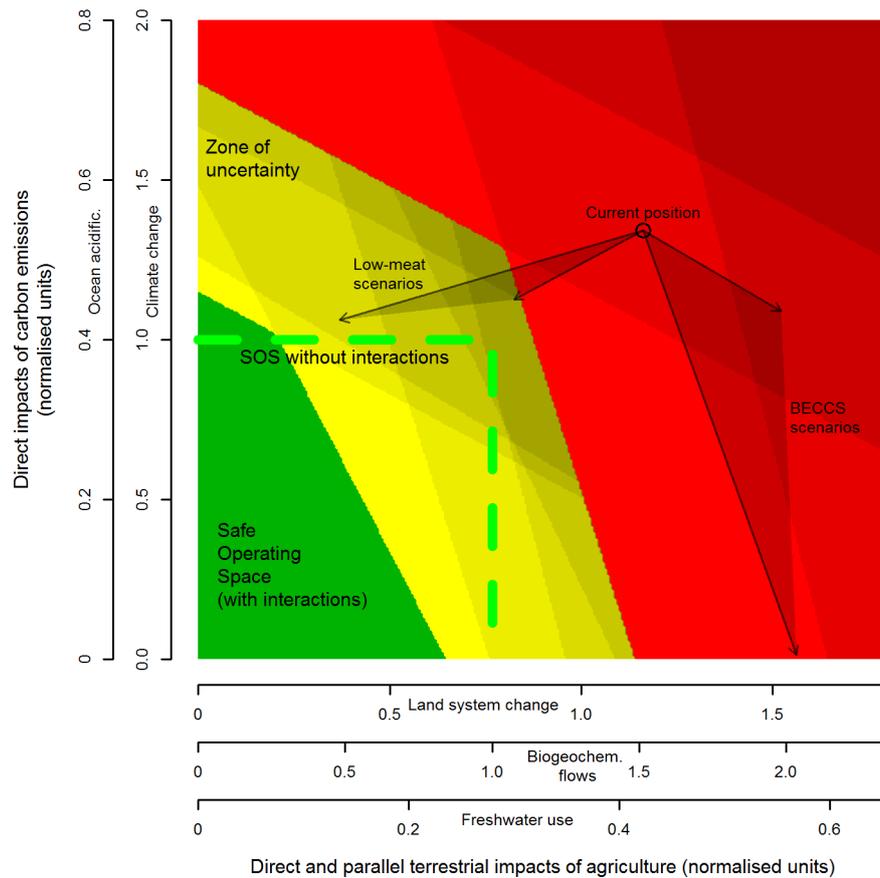
Figure 3. The role of interactions in the current state of the planetary boundaries. Contributions of planetary boundary interactions and direct impacts to the current values of control variables. Control variables are in normalised units, where values of 0 and 1 correspond to pre-industrial conditions and the planetary boundary, respectively.

700



701

702 **Figure 4: A safe operating space for human impacts on the Earth system.** Outer circle (red): safe
 703 human impacts prior to accounting for interactions. Inner circle (black): No human impacts, i.e., pre-
 704 industrial conditions. Grey bars: Safe levels of human impacts (including direct impacts, reactive
 705 human-mediated interactions and parallel human drivers) on each planetary boundary after
 706 biophysical interactions are taken into account, assuming that all other control variables are at their
 707 boundary values. Axis is in normalised units as in Fig 3. Under the assumptions made for this figure,
 708 the safe levels of human impacts on biosphere integrity are estimated by the model to be either
 709 negative (ocean and freshwater) or zero (land), due to the large impacts on biosphere integrity by
 710 other planetary boundaries.



711

712 **Figure 5: Effects of interactions between planetary boundaries on the shape of the safe operating**
 713 **space for human impacts on the Earth system.** We examined the safe operating space for the direct
 714 impacts of agriculture on land system change, biogeochemical flows and freshwater use and of
 715 carbon emissions on climate change and ocean acidification. The multiple direct impacts within each
 716 group (indicated by the parallel axis scales) are linearly co-ordinated according to our historically and
 717 globally aggregated estimates of their co-occurrence (see entries in Table S2 and Supplementary
 718 Methods for parallel human drivers). Green region: the safe operating space, where all control
 719 variables are below their planetary boundaries. Yellow region: where at least one control variable is
 720 beyond its planetary boundary; darker shades indicate more boundaries transgressed. Red region:
 721 where at least one control variable is beyond its zone of uncertainty; darker shades indicate more
 722 control variables beyond their zones of uncertainty. Dashed green line: the edge of the safe
 723 operating space without interactions. The small circle indicates the current state of direct impacts on
 724 these planetary boundaries as estimated by our model. The arrows and shading indicate the
 725 trajectories following global-scale transitions to low-meat diets and BECCS. Axes are in normalised
 726 units as in Fig 3.

727