Interactions between the Planetary Boundaries: Supplementary Information

Table S1. Control variables for the planetary boundaries analysed in this article. Values of control variables (pre-industrial, current and zone of uncertainty) and positions of the planetary boundary are taken from Steffen et al. (2015) unless otherwise noted. Normalised control variables are calculated by equation (1); values of 0 and 1 therefore correspond to control variables at pre-industrial levels and the planetary boundary, respectively.

Planetary boundary	**Control variable(s)**	**Pre-industrial value**	**Boundary value**	**Zone of uncertainty: boundary value to…**	**Zone of uncertainty (normalised value)**	**Current value (2015)**	**Normalised current value**
Climate change	Atmospheric CO_2 concentration Radiative forcing relative to pre-industrial	280 ppm 0 W/m^2	350 ppm +1.0 W/m^2	450 ppm 1.5 W/m^2	2.0** (2.4 and 1.5)	398.5 ppm 2.3 W/m^2	2.0** (1.7 and 2.3)
Change in biosphere integrity (land)	Biodiversity Intactness Index	100%	90%	30%	6.0	84.6% (Newbold et al. 2016)	1.5
Change in biosphere integrity (freshwater)	Ecosystem functioning (see Methods for further information)	-	-	-	-	-	3.8*
Change in biosphere integrity (ocean)	Ecosystem functioning (see Methods for further information)	-	-	-	-	-	1.4*
Land-system change	Area of forested land remaining	100%	75%	54%	1.8	62%	1.5
Biogeochemical flows (P and N cycles)	P flow from fertilisers to erodible soils Industrial and intentional biological fixation of N	0 Tg P yr^{-1} 0 Tg N yr^{-1}	6.2 Tg P yr^{-1} 62 Tg N yr^{-1}	11.2 Tg P yr^{-1} 82 Tg N yr^{-1}	1.6** (1.8 and 1.3)	14 Tg P yr^{-1} 150 Tg N yr^{-1}	2.3** (2.3 and 2.4)
Ocean acidification	Carbonate ion concentration aragonite saturation state compared to pre-industrial	100%	80%	70%	1.5	84%	0.80
Freshwater use	Consumptive blue water use	~0 km^3 yr^{-1}	4000 km^3 yr^{-1}	6000 km^3 yr^{-1}	1.5	2600 km^3 yr^{-1}	0.65
Aerosol loading	Aerosol optical depth (measured over Indian subcontinent)	0.17 (Carslaw et al. 2017)	0.25	0.50	4.1	0.30	1.6
Stratospheric ozone depletion	Total column ozone at mid-latitudes (see Methods for further information)	290 DU	5% reduction	10% reduction	2.0	2.2% reduction (WMO 2018)	0.44

*A global estimate has been inferred from consistency with other boundaries, see Supplementary Methods.

**Where there is more than one control variable, we take the mean of the full set of normalised control variables (shown in brackets).

Table S2: Planetary boundary interaction matrices. B, R and S denote entries in the biophysically-mediated interaction matrix, **B**, reactive human-mediated interaction matrix, **R**, and parallel human-mediated interaction matrix, **S**, respectively. To match conventional matrix algebra notation, those matrices are the transpose of this table. Question marks (?) indicate where we found there to be interactions, but have insufficient data to estimate a magnitude, and therefore for the purposes of this study take them as zero. Calculations of the interaction strengths are presented in Supplementary Methods. All interaction strengths are normalised (see Methods).

Effect of rows on columns	**Climate Change**	**BI land**	**BI freshwater**	**BI ocean**	**Land-system change**	**Biogeochem. flows**	**Ocean acidification**	**Freshwater use**	**Aerosol loading**	**Stratospheric ozone depletion**
Climate change		0.15B	0.38B	0.22B ?R	0.10B 0.05R	0.19B ?R	-0.07B 0.40P	-0.08B 0.065P	0	-0.06B
BI land	0.22B		?B	0	?B ?R	?R	0.08B	0	0	0
BI freshwater	0.17B 0.002R	0		0	0.003R	?R	0.04B	0	0	0
BI ocean	0.15B ?R	0	0		0.02R	0	0.06B	0	0	0
Land system change	0.12B 0.33P	0.80B	0.08B	0		1.3P	0.16B	-0.11B 0.36P	?B	?B
Biogeochemical flows	0.04B 0.005P	0.02B	1B	0.05B	?R		-0.03B	0	0.10B	0.01B
Ocean acidification	0.10B	0	0	1B	0	0		0	0	0
Freshwater use	?B 0.018P	?B ?R	1B ?R	?B	0	0	0		0	0
Aerosol loading	-0.56B ?R	?B	0	?B	0	0	0	0		?B
Stratospheric ozone depletion	-0.11B 0.52P	?B	?B	?B	0	0	0	?B	?B	

Supplementary Methods

1. Estimation of interaction strengths

See Methods for further information. As detailed in Methods, for each interaction $x \rightarrow y$, Δx refers to the change in the normalised control variable x that leads to a change Δy in the normalised control variable y. The corresponding symbols for changes in unnormalised control variables are ΔX and ΔY, respectively.

1.1 Impacts of climate change

Climate change -> Biosphere integrity (land)

Biophysical: Climate change will cause loss of biosphere integrity through mechanisms such as biodiversity loss and limited migration rates of tree species (Nunez et al. 2019; Colwell et al. 2008; Bellard et al. 2012; Rinawati et al. 2013; Araujo and Rahbek 2006; Pereira et al. 2010; Willis and Bhagwat 2009; Bradford and Warren 2014; Javeline et al. 2013). Impacts of climate change on forest ecosystems are particularly relevant to planetary boundary interactions, since forests store substantial amounts of carbon and regulate water runoff from precipitation. The magnitude of climate change impacts on biodiversity or other ecosystem functions are however uncertain (Bellard et al. 2012). Furthermore, biodiversity loss is assessed using a range of measures, for example species richness and abundance measures. The current control variable for biosphere integrity is biodiversity intactness index, which is an abundance-weighted measure (Scholes and Biggs 2005). We here collate a series of estimates, making the very coarse assumption that species richness and abundance losses are approximately interchangeable. (a) Under high emissions scenarios that involve a temperature change of 3.5°C, climate-mediated loss of vascular plant biodiversity may reach 5% or more by 2100 (van Vuuren, Sala, and Pereira 2006). Scaling linearly to the ‘current’ (where current refers to the time when planetary boundary control variables were last estimated, see Table S1) 0.85°C of warming (Hartmann et al. 2013) gives 5%/(0.85/3.5) = 1.2% current loss of biodiversity due to climate change. This corresponds to 1.2/(100-84.6) = 8% of total current biosphere integrity losses (using current position of biosphere integrity control variable reported in Table S1). (b) Pearson et al. (2017) estimated that 17% of carbon emissions from forest degradation are due to direct climate impacts via fires. (c) Alkemade et al. (2009) estimated that approximately 0.02/0.3 = 7% of loss of mean species abundance has been due to climate change. (d) Newbold (2018) predicted a mean local species richness change -28.8% under 4.5°C warming, converting linearly to -5.4% under 0.85°C. Newbold et al. (2016) also estimated a current 15.4% loss of species richness due to land-use effects, giving 5.4/(5.4+15.4) = 26% of current species richness losses due to climate. In summary, we have found values of 8%, 17%, 7% and 26% for the contribution of climate change to current loss of land biosphere integrity. The mean of these estimates is 14.5% (full range 7% to 26%). We weight the estimate of Newbold (2018) higher as it is the most recent and systematic estimate. We therefore use a central estimate of 20% (full range 7% to 26%), giving Δy = 20%*1.5 = 0.3 (full range 0.10 to 0.39) of current biosphere integrity loss for current levels of climate change (Δx = 2.0). Eq. (2) gives s = 0.3/2.0 = 0.15 (full range 0.05 to 0.20). This interaction is however likely to be strongly nonlinear, increasing in strength as biosphere integrity is degraded.

Human: Heck et al. (2018) show in a land use optimisation model that the trade-offs between carbon storage and terrestrial biodiversity goals are low. We therefore do not include any human-mediated interaction.

Climate change -> Biosphere integrity (freshwater)

Biophysical: Human impacts via nutrient inputs dominate impacts on freshwater systems, but climate will have an effect from altered thermal regimes and intensified drought-flood cycles (Settele et al. 2015, sec. 4.3.3.3; Woodward, Perkins, and Brown 2010; Adrian et al. 2009). Climate change will affect aquatic ecosystems and ecosystem services derived from fisheries will change in complicated ways (Biswas, Vogt, and Sharma 2017; Radinger et al. 2016; Conti et al. 2015; Ficke, Myrick, and Hansen 2007; van Vliet, Ludwig, and Kabat 2013; Harrod 2015; Knouft and Ficklin 2017; Myers et al. 2017); we were unable to obtain an estimate of the strength of interactions involving fisheries. Rising sea levels due to climate change will lead to salinisation of some freshwater ecosystems (Herbert et al. 2015; Oppenheimer et al. 2019). Here, we use an estimate of the effects of climate change on cyanobacterial levels. In North America, nutrient levels and temperature changes explain changes in cyanobacterial levels roughly in the ratio 3:1, respectively (Taranu et al. 2015). Current changes in nutrient inputs (2.3 in normalised units, see Table 1) have caused a change in freshwater biosphere integrity via the *Biogeochemical flows -> Biosphere integrity (freshwater)* link of 1*2.3 = 2.3 in normalised units (where 1 is the strength of the link, see Table S2). We attribute to climate change an additional change in freshwater biosphere integrity according to the above 3:1 ratio of $\Delta y = 2.3/3 = 0.77$. The climate control variable is currently at $\Delta y = 2.0$ (Table S1). The interaction strength is therefore $s = 0.38$ by Eq. (2). Increased runoff due to increased precipitation from climate change will also increase nutrient loading in rivers (Ockenden et al. 2017): see link *Climate change -> Biogeochemical flows.*

Climate change -> Biosphere integrity (ocean)

Biophysical: Climate change is expected to be a major driver of changes in marine biodiversity (Worm and Lotze 2016). Warming has already caused changes in range distributions of many marine organisms, leading to changed community composition and interspecies interactions (Bindoff et al. 2019). There are many aspects of ocean biosphere integrity that could be monitored (Nash et al. 2017). In this initial assessment, we focus on potential impacts on fisheries. In fisheries, climate change could cause a decrease in global maximum catch potential of $\Delta Y = -7.7\%$ by 2050 under RCP8.5 (Lam et al. 2016). This scenario involves a change in CO_2 concentrations of $\Delta X = (489.4 - 398.5)$ ppm = 90.9 ppm (Riahi, Grübler, and Nakicenovic 2007; data taken from https://tntcat.iiasa.ac.at/RcpDb) from current conditions, leading to an interaction strength of $s = 0.12$ by Eq. (3) if we set a critical level of fishery depensation at $Y_{PB} = 50\%$. Free et al. (2019) estimated that historical climate change ($\Delta x = 2.0$) has led to a 4.3% decrease in maximum sustainable yield for a global sample of fisheries, leading to an interaction strength $s = 0.04$ by the same method. In coral reefs, temperature and climate effects have reduced coral cover on the Great Barrier Reef by half (Gattuso, Hoegh-Guldberg, and Pörtner 2014). If we consider this a dangerous level of loss ($\Delta y = 1$, that is, the control variable changes from pre-industrial to the planetary boundary) at current levels of climate change ($\Delta x = 2.0$, Table S1), Eq. (2) gives $s = 0.5$, with all other factors fixed. Taking the mean of these three estimates, we set the interaction strength to 0.22 (full range 0.04 to 0.5).

Human (reactive): Sea level rise due to climate change may lead to human responses such as building dykes that damage coastal ecosystems especially away from city areas (Warren 2011; Oppenheimer et al. 2019). We do not have data to estimate the strength of this interaction.

Climate change -> Land system change

Biophysical: Climate change alone is unlikely to induce tipping of major forest biomes in the near future, but in conjunction with direct deforestation could trigger a collapse of tropical forests (Settele et al. 2015).

Boreal forests will likely migrate northward, but whether this leads to a change in forest area is uncertain. The Amazon is approximately 15% of global forest area (Dixon et al. 1994). Let us assume that climate change would contribute 50% of the contribution to tipping of Amazon rainforest. We set $\Delta Y = -0.15*0.5 = -0.075$, giving $\Delta y = 0.3$ using Eq. (1). An extreme climate scenario triggering this tipping could involve moving to three times the planetary boundary, so we set $\Delta x = 3$. Using Eq. (2), $s = 0.10$.

Human (reactive): Integrated assessment models indicate that agricultural yields could decrease by 10% under climate scenario A1B by 2050 (Porter et al. 2014 Box 7-1). This yield loss could lead to compensation by increased land clearing. Agricultural land is currently 37.4% of the land surface, while forest is 30.7% (FAO 2017). Yield compensation would therefore require another 10%*37.4% = 3.7% of land surface for agriculture. If currently forested land is used for agriculture (following a dominant past trend of deforestation), remaining forest as fraction of original cover would decrease below its current value by 62%*(-3.7%/30.7%) = -7.5%. Elasticities for land use generally vary between 0 and 0.2 in the global North and 0.3 and 1 in the global South (Tabeau, Helming, and Philippidis 2017). We use an intermediate global elasticity of 0.3, giving $\Delta Y = -7.5\%*0.3 = -2.3\%$ (the full elasticity range 0 to 1 gives a range for ΔY of 0 to -7.5%). Scenario A1B has an atmospheric carbon concentration of 532 ppm by 2050 (Houghton et al. 2001), therefore $\Delta X = (532 - 398.5)$ ppm = 133.5 ppm compared to the conditions reported in Table S1. Using Eq. (3), $s = 0.05$ (with full range 0 to 0.16).

Climate change -> Biogeochemical flows

Biophysical: Intensified drought-flood cycles will cause net increases in erosion and nutrient flux from land to water. We used the model of Motew et al. (2017) to run 70 years of each of the four Yahara2070 scenarios (https://Yahara2070.org and https://wsc.limnology.wisc.edu). These scenarios include 4 IPCC warming scenarios downscaled to the Yahara watershed by the University of Wisconsin-Madison Climate Research Center. Using the annual results for four different watersheds over a total of $n = 3648$ simulated years, we used a multiple regression model to estimate the effect of maximum daily precipitation on the log of P yield from the land (kg/ha). This multiple regression includes other variates for land use, land management, and other climate variables but we want the maximum precipitation effect. We obtained

$$\log(V) = A + 0.012*U$$

where V is P yield in kg/(ha yr), U is maximum precipitation in mm, and A is the effect of all the other covariates bundled together. (We note that while it is P concentration that ultimately affects freshwater ecosystems, we use P yield here since excess water volumes associated with extreme rainfall events will rapidly drain away or evaporate while the excess P will remain in the freshwater system.) A 1 mm increase in maximum precipitation therefore increases $\log(V)$ by 0.012, with a standard error of 0.00015. The mean U and $\log(V)$ values over the whole data set are 86.5 mm and -1.3, respectively. Barbero et al (2017) found that extreme daily precipitation amounts increase by 6.9%/°C; therefore we predict an increase in $\log(V)$ of 0.012*0.069*86.5 mm = 0.072 per °C. One degree of warming would therefore increase P runoff to surface water from exp(-1.3) = 0.27 kg/(ha yr) to exp(-1.3 + 0.072) = 0.29 kg/(ha yr), or an increase of 7.4%. [This increase matches well with the 14% predicted P runoff changes predicted in the Baltic under RCP8.5 to 2050, that is, about 10% change per °C (SOILS2SEA 2018).] Scaling to current global P runoff ($Y = 14$ Tg P yr^{-1}), and current climate change ($\Delta x = 2.0$, Table S1) in which temperatures have risen 0.85°C since pre-industrial as at the last IPCC report (Hartmann et al. 2013), we find an increase in nutrient runoff of (% increase in runoff per °C)*(temperature change °C)*(global nutrient runoff) = 7.4%*0.85*14 = 0.88 Tg P yr^{-1}. This increase in runoff reduces the safe level of fertiliser application. Using Eq. (5) with $Y_{PB} = 6.2$ Tg P yr^{-1} and $Y'_{PB} = 6.2-0.88 = 5.32$ Tg P yr^{-1}, we find $s = 0.19$. Carrying through the standard error of the regression coefficient described above gives an uncertainty in s of 0.003. We caution that the Motew et al. model is for midwestern US lakes in relatively flat watersheds dominated by intensive agriculture, a mix of row crops and animal herds especially dairy cows. Watersheds used solely for grazing could have lower exports of P, while watersheds on more sloped topography could have higher exports of P. We therefore judge that we have significantly less certainty in $s = 0.19$ as a globally aggregated estimate of the relationship between climate change and biogeochemical flows than the analysis indicated above, but do not have a means of estimating this contribution to uncertainty.

Human (reactive): Decreased productivity under climate change could lead to additional nutrients being applied. We do not however have data available to estimate the strength of this interaction.

Climate change -> Ocean acidification

Biophysical: Warming from climate change decreases solubility of carbon dioxide in water and therefore partially buffers against increasing acidification. McNeil & Matear (2007) found this interaction buffered decrease in aragonite saturation state by 15%. Applying this buffering to current levels of ocean acidification (0.80) indicates that without buffering ocean acidification would have been 0.8/(1-0.15) = 0.94. By this calculation, current levels of climate change ($\Delta x = 2.0$) have buffered ocean acidification by $\Delta y = 0.8 – 0.94 = -0.14$, giving $s = -0.07$ by Eq. (2).

Additionally, increases in atmospheric carbon dioxide, which is one of the control variables for climate change, lead to absorption by the oceans and ocean acidification. Within our framework, this mechanism could therefore contribute to this interaction even though the mechanism does not include the temperature effects of climate change. To avoid confusion, we do not account for atmosphere-ocean exchange of carbon dioxide here but rather attribute the mechanism to the sources of carbon dioxide emissions, for example *Land system change -> Ocean acidification*.

A further potential interaction between climate and ocean acidification is the acceleration by climate change of the rock weathering that adds alkalinity to the ocean (Ridgwell and Zeebe 2005). Weathering is critical to the global carbon cycle on long time scales (Colbourn, Ridgwell, and Lenton 2015; Lenton 2016), but on the policy-relevant 100-year time scales considered here is unlikely to be significant.

Human (parallel): Anthropogenic carbon dioxide emissions affect both climate change and ocean acidification. We assume proportionality, that is, direct human emissions have contributed to the same fraction of anthropogenic atmospheric and ocean CO2 content. Using current levels of climate change ($\Delta x = 2.0$) and ocean acidification ($\Delta y = 0.8$), Eq. (2) gives $s = 0.40$.

Climate change -> Freshwater use

Biophysical: Current climate change ($\Delta x = 2.0$) has been estimated to have increased global runoff by approximately 1300km^3/yr (Sterling, Ducharne, and Polcher 2013). This increased runoff is potentially available for human consumption, although locally some areas are drying, some of the additional runoff may be unusable in the form of extreme floods (Arnell and Lloyd-Hughes 2014; Gerten et al. 2013). Using Eq. (5) with $Y_{PB} = 4000$ km^3 yr^{-1}, $Y'_{PB} = (4000 + 1300)$ km^3 yr^{-1} = 5300 km^3 yr^{-1} and $Y = 2600$ km^3 yr^{-1} gives $s = -0.08$.

Human (parallel): The global energy sector is responsible for about half of global carbon emissions (FAO 2016a), so we attribute half of current climate change to the energy sector ($\Delta x = 2.0/2 = 1.0$). Energy production is responsible for around 10% of global water withdrawals ($\Delta y = 0.1*y = 0.065$) (Kęsicki and

Walton 2016). Using Eq. (2) gives $s = 0.065$. This analysis does not consider the likely future changes in means of energy generation.

Climate change -> Stratospheric ozone depletion

Biophysical: Anthropogenic carbon dioxide leads to cooling of the stratosphere, due to heat being trapped at lower levels of the atmosphere. This cooling slows the rates of chemical reactions that deplete ozone and also increases the chemical destruction of nitrous oxides (Stolarski et al. 2015). According to one model (Portmann, Daniel, and Ravishankara 2012), anthropogenic CO2 lead to a change in global mean ozone of 2.40 DU in 2000 compared to a change with all source gas levels of -13.35 DU. Scaling to the 2.2% decrease ($y = 0.44$ in normalised units, Table S1) assessed by the WMO (2018), $\Delta y = y^*(2.4/-13.35) = 0.44^*(2.4/-13.35) = -0.079$ for atmospheric CO_2 concentrations of 369 ppm in the year 2000 (Houghton et al. 2001), that is, $\Delta x = (369-280)/(350-280) = 1.27$ using Eq. (1). Using Eq. (2), $s = -0.06$. This estimate does not include the effect of stratospheric cooling on destruction of nitrous oxides; the interactions framework used here cannot incorporate three-way interactions (in this case, involving biogeochemical flows, climate change, and ozone depletion).

1.2 Impacts of changes in biosphere integrity

As detailed in the main text, we separate the biosphere integrity planetary boundary into land, freshwater and ocean components.

Biosphere integrity (land) -> Climate change

Biophysical: Here, we use the direct biodiversity-productivity hypothesis, in which a less biodiverse ecosystem is less productive and therefore stores less carbon. There is substantial empirical evidence for this relationship (Liang et al. 2016, 2015; Poorter et al. 2015; Weisser et al. 2017; Naeem, Kawabata, and Loreau, M. 1998; Ricketts et al. 2016), though there remains debate about how broadly it is applicable (Cardinale et al. 2012). Using the relationship obtained by Liang et al. (2016), and making the very coarse assumption that species richness and abundance losses are approximately interchangeable, a decrease from 100% biosphere integrity to the planetary boundary (90%, that is, $\Delta X = -10\%$) would lead to a decrease in productivity of 2.7%. Compared to active terrestrial carbon storage of around 1875 GtC [1325 PgC of soil organic carbon in top metre of soil (Köchy, Hiederer, and Freibauer 2015) plus midrange of vegetation carbon estimate by Ciais et al. (2013)], this loss of productivity could have resulted in a loss terrestrial carbon sinks of around 1875*2.7% = 50 GtC = 23.4 ppm. At present, ocean sinks take up about half as much carbon as remains in the atmosphere (Ciais et al. 2013), therefore we could expect around 2/3 of these extra emissions to remain in the atmosphere, that is, $\Delta Y = (2/3)^*23.4$ ppm = 15.3 ppm. Using Eq. (3), $s = 0.22$.

Human: Heck et al. (2018) show in a land use optimisation model that the trade-offs between carbon storage and terrestrial biodiversity goals are low. We therefore do not include any human-mediated interaction.

Biosphere integrity (land) -> Biosphere integrity (freshwater)

Biophysical: Mechanisms such as increased nutrient runoff are captured via *Land use change -> Biosphere integrity (freshwater)*. Given many freshwater organisms spend some proportion of their lifespan on land, land biosphere integrity may affect freshwater biosphere integrity. Land biosphere integrity may also affect the quality of runoff into freshwater systems. We do not estimate the magnitude of these mechanisms here.

Biosphere integrity (land) -> Land system change

Biophysical: Decreased biosphere integrity may make forests more vulnerable to insect invasions or other shock. We do not have any clear avenue to estimate the strength of this interaction.

Human (reactive): In forest, decreased biosphere integrity may increase the incentive to protect more forest, but with degraded experiences of nature may lessen the public motivation to do so. On agricultural land, decreased agricultural productivity due to soil and biodiversity degradation may lead to additional land being cleared to maintain production. These factors are hard to predict and we do not estimate them here.

Biosphere integrity (land) -> Biogeochemical flows

Human (reactive): Reductions in biodiversity may lead to reductions in ecosystem functions and services such as pollination, pest control and nutrient cycling (Hooper et al. 2012; Isbell et al. 2011) that decrease crop yields. These reductions may lead to extra nutrients being added to compensate for the missing functions and services, however we are not able to estimate the magnitude of the effect here.

Biosphere integrity (land) -> Ocean acidification

Biophysical: The *Biosphere integrity (land) -> Climate change* link above showed that a loss of biosphere integrity $\Delta x = 1.0$ ($\Delta X = -10\%$) could lead a loss of terrestrial carbon sinks of 50 GtC. At present, ocean sinks take up about half as much carbon as remains in the atmosphere (Ciais et al. 2013), therefore we could expect around 1/3 of these extra emissions to be taken up by the ocean, that is, 50/3 = 16.7 GtC. Current anthropogenic ocean carbon content is around 155 GtC (Ciais et al. 2013) which has led to ocean acidification of 0.8 in normalised units. We therefore estimate that the additional carbon absorbed from loss of biosphere integrity would lead to additional acidification of $\Delta y = 0.8*(16.7/155) = 0.08$. Using Eq. (2), $s = 0.08$.

Biosphere integrity (freshwater) -> Climate change

Biophysical: Increased productivity due to moderate levels of increased eutrophication could lead to increased greenhouse gas emissions of 1 PgC/year (DelSontro, Beaulieu, and Downing 2018). Compared to global annual emissions of 9.5 PgC/year (Ciais et al. 2013), these emissions would accelerate climate change by 1/9.5 = 11% or $\Delta y = y*11\% = 2.0*11\% = 0.21$. The model treatment generating these emissions involved an increase in chlorophyll-a concentrations (an indicator of nitrogen loading) of 10 μg/L (DelSontro, Beaulieu, and Downing 2018) compared to current global average freshwater concentrations of 19 μg/L (Sayers et al. 2015), that is, an increase in the current position of the phosphorus loading of 53%, or $\Delta x = 2.3*53\% = 1.2$. The interaction strength for the chain *Biogeochemical flows -> Biosphere integrity (freshwater) -> Climate change* is therefore 0.21/1.2 = 0.17 using Eq. (2). Since the strength of the *Biogeochemical flows -> Biosphere integrity (freshwater)* link is 1, and the strength for a chain of interactions is the product of each interaction strength in the chain, we set the strength of the present link to 0.17/1 = 0.17.

Human (reactive): Declines in surface water quality can lead to increased energy consumption to treat or generate alternative potable water, especially in those countries with the available financial resources to do so. Currently, around 65 TWh of electricity is used for water treatment per year, 200 TWh for wastewater treatment to avoid further water pollution, and around 40 TWh for water re-use and desalination (Kęsicki and Walton 2016): a total of approximately 300 TWh. Globally averaged carbon intensity of electricity was recently estimated at 0.51 $kgCO_2/kWh$ = 0.00014 PgC/TWh (Goh et al. 2018). We estimate that declines in surface water quality therefore contribute to emissions of approximately 0.00014*300 = 0.041 PgC/yr. Compared to global annual emissions of 9.5 PgC/yr (Ciais et al. 2013), this would accelerate current climate change by a further 0.041 / 9.5 = 0.44%, or Δy = 2*0.44% = 0.0087. Setting Δx = 3.7, the estimated current value of the freshwater biosphere integrity control variable, Eq. (2) gives s = 0.002.

Biosphere integrity (freshwater) -> Land system change

Human (reactive): Decline in fish catch from rivers due to the construction of dams on the Mekong River may lead to increase in water consumption and pasture area to compensate for the fish protein lost (Orr et al. 2012). It is unlikely to be compensated for increases in aquaculture (Orr et al. 2012) These magnitude of these effects will however be highly location-dependent, depending for example on the fraction of protein consumption contributed by fish. We use the same global argument as in *Biosphere integrity (ocean) -> Land system change* below. To calculate the strength of the interaction, let us assume a collapse in freshwater capture fisheries (Δx = 1). Fisheries contribute currently 6.7% of global protein consumption, about 7% of which comes from freshwater capture fisheries (FAO 2016b). Agriculture is responsible for 80% of the impact on the land use change planetary boundary (Campbell et al. 2017). To replace lost fish protein, assuming new agriculture produces protein at the global average, would increase land use change by Δy = 80%*6.7%*1.5*7%*0.5 = 0.003. Here we used a land supply elasticity of 0.5 (Tabeau, Helming, and Philippidis 2017) which is typical of the Global South where we expect much of the agricultural displacement to occur. Using Eq. (2), s = 0.003. This increased agricultural activity will flow on to *Biogeochemical flows* and *Freshwater use* by via the parallel links from *Land-system change* as described below.

Biosphere integrity (freshwater) -> Biogeochemical flows

Human (reactive): Decline in freshwater biosphere integrity may motivate people to reduce nutrient use. However there has been little change in global nitrogen use efficiency over the last 40 years (Lassaletta et al. 2016).

Biosphere integrity (freshwater) -> Ocean acidification

Biophysical: Increased productivity due to moderate levels of increased eutrophication could lead to increased CO_2-eq greenhouse gas emissions of 1 PgC/year, of which CO_2 contributes around 20% (DelSontro, Beaulieu, and Downing 2018). Compared to current fossil fuel and cement carbon emissions of 9.5 PgC/year (Ciais et al. 2013), these emissions would accelerate ocean acidification by $\Delta y = y$*(1*20%/9.5) = 2.0*(1*20%/9.5) = 0.042. Following the reasoning outlined in *Biosphere integrity (freshwater) -> Climate change*, this leads to an interaction strength s = 0.04/1.2 = 0.035, which we round to 0.04.*Biosphere integrity (ocean) -> Climate change*

Biophysical: The marine biological pump is responsible for sequestering around 13 PgC/yr from the upper ocean mixed layer into the deep ocean (Ciais et al. 2013). Changes in ocean biodiversity, triggered by temperature changes or ocean acidification, may lead to reduction in the efficiency of the biological pump (Beaugrand, Edwards, and Legendre 2010; Segschneider and Bendtsen 2013; Riebesell et al. 2017; Bindoff et al. 2019). Since biosphere integrity is not well quantified for the ocean (Nash et al. 2017), we estimate this link indirectly as follows, considering both acidification and temperature mechanisms. For acidification effects, we use the experimental sedimentation rate results of Riebesell et al. (2017) to estimate that ocean acidification weakens the biological pump by 0.019%/μatm per μatm change in partial pressure of CO_2. A change in the climate change planetary boundary from pre-industrial to the boundary value (70 ppm, $\Delta x = 1$) would therefore lead to a weakening of the biological pump of 0.019%*70 = 1.3% (assuming rapid equilibration of ocean mixed layer CO_2 relative to atmospheric CO_2) and 13*1.3% = 0.17 PgC/yr not sunk. Compared to annual emissions of 9.5 PgC/yr (Ciais et al. 2013), acidification-induced weakening of the biological pump could accelerate climate change by 0.17/9.5 = 1.8%, that is, Δy = 2.0*1.8% = 0.036 in normalised units. This leads to an interaction strength for the full feedback *Climate change -> Ocean acidification -> Biosphere integrity (ocean) -> Climate change* of 0.036 using Eq. (2). We are only interested in the last link, so we divide the total link by the other two estimated elsewhere in this article, giving an interaction strength 0.036/(1*0.4) = 0.09. For the temperature effect, we use the decreased atmosphere to ocean flux predicted by Segschneider and Bendtsen (2013) of 0.2 PgC/year by 2100 under RCP8.5 in addition to reductions caused by already identified climate-carbon cycle feedbacks. Compared to annual emissions of 9.5 PgC/yr, we attribute an additional 0.2/9.5 = 2.1% to climate change, a change of Δy = 2.0*2.1% = 0.042 in normalised units. This scenario involves a change in CO_2 concentrations of ΔX = (489.4 - 280) ppm = 209.4 ppm (Riahi, Grübler, and Nakicenovic 2007; data taken from https://tntcat.iiasa.ac.at/RcpDb) from pre-industrial conditions, or Δx = 3.0 using Eq. (1). Using Eq. (2), the additional carbon feedback via temperature change therefore leads to an interaction strength for the feedback *Climate change -> Biosphere integrity (ocean) -> Climate change* of 0.014. Since we are only interested in the last link, we divide by the interaction strength *Climate change -> Biosphere integrity (ocean)* estimated above, giving an interaction strength 0.014/0.22 = 0.06. We sum the results for the temperature-mediated and the acidification-mediated interactions to obtain a total interaction strength 0.09 + 0.06 = 0.15 for *Biosphere integrity (ocean) -> Climate change*.

Human (reactive): Decreases in ocean biosphere integrity may lead to more energy intensive fishing, leading to increased fuel consumption. Emissions from fishing vessels at 174 million tonnes CO_2-eq per year, while large, are however a small fraction (0.5%) of total global emissions. Changes in these emissions due to behavioural changes may be less than 0.1% of global emissions. We therefore do not include this interaction in our estimates.

Biosphere integrity (ocean) -> Land system change

Human (reactive): A hypothetical shift in ocean biosphere integrity from pre-industrial to the planetary boundary ($\Delta x = 1$) would imply possible collapse of global fisheries. We speculate that collapse of fisheries could lead to a shift to increased land agriculture to compensate for lost protein. Fisheries contribute currently 6.7% of global protein consumption, and about half the global fishery catch comes from marine capture fisheries (FAO 2016b). Agriculture is responsible for 80% of the impact on the land use change planetary boundary (Campbell et al. 2017). In developing countries, which are generally those more reliant on fisheries, elasticity of land supply ranges from 0.3 to 1 (Tabeau, Helming, and Philippidis 2017); we choose an intermediate value 0.5. Demand for new agriculture to replace lost fish protein would increase land use change Δy = 80%*6.7%*1.5/2*0.5 = 0.02 (full range 0.01 to 0.04). Using Eq. (2), s = 0.02 (full range 0.01 to 0.04). This increased agricultural activity will flow on to *Biogeochemical flows* and *Freshwater use* by via the parallel links from *Land-system change* as described below.

Biosphere integrity (ocean) -> Ocean acidification

Biophysical: As described in the *Biosphere integrity (ocean) -> Climate change* link, slowing of the marine biological pump due to ocean acidification and warming could lead to an acceleration of atmospheric carbon concentration with a combined interaction strength of 0.15. Loss of the sink capacity of the marine biological pump will also feed back on ocean acidification. Following through the computation in *Biosphere integrity (ocean) -> Climate change*, the only figure that changes is the current level of climate change, which we need to replace by the current level of ocean acidification for the present link. This replacement re-scales the interaction strength to s = 0.15*0.8/2.0 = 0.06.

1.3 Impacts of land system change

Land system change -> Climate change

Biophysical: We consider effects of land system change on climate change via both carbon emissions and changes in surface properties. Land use change has contributed (180 ± 60) PgC out of total (610 ± 60) PgC anthropogenic carbon emissions since 1870 (Le Quéré et al. 2018). Setting $\Delta x = x = 1.5$ and $\Delta y = y$*(180/610) = 2.0*(180/610) = 0.59, Eq. (2) gives $s = 0.39$. Biogeophysical effects of land use change (such as changes in albedo) have reduced effective radiative forcing by $\Delta Y = -0.4$ W m^{-2} (Andrews et al. 2017). This is equivalent to $\Delta y = -0.4$ in normalised units. Setting $\Delta x = x = 1.5$, Eq. (2) gives $s = -0.27$. We add the effects of these two mechanisms, giving an overall interaction strength 0.39 – 0.27 = 0.13. The recently released IPCC Special Report on Climate Change and Land (Jia et al. 2019) estimates that anthropogenic land cover change has contributed 0.078 ± 0.093°C due to biogeochemical and biophysical mechanisms combined. Using the mid-point of this range, 0.078°C compared to current warming 0.85°C (Hartmann et al. 2013) gives a contribution to the current value of the control variable of Δy = 2.0*0.078/0.85 = 0.18. With current land-cover change Δx = 1.5 gives an interaction strength 0.18/1.5 = 0.12 by Eq. (2), in excellent agreement with our estimate above.

Human (parallel): Land system change for agricultural purposes is generally followed by greenhouse gas emissions from agricultural activity on that land. Agriculture emits 25% of all anthropogenic greenhouse gases excluding emissions due to land clearing (Campbell et al. 2017). We therefore set $\Delta x = x = 1.5$ and Δy = y*25% = 2.0*25% = 0.5. Using Eq. (2), $s = 0.33$. On the other hand, some forest is cleared not for food production but for biofuels. The intention is that the carbon taken up by crops will compensate for emissions when the fuel is combusted. The net effect of clearing forest has been estimated to increase, not decrease, emissions (Searchinger et al. 2008; Righelato and Spracklen 2007). However the fraction of land cleared for biofuels is very difficult to estimate (Gao et al. n.d.).

Land system change -> Biosphere integrity (land)

Biophysical: Land system change has historically been the main driver of losses of biosphere integrity. Campbell (2017) found that agriculture through land use change has contributed to 80% of the change in biosphere integrity. Similarly, Alkemade et al. (2009) found land system change including the effects of forestry, agriculture, fragmentation and infrastructure contributed to 0.27/0.30 = 90% of loss of mean species abundance up until the year 2000. We set the change in biosphere integrity contributed by land use change to Δy = 80%*1.5 = 1.2 and $\Delta x = 1.5$ corresponding to current land use change. Using Eq. (2), $s = 0.80$.

Land system change -> Biosphere integrity (freshwater)

Biophysical: Land system change leads to decreased water quality through sedimentation, altered flows, anthropogenic pesticides, etc. In one recent Amazon study, regression analysis shows that reduction from 60% to 0% forest cover in the immediate vicinity of the river ($\Delta X = -60\%$, or $\Delta x = 2.4$) reduces multispecies fishery CPUE (catch per unit effort) by half (Castello et al. 2018). Let us assume that halving of CPUE corresponds to reducing freshwater biosphere integrity to its boundary value ($\Delta y = 1$). Using Eq. (2) gives s = 0.42. Castello et al., however, only analysed the effect of forest clearing close to the river. Distant forest clearing presumably affects freshwater biosphere integrity less; we therefore reduce the strength of this interaction by an additional factor of 5. We therefore set the interaction strength to 0.42/5 = 0.08. This result is consistent with the analysis of Feld et al. (2016), who found that land use has much less effect than geo-climactic factors in freshwater biodiversity in Europe. On the other hand, near-complete land clearing can lead to widespread extinctions of freshwater fish, amphibians and crustaceans (Brook, Sodhi, and Ng 2003). We therefore anticipate may be highly nonlinear; we retain the above estimate for small degrees of land-system change within the safe operating space, but expect large land-system change may lead to more than proportionate changes in freshwater biosphere integrity. This estimation is highly speculative and would benefit from further research.

Land system change -> Biogeochemical flows

Human (parallel): Nutrient use on croplands is frequently preceded by clearing that land from forest (Foley et al. 2005). At present, $\Delta x = 1.5$ (Table S1) of forest has been cleared. Agriculture is responsible for around 85% of current nutrient use (Campbell et al. 2017); we therefore set $\Delta y = 85\% * y = 85\% * 2.3 = 2.0$). Using Eq. (2), $s = 1.3$.

Land system change -> Ocean acidification

Land cover change has contributed (180 ± 60) PgC out of total (610 ± 60) PgC anthropogenic carbon emissions since 1870 (Le Quéré et al. 2018). These emissions contribute to ocean acidification. Setting $\Delta x = x = 1.5$ to correspond to historical levels of land cover change and $\Delta y = y*(180/610) = 0.8*(180/610) = 0.24$ to correspond to the degree of ocean acidification this has contributed, Eq. (2) then gives $s = 0.16$.

Land system change -> Freshwater use

Biophysical: Sterling, Ducharne, and Polcher (2013) found that historical land system change ($\Delta x = 1.5$, Table S1) has led to an increase in runoff of approximately 1900 $\text{km}^3\ \text{yr}^{-1}$. Rost, Gerten and Heyder (2008) found that historical land use change has increased river discharge by 6.6%; at 12,500 km^3/yr historically accessible for human use (Rockström et al. 2009; Postel 1998) this increases accessible freshwater by 6.6%*12500 = 825 $\text{km}^3\ \text{yr}^{-1}$. We take the average of these two estimates, 1362.5 $\text{km}^3\ \text{yr}^{-1}$ (full range 825 to 1900 $\text{km}^3\ \text{yr}^{-1}$). This increase in runoff increases (in the global aggregate) the safe level of human extraction from freshwater systems. Using $Y_{\text{PB}} = 4000\ \text{km}^3\ \text{yr}^{-1}$ and $Y'_{\text{PB}} = (4000 + 1362.5)\ \text{km}^3\ \text{yr}^{-1} = 5362.5\ \text{km}^3\ \text{yr}^{-1}$, Eq. (5) gives $s = -0.11$ (full range -0.07 to -0.14). Since part of the additional water may be inaccessible due to high flow or remote regions, this value may be an overestimate.

Human (parallel): Clearing of land for agriculture has come with increased global freshwater consumption for irrigation. At present, $\Delta x = 1.5$ of land has been cleared (Table S1). Agriculture is responsible for 84% of current freshwater consumption (Campbell et al. 2017), so $\Delta y = 84\% * y = 84\% * 0.65 = 0.55$. Using Eq. (2), $s = 0.36$.

Land system change -> Aerosol loading

Biophysical: Forest fires associated with land clearing emit large quantities of aerosols (Boucher et al. 2013; Munroe et al. 2008) and agricultural land emits increased levels of aerosols (Chen et al. 2019). However we were unable to estimate the proportion of aerosol emissions that can be attributed to land clearing.

Land system change -> Stratospheric ozone depletion

Biophysical: Increasing land surface albedo due to land system change leads to increased UV radiation at the Earth's surface due to scattering of UV photons that have been reflected, thereby decreasing the safe level of ozone depletion (EEAP 2019). We do not have data to estimate the strength of this interaction.

1.4 Impacts of changes in biogeochemical flows

Biogeochemical flows -> Climate change

Biophysical: Nutrient use in agriculture leads to emission of nitrous oxides that contribute to climate change, but also leads to increased carbon uptake directly through N fertilisation and in non-agricultural soils by ammonia deposition. Nutrient application on land also runs off to stimulate productivity and carbon uptake in freshwater and marine ecosystems (see *Biogeochemical flows -> Ocean acidification* below). The net effect on terrestrial, freshwater and marine ecosystems of current nutrient application (Δx = 2.3, Table S1) is estimated to be greenhouse gas emissions equivalent to approximately 0.41 PgC/yr (De Vries et al. 2016). Compared to annual emissions equivalent to 9.5 PgC/yr, we attribute 0.41/9.5 = 4.3% of current climate change to nutrient use (Δy = 4.3% * y = 4.3% * 2 = 0.086). Using Eq. (2), s = 0.04.

Human (parallel): Current nutrient production (Δx = 2.3, Table S1) uses about 1.2% of global energy consumption (Bernstein et al. 2007). Global energy consumption is in turn about half of total fossil fuel emissions (FAO 2016a). We therefore attribute approximately 1.2%/2 = 0.6% of current climate change (Δy = 0.6%*y = 0.6%*2.0 = 0.012) to energy use by global nutrient production. Using Eq. (2), s = 0.005.

Biogeochemical flows -> Biosphere integrity (land)

Biophysical: Moderate nutrient application improves land productivity, but excessive nutrient application can degrade farmland, for example via soil acidification (Guo et al. 2010), eutrophication, and simplification of ecosystems. On agricultural farmland, the net effect of these mechanisms is difficult to currently estimate. On non-agricultural farmland, nitrogen application has been estimated to have contributed to 0.01/0.3 = 3% of decreases in Mean Species Abundance (MSY) as of the year 2000 (Alkemade et al. 2009). We set Δy = 3%*y = 3%*1.5 = 0.045 (normalised units) and use Δx = 2.3 corresponding to current levels of nutrient application (Table S1). Using Eq. (2), s = 0.02.

Biogeochemical flows -> Biosphere integrity (freshwater)

Biophysical: Nutrient runoff from agricultural application leads to algal blooms, dead zones, loss of fish species, and other degradation of freshwater ecosystems. The nitrogen planetary boundary is currently set at a level according to the safe level of impact on freshwater systems (Steffen et al. 2015). The regional-scale phosphorus use boundary was also recently set based on its impact on freshwater ecosystems (Steffen et al. 2015). Since moving biogeochemical flows from pre-industrial to the planetary boundary (Δx = 1 by definition) causes the freshwater biosphere integrity planetary boundary to be reached ($\Delta y = 1$ by definition), we set $s = 1$ by Eq. (2).

Biogeochemical flows -> Biosphere integrity (ocean)

Biophysical: The phosphorus use boundary was originally defined at 11 Tg P/yr flow from freshwater systems into the ocean as the threshold at which large-scale ocean hypoxic events may begin to occur (Rockström et al. 2009), which would indicate an interaction strength of 1 by the same argument as for *Biogeochemical flows -> Biosphere integrity (freshwater)*. Rockström et al. (2009) acknowledged however that the appropriate location of this boundary is however highly uncertain. A large-scale ocean hypoxic event is not currently underway and may not occur for another 1000 years at current rates of phosphorus use (Rockström et al. 2009), despite global phosphorus flows into the ocean at ~22 Tg P/yr (Steffen et al. 2015) being well over the planetary boundary. We therefore downgrade the interaction strength by a factor of 20 to account for a policy-relevant 50-year time scale, setting $s = 1/20 = 0.05$.

Biogeochemical flows -> Land system change

Human (reactive): Erisman et al. (2008) estimated that artificial fertilisers are responsible for feeding 48% of the world’s population. At current population levels with current food production practices, land system change would therefore have to be almost doubled to feed the same population if use of artificial fertiliser were ceased. In this hypothetical situation, however, more expensive food may mean that the global population would not have grown as quickly, reducing demand for land and reducing land system change. More expensive production may also reduce the attractiveness of land clearing for agriculture. We judge there is insufficient data to estimate the strength of this interaction.

Biogeochemical flows -> Ocean acidification

Biophysical: Current nutrient use ($\Delta x = 2.3$) in agriculture leads to increased carbon uptake through fertilisation of terrestrial, freshwater and marine ecosystems of approximately 1.02 PgC/yr but N-induced O_3 exposure reduces CO_2 uptake by 0.14 PgC/yr giving a net uptake of 0.88 PgC/yr (De Vries et al. 2016). Compared to annual fossil fuel and cement carbon emissions equivalent to 9.5 PgC/yr, nutrient application has therefore slowed ocean acidification by $\Delta y = 0.8*(-0.88/9.5) = -0.074$. Using Eq. (2), $s = -0.03$.

Eutrophication in coastal waters from increased nutrient runoff can produce carbon dioxide due to increased biological activity and thereby increase ocean acidification (Cai et al. 2011; Wallace et al. 2014). We do not have data available to globally estimate the strength of this interaction. We expect however the interaction to be positive in sign and therefore potentially counteract the negative interaction contributed by terrestrial productivity.*Biogeochemical flows -> Aerosol loading*

Biophysical: Increased nutrient input levels cause elevated NH_3 emissions (and also slightly higher NO_x emissions), which and lead to an increase in particulate matter (PM) due to the formation of ammonium nitrate and ammonium sulphate aerosols in the atmosphere, causing impacts on health. The contribution of ammonia emissions to the formation of secondary inorganic aerosols (SIA) generally represents 10–20% of fine particle mass in densely populated areas in Europe, and higher in areas with intensive livestock farming (Hendriks et al. 2013). A recent study showed that a relatively strong reduction in PM2.5 levels can be achieved by decreasing agricultural ammonia emissions (Pozzer et al. 2017). The study showed that a 50% reduction of agricultural emissions could reduce prevent the mortality attributable to air pollution by 30, 19, 8 and 3% over North America, Europe, East and South Asia, respectively, which could imply related reductions in PM2.5 concentrations. We assume that current levels of biogeochemical flows (Δx= 2.3) contribute an intermediate value of 15% (full range 0 to 30) of changes in aerosol levels since pre-industrial. We therefore set $\Delta y = 15\% \times y = 15\% \times 1.6 = 0.18$. Using Eq. (2), $s = 0.10$ (full range 0 to 0.20).

Biogeochemical flows -> Stratospheric ozone depletion

Biophysical: Nitrous oxide (N_2O) is currently the most significant anthropogenic ozone-depleting substance being emitted (Ravishankara, Daniel, and Portmann 2009). According to one model, it was responsible for a change in global mean ozone of -1.18 DU in 2000 (Portmann, Daniel, and Ravishankara 2012). Following the same calculation as for *Climate change -> Stratospheric ozone depletion*, we scale this figure to 0.44*(-1.18/-13.35) = 0.039. The dominant source of anthropogenic N_2O is soils and is mainly associated with application of nitrogen fertilisers (Campbell et al. 2017). Estimates of the precise contribution of agricultural activity include 66-90% and 49-83%; the mean of the midranges of these estimates is 72%. We therefore attribute $\Delta y = 0.039 * 72\% = 0.028$ ozone depletion to current biogeochemical flows $\Delta x = 2.3$. Using Eq. (2), $s = 0.012$.

1.5 Impacts of ocean acidification, freshwater use, aerosol loading and stratospheric ozone depletion

Ocean acidification -> Climate change

Ocean acidification will decrease the capacity of marine organisms to form carbonate shells, which in turn will allow the ocean to absorb more carbon dioxide (Barker, Higgins, and Elderfield 2003). This feedback contributed up to 3.2 PgC/118 PgC = 2.7% of anthropogenic marine carbon in 1994, and may increase the marine carbon sink by 4-13% by the year 3000 (Ridgwell et al. 2007). Taking an intermediate value of 4%, we set the contribution to current climate change at $\Delta y = -4\% * y = -4\% * 2.0 = -0.08$ from current ocean acidification $\Delta x = 0.8$. Using Eq. (2), $s = 0.10$.

Ocean acidification -> Biosphere integrity (ocean)

Biophysical: The ocean acidification boundary value ($\Delta x = 1$) is set to the level that will cause severe degradation of marine ecosystems ($\Delta y = 1$) such as the depletion of aragonite-forming organisms (Rockström et al. 2009). Using Eq. (2), we therefore set the interaction strength to s = 1.

Freshwater use -> Climate change

Biophysical: Freshwater systems play a significant role in the global carbon cycle (Raymond et al. 2013). How the freshwater carbon cycle is affected by changing river flows is however highly uncertain (Biddanda 2017), so we do not estimate a value here.

Human (parallel): Current freshwater use ($\Delta x = 0.65$, Table S1) led to energy consumption of approximately 120 Mtoe (million tonnes of oil equivalent) in 2014 (Kęsicki and Walton 2016). Using an energy intensity depending on energy source of around 0.25 kg CO_2/kWh, freshwater consumption led to carbon emissions of around 120 Mtoe $\times$ 0.25 kgCO_2/kWh $\times$ 1.163×10^{10} kWh/Mtoe $\times$ 12/44 kgC/kgCO_2 =0.095 PgC per year. We subtract from this consumption the 0.041 PgC/yr identified in the human link *Biosphere integrity (freshwater) -> Climate change* to avoid double counting of emissions, leaving 0.054 PgC/yr. Compared to annual emissions of 9.5 PgC/yr (Ciais et al. 2013), we therefore attribute 0.054/9.5 = 0.6% of climate change to freshwater use, that is, $\Delta y = 0.6\% * y = 0.6\% * 2.0 = 0.02$. Using Eq. (2), $s = 0.018$.

Freshwater use -> Biosphere integrity (land)

Biophysical: Use of freshwater could drain aquifers and reduce river flow and therefore decrease productivity and lead to salinisation on agricultural and non-agricultural lands (Alaghmand, Beecham, and Hassanli 2013; Kath et al. 2015; Verones et al. 2017; Pfautsch et al. 2015). We lack data to quantify this relationship, however.

Human (reactive): Declining freshwater availability may lead to human responses that damage terrestrial ecosystems, such as the construction of dams that inundate forests (Warren 2011). We do not have data available to estimate the strength of this interaction.

Freshwater use -> Biosphere integrity (freshwater)

Biophysical: Flow regimes are a major driver of river ecosystems (Bunn and Arthington 2002). The freshwater use boundary value ($\Delta x = 1$) is set to the value that will cause critical degradation of freshwater systems ($\Delta y = 1$). Using Eq. (2), we therefore set the interaction strength to $s = 1$.

Human (reactive): Declining freshwater availability may lead to human responses such that damage terrestrial ecosystems such as the construction of dams that impact the functioning of freshwater ecosystems (Warren 2011). We do not have data available to estimate the strength of this interaction.

Freshwater use -> Biosphere integrity (ocean)

Biophysical: Changing freshwater flows can impact coastal ecosystems in complicated ways. For example, reductions in flows could lead to more, the same, or fewer fish landings (Gillson 2011). We are unable to estimate a globally aggregated strength of this interaction.*Aerosol loading -> Climate change*

Biophysical: Current levels of aerosol loading ($\Delta x = 1.6$, Table S1) has led to a change in radiative forcing of -0.9 W m^{-2} since pre-industrial (Boucher et al. 2013), that is, $\Delta y = -0.9 \text{ W m}^{-2} / 1 \text{ W m}^{-2} = -0.9$. Using Eq. (2), $s = -0.56$.

Human (reactive): Human concern about air pollution could lead to reductions in polluting activities that also reduce greenhouse gas emissions, as for example is happening in China (Burck, Marten, and Bals 2013). We have not been able, however, to estimate the strength of the effect.

Aerosol loading -> Biosphere integrity (land)

Biophysical: Changed aerosol levels could have a range of impacts on terrestrial ecosystems, including modifying incoming radiation and thereby photosynthetic activity, contributing an additional source of nutrients and acidification of precipitation (Boucher 2015). We have not been able to quantify these effects.

Aerosol loading -> Biosphere integrity (ocean)

Biophysical: Changed aerosol levels could also affect marine ecosystems, primarily through nutrient inputs, but also through modification of incoming radiation (Boucher 2015). We have not been able to quantify these effects.

Aerosol loading -> Freshwater use

Biophysical: Current levels of anthropogenic aerosol loading ($\Delta x = -1.6$, Table S1) under different estimates have decreased global precipitation by 2.0-4.6% (Samset et al. 2018) or 0 to 0.13 mm/day, equivalent to 0 to 4.8% (Lohmann 2008). We assume this would lead to a corresponding fractional change in total runoff accessible for human use, historically 12,500 km^3/yr (Rockström et al. 2009; Postel 1998) and that this decrease in runoff decreases the safe level of human freshwater consumption. Therefore, with Y_{PB} = 4000 km^3 yr^{-1}, Y'_{PB} = 4000 - 12500*[2.0% to 4.6%] = 3750 to 3425 km^3 yr^{-1} and Y'_{PB} = 4000 - 12500*[0% to 4.8%] = 4000 to 3400 km^3 yr^{-1} for the two estimates respectively. Using Eq. (5), we obtain normalised interaction strengths s = 0.027 to 0.068 and s = 0 to 0.072 from the two estimates, respectively. However, much of the impact of aerosols on precipitation is mediated by changes in surface temperature (Lohmann 2008). This link is already accounted for by our two biophysically-mediated interactions *Aerosol loading* → *Climate change* and *Climate change* → *Freshwater use*. This interaction pathway has strength -0.56*-0.08 = 0.045. This is close to the mid-range of our direct estimates above. We therefore judge that the *Aerosol loading* → *Freshwater use* interaction strength is already accounted for by the indirect pathway and set the strength of the direct pathway to zero.

Aerosol loading -> Stratospheric ozone depletion

Aerosols absorb UV radiation and therefore generally increase the safe level of stratospheric ozone depletion (EEAP 2019). We do not have data to estimate the strength of this interaction on the global scale. In the planetary boundaries framework, the chlorofluorocarbons and other artificial chemicals that have caused stratospheric ozone depletion are counted within the 'Novel entities' boundary (Steffen et al. 2015), which is not assessed here.

Stratospheric ozone depletion -> Climate change

Biophysical: Stratospheric ozone is a greenhouse gas; depletion of stratospheric ozone has therefore decreased radiative forcing. The decrease has been estimated at ΔY = -0.05 ± 0.10 W m^{-2} (Myhre et al. 2013) (Δy = -0.05 using Eq. (1) at the midpoint of the uncertainty range) for historical changes in ozone Δx = 0.44. Using Eq. (3), s = -0.11. Elevated UV radiation due to ozone depletion could also accelerate decomposition of terrestrial organic matter increasing carbon dioxide emissions (EEAP 2019), but we lack data to estimate the strength of this effect.

Human (parallel): The ozone-depleting substances emitted by human activity are themselves greenhouse gases. The net radiative forcing of ozone-depleting substances, including both direct effects and mediated by stratospheric ozone depletion, has been estimated as 0.18 ± 0.15 W m^{-2} (Myhre et al. 2013) (Δy = 0.18 using Eq. (1) at the midpoint of the uncertainty range) for historical changes in ozone Δx = 0.44. Using Eq. (3), gives an interaction strength 0.41. To avoid double counting, we subtract the strength of the biophysical link estimated above (which is negative), giving s = 0.52 for the direct radiative forcing of ozone-depleting substances.

Stratospheric ozone depletion -> Biosphere integrity (land, freshwater, ocean)

Biophysical: Elevated UV radiation due to widespread stratospheric ozone depletion could damage plants and animals, increase rates of decomposition, modify animal sensing and interactions and change community compositions (EEAP 2019). At the same time, moderate increases in UV radiation can have beneficial as well as detrimental impacts on plants (EEAP 2019). Since stratospheric ozone depletion has been confined to high latitudes in the southern hemisphere, relatively few terrestrial or freshwater ecosystems have experienced elevated UV radiation to date. Many southern hemisphere terrestrial ecosystems have however experienced local climate changes resulting from ozone depletion (EEAP 2019). Climate changes driven by stratospheric ozone depletion such as changes in precipitation could affect coastal ecosystems (EEAP 2019). These climate changes have led to significant effects on ecosystems in some cases. We do not have data to estimate the strength of this interaction at a globally aggregated scale, but expect the magnitude of any effect it is currently small compared to other anthropocentric drivers of ecosystem change.

Stratospheric ozone depletion -> Freshwater use

Biophysical: Changed climate patterns driven by stratospheric ozone depletion may have changed precipitation over Australia, New Zealand, and south-eastern South America (EEAP 2019), thereby changing the safe level of freshwater extraction. We do not have data to estimate the strength of this interaction. Given that this effect has led to decreases in precipitation in some areas and increases in others (EEAP 2019), the aggregate effect on global precipitation may be limited.

Stratospheric ozone depletion -> Aerosol loading

Biophysical: Elevated UV radiation due to stratospheric ozone depletion may accelerate the transformation of emitted chemicals such as hydrocarbons into more toxic secondary aerosols such as particulate matter (EEAP 2019), thereby decreasing the safe level of aerosol loading. We do not have data to estimate the strength of this interaction. Currently the strength of this effect may be small since the regions with significant aerosol pollution have experienced relatively small depletion of stratospheric ozone.

2. Policy interventions

We estimate the additional direct impacts Δd on the climate change and land system change planetary boundaries created by the following policy interventions.

2.1 Bio-energy carbon capture and storage (BECCS)

We used two BECCS scenarios from a global modelling study that cast its results in terms of planetary boundaries (Heck, Gerten, et al. 2018).

Climate change: BECCS could result in negative emissions of between -1.2 to -6.3 PgC/yr depending on socio-economic scenario and the technology used (Heck, Gerten, et al. 2018). Compared to current carbon emissions of 9.5 PgC/yr (Ciais et al. 2013), we attribute a possible future reduction in climate change of [-1.2 to -6.3]/9.5 = -13% to -66%, leading to Δd = [-13% to -66%] * x = [-13% to -66%] * 2.0 = -0.25 to -1.33 in normalised units.

Land system change: Heck et al. (2018) estimated an additional 9-10% loss of forest cover in a large-scale BECCS scenario. Since Eq. (1) is linear in X, we can use it to convert to normalised units, Δd = [-9% to -10%]/(75%-100%) = 0.36 to 0.40.

Heck, Gerten, et al. (2018) also furnish estimates of impacts on other planetary boundaries. In our model, these impacts occur due to interactions and therefore do not include them as direct impacts. The calculations below show that our model's estimates are conservative, at around half the magnitude estimated by Heck et al., likely because BECCS involves more intensive agriculture than the simple globally and historically aggregated agricultural interactions assumed in our model.

Biosphere integrity (land): Heck et al. (2018) estimated an additional 7% loss of land biosphere integrity in a large-scale BECCS scenario. Using Eq. (1), this is a change in normalised control variable of -7%/(90%-100%) = 0.7. For comparison, using our biophysically-mediated *Land-system change -> Biosphere integrity (land)* interaction gives a change in normalised control variable of [0.36 to 0.40]*0.80 = 0.29 to 0.32.

Biogeochemical flows: Heck et al. (2018) estimated additional nitrogen use due to increased agricultural activity of around 60 TgN/yr in a large-scale BECCS scenario. Using Eq. (1), this is a change in normalised control variable of 60/(62-0) = 0.97. For comparison, using our parallel human-mediated *Land-system change -> Biogeochemical flows* gives a change in normalised control variable of [0.36 to 0.4]*1.3 = 0.47 to 0.52.

Freshwater use: Heck et al. (2018) estimated an increase in freshwater use of 1167 km^3/yr in a large-scale BECCS scenario. Using Eq. (1), this is a change in normalised control variable of 1167/(4000-0) = 0.29. For comparison, using our parallel human-mediated *Land-system change -> Biogeochemical flows* gives a change in normalised control variable of 0.36*[0.36 to 0.40] = 0.13 to 0.14.

2.2 Low-meat diets

From a systematic review of dietary changes (Aleksandrowicz et al. 2016), we selected the only two studies (Tilman and Clark 2014; Davis et al. 2016) that estimated both land use and climate impacts for a global transition to vegetarian diets.

Land system change: The two studies selected from the systematic review found a 66% and 28% reduction in agricultural land use (Aleksandrowicz et al. 2016). Agriculture currently contributes 80% of global land system change (Campbell et al. 2017), therefore compared to current land use change Δd = [-66% and -28%] × 80% × x = [-66% and -28%] × 80% × 1.5 = -0.79 and -0.34.

Climate change: The same two studies selected from the systematic review found a 56% and 43% reduction in greenhouse gas emissions, respectively (Aleksandrowicz et al. 2016). Agriculture currently contributes 25% of carbon emissions (Campbell et al. 2017), therefore compared to current climate change Δd = [-56% and -43%] × 25% × x = [-56% and -43%] × 25% × 2.0 = -0.28 and -0.22.

These are the two direct impacts that we plot in Fig 5. Impacts on the other planetary boundaries are mediated by interactions in our model. Below, we show that our model's estimates of interaction-mediated impacts on other planetary boundaries are of similar magnitude to independent estimations from the literature of the effects of low-meat diets on these planetary boundaries. This result is additional evidence of the plausibility of our model.

Biogeochemical flows: Davis et al. (2016) found that a global vegetarian diet would reduce nitrogen use by approximately 5.4 kg N/year per capita, which at current global population corresponds to 27% of current global nitrogen use. This corresponds to a change in the normalised control variable of -27% × x = -27% × 2.3 = -0.62. For comparison, using our parallel human-mediated *Land-system change -> Biogeochemical flows* gives a change in normalised control variable of [-0.79 and -0.34]*1.3 = -1.03 and -0.44 for the two scenarios.

Freshwater use: Jalava et al. (2014) found that a global switch to a vegetarian diet (0% animal protein) would reduce global blue water consumption use by 14%, corresponding to a change in the normalised control variable of -14% × x = -14% × 0.65 = -0.09. For comparison, using our parallel human-mediated *Land-system change -> Freshwater use* gives a change in normalised control variable of [-0.79 and -0.34]*0.36 = -0.10 and -0.07.

3. References

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