www.sciencemag.org/cgi/content/full/science.1259855/DC1

Supplementary Materials for

Planetary boundaries: Guiding human development on a changing planet

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Published 15 January 2015 on *Science* Express
DOI: 10.1126/science.1259855

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Planetary Boundaries: Guiding human development on a changing planet

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Methods

Biogeochemical flows: phosphorus

Control variables

Ocean anoxia (global): For this component of the P boundary we retain as the control variable the inflow of P to the ocean, as compared to the natural background weathering rate.

Freshwater eutrophication (regional/croplands): Carpenter and Bennett (3) proposed three possible control variables: the flow of P from land to freshwater, the flow of P to erodible soils, and the total mass of erodible P on the continents. They computed the planetary boundary and its sensitivities to different water quality criteria and to a range of assumed flow rates of P to the sea. The water quality criterion they propose is based on a relationship (Carlson's index) that connects several metrics of water quality, including P concentration, to phytoplankton biomass (97). A water quality criterion of 160 mg m^{-3} is appropriate for rivers, while a level of 24 mg P m^{-3} avoids the eutrophication of freshwater lakes and reservoirs.

We adopt a flow rate of P to the sea consistent with the ocean anoxia boundary. We then adopt the flow of P to erodible soil as the control variable. It would arguably be more appropriate to use the flow of P from soil to the freshwater system as the control variable, as this is more directly related to eutrophication, but this component is more difficult to measure than the application of P to soils and is also less amenable to management control. However, a drawback of using P application rate to soil is that the estimated boundary is based on an assumed and constant flow rate of P to the sea. This is unlikely to be the case as erosion rates have changed dramatically since pre-historic times (98). Also, we assume here that all cropland soils are in principle "erodible" in terms of flow of P from soil to freshwater, but that actual erodibility will, in practice, vary considerably depending on the nature of the soil and the tillage practice.

Proposed boundary values

Ocean anoxia (global): We assume a relatively low natural background rate of P inflow to the ocean of about 1.1 Tg P yr^{-1}, which implies a boundary of about 1.2 to 1.3 Tg P yr^{-1}(1). However, even larger increases would have to be maintained for 10,000 years or more to double the amount of P in the oceans. Approaching a human-induced threshold for an ocean anoxic event would probably be at least 1000 years in the future at present rates of P inflow (8 or 9 Tg P yr^{-1}), and much longer at inflows of about 1.3 Tg P yr^{-1}. Given these very long timeframes, the original P boundary was set at about 10 times the natural background weathering rate, or 11 Tg P yr^{-1}, with a zone of uncertainty of 11 to 100 Tg P yr^{-1} (1).

Freshwater eutrophication (regional/croplands): Based on the Carpenter and Bennett (3) analysis, we adopt the riverine water quality criterion of 160 mg m^{-3} and a flow rate to the ocean of 9 Tg P yr^{-1}. For this water quality criterion to be appropriate, we assume that sedimentation will reduce the P concentration in lakes below the lake water quality criterion of 24 mg m^{-3}. That is, we are ***not*** proposing a lake and reservoir water quality criterion of 160 mg m^{-3}.

These parameters give a boundary of 26.2 Tg P yr^{-1} (Table A.1 in (3)). This boundary also includes the fluxes from natural and human-induced weathering, which are estimated to be 15-20 Tg P yr^{-1} (3). Subtracting these fluxes then gives a lower boundary, in terms of fertilizer-P flux to soil, of 6.2 Tg P yr^{-1} and a zone of uncertainty of 6.2-11.2 Tg P yr^{-1}. This can be converted to a uniform rate of P addition to croplands of ca. 4.1 kg ha^{-1} yr^{-1}, assuming a total global cropland area of 1494 x 10^6 ha (99). Applying the zone of uncertainty gives a range of 4.1 kg ha^{-1} yr^{-1} to 7.5 kg ha^{-1} yr^{-1} for the P addition rate (Fig S5A).

For the P planetary boundary we focus on mined P applied to soils as a fertilizer. Significant amounts of P are also applied as manure (50,100). However, we differentiate them here because manure is P recycled internally in the agricultural system, while fertilizer P represents additional P added to agricultural systems from an inert source. It is important, however, in the context of this component of the P planetary boundary to recognize that more effective recycling of manure P can reduce P runoff and will also reduce the demand for fertilizer P.

Biogeochemical flows: nitrogen

Control variable

Anthropogenic input of reactive N to the Earth System occurs through (i) the anthropogenic industrial fixation of nitrogen from atmospheric N_2 via the Haber-Bosch process; (ii) intended biological N fixation; and (iii) unintended N fixation due to the emission of nitrogen oxides (NO_x) from transport and industry (5). N fixation via the Haber-Bosch process is by far the quantitatively most important mode of the intended anthropogenic N-fixation. As suggested by De Vries et al. (5), the combined input of N from intended human fixation processes ((i) and (ii) above) is proposed as the control variable for the planetary N-boundary. The unintended N fixation is not included in the control variable.

Proposed boundary value

De Vries et al. (5) estimated individual boundaries for nitrogen fixation based on critical limits for four major environmental concerns: atmospheric NH_3 concentrations, radiative forcing by N_2O, drinking water contamination by NO_3^-, and eutrophication of aquatic ecosystems. Depending on which of the environmental concerns was being addressed, the De Vries et al. (5) calculations suggest boundaries ranging from 20 to > 130 Tg N yr^{-1}.

Applying a climatic (N_2O) constraint results in the most stringent of these estimates (20 Tg N yr^{-1}), based on a climate change boundary set at a +1 W m^{-2} change in radiative forcing (1). All of the other potential N boundaries fall in the range 62-133 Tg N yr^{-1} (5).

Assuming that this stringent climatic-based potential N boundary is addressed in the climate change boundary, we then consider eutrophication of aquatic ecosystems as the environmental concern being addressed, as for P. Also, as for P, the appropriate control variable for the N boundary is the flow of N from soil to the freshwater system, as this is directly related to the risk of eutrophication. However, again for pragmatic reasons we adopt the application rate of intentionally fixed reactive N to the agricultural system. This control variable is easier to measure and track, and is more directly amenable to policy and management interventions. On this basis, the proposed boundary is 62-82 Tg N yr^{-1}, depending on the critical N concentration used (5). We take the lower value, 62 Tg N yr^{-1}, as the boundary itself and set the zone of uncertainty at 62-82 Tg N yr^{-1}. As for P, this range can be converted to a uniform rate of N addition to croplands of 41-55 kg ha^{-1} yr^{-1}, based on the total global cropland area (99; Fig. S5B).

In their analysis of potential planetary boundaries for N, De Vries et al. (5) also considered the human needs for food production. They projected a baseline human need for N fixation for a population of nine billion people of ~50-80 Tg N yr^{-1}, with the higher number assuming current N-use efficiency in agriculture and the lower a 25% increase in N-use efficiency (5). Their results are in the same order of magnitude as a recent global model analysis by Bodirsky et al. (2014) (101), who estimated the N amount required to satisfy a given future demand for agricultural products under different assumptions regarding consumption patterns and production technology. Using a combination of dietary changes (less consumption of animal products) and mitigation actions, including increased household waste recycling, reduced losses in animal waste management, and increased efficiencies in fertilization and livestock management, they showed that food requirements can be fulfilled at an N input of 95 Tg N yr^{-1}. The analysis of De Vries et al. (5) is even lower, but assumes even more rigorous mitigation approaches. Our proposed boundary and zone of uncertainty, calculated on environmental criteria, of 62-82 Tg N yr^{-1} compares well with these “N needs” estimates.

Biogeochemical flows: linkage between phosphorus and nitrogen boundaries

Our approach to exploring the links between the P and N boundaries is based on the coupling of these elements in plant growth. The average N:P ratio in growing plant tissue is approximately 11.8:1 (55). Currently the global N:P input ratio, based on N and P fertilizer application rates and agricultural N fixation, is approximately 8.6:1 (121:14 Tg y^{-1}), based on estimates for the year 2000 (53). This is lower than the ratio of approximately 11.8:1 in growing plant tissue. We consider that an application rate of N and P in fertilizers somewhat nearer the ratio that the crop takes up would be desirable. Using this approach would require the ratio of losses of N and P to the environment via leaching and emissions to the atmosphere to be equivalent to the N:P input ratio.

Currently the global N:P loss ratio is approximately 11.2:1 (138 vs 12 Tg y^{-1}), based on estimates for the year 2000 (53), thus being close to 11.8:1.

Using the lower P boundary as the basis, the N boundary would be 6.2 x 11.8 = 73 Tg N yr^{-1}, while using the upper end of the zone of uncertainty for P would lead to 11.2 x 11.8 = 132 Tg N yr^{-1}. Conversely, using the lower and upper values of the N zone of uncertainty (62 and 82 Tg N yr^{-1}, respectively) as the basis, the P boundary would be 5.3–6.9 Tg P yr^{-1}, being near the lower range of the P boundary. Comparing the two boundary values for each of P and N shows the high level of consistency between the two approaches:

P (independent): 6.2 Tg P yr^{-1}; P (from N and N:P ratio): 5.3 Tg P yr^{-1}
N (independent): 62 Tg N yr^{-1}; N (from P and N:P ratio): 73 Tg N yr^{-1}

The differences in these values are likely to be non-significant given the level of precision of the data available for the calculations.

We realize that use of an N:P ratio of 11.8 for the N to P inputs based on crop uptake could potentially lead to an overloading of aquatic systems with P relative to N, since the typical aquatic N:P mass ratio is near 14. The aquatic N:P ratio represents the net outcome of input and loss processes including denitrification and sedimentation. The ratio of N and P deposited on agricultural ecosystems is, however, different from the N:P ratio in runoff that flows into freshwaters, due to differences in the behavior of N and P in soil. N storage in agriculture soils is limited to biological process (net immobilization) and, in general, the N surplus (N input minus N removal by crops) is predominantly lost to air (NH_3, N_2O, NO_x and N_2 emissions) and water. On the other hand, P storage in agriculture soils is predominantly due to physicochemical processes (adsorption) and, in general, the P surplus is predominantly accumulated in soil, while only a small fraction is lost to water. Consequently, the current ratio of N/P loading to water is near 14, whereas the input ratio is near 8 (53). In summary, even though the N:P ratio of 11.8 is below 14, it does not necessarily lead to an overloading of aquatic systems with P relative to N due to differences in N and P retention in soils and processing in aquatic ecosystems.

The current pattern of P and N addition to agricultural areas is highly uneven, with a few areas of very high rates of usage (e.g., central North America, western Europe and northern China) and large areas of very low rates of usage (Fig. S5A,B). In this context, it is important to note that De Vries et al. (5) derived the planetary N boundaries of 62-82 Tg N yr^{-1} to avoid eutrophication of surface waters by reducing present N inputs in agricultural areas where N losses currently exceed critical limits for N in surface water. Inversely, they did not elevate the N inputs in areas where current concentrations were below critical limits (mostly in remote areas with less intense agriculture). In nitrogen-poor areas, agricultural production can be increased by allowing an increase in N input while still remaining well below the critical limits for eutrophication. Including such an increase would have raised the planetary boundary calculated by De Vries et al. (5). First indicative calculations indicate that this could be as high as the N boundary derived from the upper P boundary, i.e near 132 Tg N yr^{-1}. The proposed N boundaries here are thus likely an underestimate if an optimal allocation of N (and P) can be achieved across the planet.

The current globally aggregated rates of P and N application are 14 Tg P yr^{-1} (52) and 150 Tg N yr^{-1} (100), respectively. Thus, even if complete optimal allocation of P and N can be achieved across the planet, current loadings of P and N exceed environmental limits, and thus are transgressing our proposed planetary boundaries (see Fig. 3 in main text).

Land-system change

Control variables

Global: The area of forested land that is maintained on the ice-free land surface, expressed as a percentage of the potential area of forested land in the Holocene (that is, the area of forest assuming no human land-cover change).

Biome: The area of forested land that is maintained in each of the three major forest biomes – tropical, temperate, boreal – expressed as a percentage of the potential forest area in each of these three biomes.

Proposed boundary values

Global: 75% of potential forest cover should be maintained (or approximately 47.9 million km^2 of the ice-free land surface of Earth, based on areal estimates (56)). This boundary has been constructed as a weighted aggregate of the three individual biome boundaries as described below.

Biome: The estimated boundary for each of the biomes is based on (i) the relative potential of land cover change within each biome to influence the climate system remotely, especially at the global level (102); and (ii) the potential for a threshold within each of the forest biomes in which land-cover change beyond a certain area activates self-reinforcing feedbacks that lead to land-cover change across a much larger area.

Tropical Forest: 85% of potential forest cover should be maintained (approximately 19.3 million km^2), based on the following rationale. There are well-founded arguments that a threshold of land-cover change exists that, if crossed, would trigger the widespread conversion of the Amazon Basin tropical forest to a savanna or grassland (103-106). The self-reinforcing feedback mechanism involved in the threshold is the reduction of evapotranspiration resulting from the conversion of forest to cropland or grazing land, which beyond a certain point leads to a reduction in rainfall, which triggers further conversion of forested land to savanna or grassland.

A more difficult question is where this threshold might lie. For the present, a boundary at 15% conversion of the rainforest (85% forest remaining) has been suggested, which is approximately the present amount of deforestation. There is no strong evidence that the biome-level threshold has been crossed, although there is some evidence of regional regime shifts (107-109). There is also a suggestion that in the last decade the Amazon forests have become more vulnerable to drought and wildfire (110), which could be a harbinger of conversion to drier ecosystems.

Temperate Forest: 50% of potential forest cover should be maintained (approximately 9.5 million km^2). This is a provisional boundary only, based on sensitivity studies that evaluate the influence of the world's terrestrial biomes on the global climate (56,57). Both tropical forests (changing evapotranspiration) and boreal forests (changing albedo) have strong impacts on the climate system with global teleconnections from the regional changes, while temperate forests are assessed to have only moderate influence on the global climate.

Boreal Forest: 85% of potential forest cover should be maintained (approximately 19.1 million km^2). This is also a provisional boundary, as there is no equivalent research on the boreal forest biome (as for tropical forests) exploring where thresholds might lie in terms of the fraction of forest converted before self-reinforcing feedback mechanisms are activated, such as changes in fire regimes.

Figure S6 shows the area of forest cover remaining in the world's major forest biomes compared to the potential forest cover, color-coded to show the position of the control variable (area of forest land remaining) with respect to the boundary. The results shown in Figure S6 need to be interpreted with considerable caution. The database used to define the potential area of the forest biomes and that used to estimate the area of forest remaining do not use identical definitions of various forest types or what constitutes a forest compared to a woodland. In using the ESA GlobCover 2009 database (111) to estimate current forest cover, we used the 100-40% cover category of remaining forest to define where forest was present in a given area. This category would also include some degraded or partially cleared forests as "remaining forest", as well as some plantation forests such as palm oil. This category thus probably overestimates the actual amount of original forest cover remaining. This would lead to somewhat high percentages of remaining forest and thus to an optimistic estimate of the actual position of the control variable with respect to the boundary.

Aggregating the forest remaining compared to the potential forest for all of the biomes gives a global value of 62% forest remaining. The global boundary is 75% with a zone of uncertainty between 75% and 54%. Thus, the current value transgresses the boundary but lies within the zone of uncertainty. An independent estimate of the overall status of the land-system change boundary, which includes all forests, yields a value of 68% cover remaining (58), consistent with our estimate based on major, contiguous forest biomes only.

Freshwater Use

Control Variables

Global: At the planetary scale the control variable is defined as the maximum amount of consumptive blue water use (km^3/yr)

River basin scale: The control variable is the maximum allowed amount of blue water withdrawal from a river basin defined as average % of mean monthly flow (MMF).

The river basin control variable is based on the concept of "environmental water flow", EWF (112), which is defined as the minimum amount of blue water that must remain within a river basin (as an average % of mean monthly flow) to sustain ecosystem processes and resilience of inland and coastal landscapes. Thus, the withdrawal of water from a river basin and the EWF must add up to the mean monthly flow.

Determining EWF for a hydrological regime is complex, and specific to spatial eco-hydrological conditions (113). This complexity is reflected by the proposal of over 200 methods based on hydrological, hydraulic, habitation simulation and holistic approaches to estimate EWF (63). Nevertheless, a set of generic "rules" can be defined based on key characteristics of different river basins.

EWFs are based on the characterization of the quantity, timing, duration, frequency and quality of blue water flows required to sustain freshwater, estuarine and near-shore ecosystems and the human livelihoods and well-being that depend on them (60,114). EWF includes both baseflow and stormflow, i.e., low and high flow requirements to sustain ecosystem functions in river basins (115,116). EWF thus provides a reasonable aggregate proxy on which to base sustainable water use in a river basin.

Proposed boundary values

Global: A global consumptive water use of blue water not exceeding 4000 km^3 yr^{-1} (uncertainty range 4000-6000 km^3 yr^{-1})

River basin: A maximum amount of average monthly blue water withdrawals in river basins/segments of 25% of mean monthly flow for periods of low flow (25–55%), 40% for periods of intermediate flow (40–70%) and 55% for periods of high flow (55–85%).

Methodology for estimating river basin boundary

The boundary definition of allowed blue water withdrawals at river basin scale is calculated based on the EWF requirements:

River basin water withdrawal boundary (%) =

(MMF–(EWF+0.15*MMF))/MMF*100,

where MMF is mean monthly river flow, analyzed for each river segment. The rationale for the factor of 0.15*MMF added to EWF to determine the boundary is explained below.

MMF is relatively well quantified from hydrological observations, assessments, and models (117-119). The challenge is to define EWF. Different river types and river stretches have different minimum water requirements according to their seasonal hydrographs. For example, there are differences between rivers characterized by stable flow regimes (with year-round baseflow), monsoon rivers with >80% runoff flows concentrated in a 3-4 month rainy season, and ephemeral and unpredictable rainfed rivers with long periods of low or no flow. River basins may therefore be classified according to similarity in hydrological regime (61). Despite these difficulties several hydrological methods have been advanced to estimate EWFs (120-123, reviewed by (63)).[1] We acknowledge that other methods and metrics may be used to assess the effect of human water withdrawals and flow modifications on rivers and their ecosystems, such as those used in Nilsson et al. (124) and Vörösmarty et al (125).

Pastor et al. (63) have developed the new Variable Monthly Flow (VMF) method, which we have used in calculating the basin scale planetary boundary for water. The VMF method takes into consideration the need to sustain natural variable flow regimes while it can also be aggregated and validated at basin and global scale. It classifies flow regimes into high-, intermediate- and low-flow months by taking into account intra-annual variability. It then allocates EWF as a percentage of mean monthly flow (MMF), following the natural variability of river flow. Specifically, it allocates 30% of MMF as EWF during high flow seasons (when MMF is > 80% of MAF, where MAF is mean annual flow), 45% of MMF during intermediate-flow seasons (when MMF is 40–80% of MAF), and 60% of MMF during low-flow seasons (when MMF < 40% of MAF). In extremely dry conditions (MMF < 1 $m^3 s^{-1}$) there is no EWF allocation.

Table S2 shows EWF calculated by the VMF methodology and the average maximum withdrawals (1 – EWF) that emerge from these estimates. A range of uncertainty is added to reflect the variability in EWF estimates from different EWF methodologies (as compared to the VMF method; 63). The planetary boundary level is placed at the lower end of the uncertainty range for each flow regime (low/intermediate/high), necessitating the term 0.15*MMF to be added to EWF to determine the boundary value as MMF – (EWF+0.15*MMF).

The estimate of monthly and annual EWF requirements is based on simulations of "pristine" river discharge conditions in the absence of current anthropogenic land use, irrigation and reservoir storage. Note, however, that irrigation, land use, reservoir storage

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[1] For instance, the Tessmann method allocates a percentage of mean monthly flow varying from 40% of MMF during high flow seasons to 100% of MMF during low flow seasons. The Tennant method allocates 20% of mean annual flow (MAF) during low flow seasons and 40% of MAF during high flow seasons. The Smakhtin method allocates Q90 as a base flow and an additional percentage of MAF during high flow seasons.

and reservoir operation were considered in the analysis of withdrawals in order to derive their aggregate (including possible downstream) impacts on the naturalized flow conditions. We carried out a new analysis for this paper using the dynamic global vegetation and water balance model LPJmL ((126), with an updated version of the land use patterns in (127)). The model was used to simulate river flow globally at a spatial resolution of 0.5° by 0.5° on a daily time step over the period 1981-2000 (after (63) as in (6)). The model runs were forced by the GPCC full reanalysis dataset version 5 for precipitation (128) with a synthetic number of wet days per month (129), and the CRU TS3.10 climatology for cloudiness and temperature (130). These flow volumes were translated into monthly EWFs and averaged over the 20-yr period. River basins are delineated according to the STN-30p drainage network (http://www.wsag.unh.edu/Stn-30/stn-30.html).

The range of average maximum withdrawals for different flow regimes based on EWF (from 40% at high flow to 70% at low flow) is a reflection of different eco-hydrologic characteristics of rivers. The scientific uncertainty, which is estimated at ±15% for each flow regime (Table S2), originates from an assessment of the variability in EWF estimates when applying different EWF methods (see 6,63). It is this uncertainty range (Table S2), and not the average maximum allowed withdrawal based directly on EWF itself, that determines the boundaries and zones of uncertainty in Table 1 (main text).

The LPJmL simulations applying the VMF methodology result in a global average EWF of 33% of MAF; for the –15% and +15% cases EWFs are 18% and 48% of MAF, respectively. This compares well with other EWF methodologies, where a comparison of five different methods in LPJmL resulted in a global average EWF of 25–46% of MAF, with variable flow regimes such as the Nile having lower EWFs (ranging from 12 to 48% of MAF, depending on the EWF estimation method) than stable tropical regimes such as the Amazon (ranging from 30 to 67% of MAF) (details in 63).

In order to assess the current status of (non)-transgression of EWF (i.e., the degree to which average monthly water withdrawals already exceed the allowed volumes), daily water withdrawals for irrigated agriculture (summed up to mean monthly values) were calculated using LPJmL for each 0.5° grid cell and month over the period 1981-2000 (following (126) and (131)). Domestic, manufacturing, thermoelectric and livestock water use were accounted for using data available annually for 1981–2000 from (132) and disaggregated to 20-yr monthly averages.

Figure S7 shows the results of this assessment. For each cell an annual monthly average EWF is calculated based on the three boundary definitions in Table S2, which together with the withdrawal estimates gives an annual average value of actual (non)-exceedance of allowed withdrawal as compared to EWF. Note that this figure presents the average situation for months with transgression only (see complementary analysis below). The differentiation between a safe operating space (in green), entering a danger zone (in yellow) and entering a high risk zone (in red), are defined by including the ±15 % uncertainty range for different EWF methods, as shown in Table S2 (that is, MMF – (EWF+0.15*MMF) defines the boundary for water withdrawals and MMF – (EWF-

0.15*MMF) defines the other end of the uncertainty zone).

The patterns shown in Figure S7 support an earlier analysis by Smakhtin et al. (122), who used a method based on annual flow values determined at river outlets. We stress that our results reflect the regionally and temporally variable patterns of environmental flows compared to the patterns of withdrawals, which enables us to identify fractions of a river and its basin with transgressions. Thus, our analysis demonstrates a "danger zone" or "high risk zone" only for some, yet rather extensive, parts of the Murray-Darling and Colorado basins rather than for the entire basins. We note that model uncertainties may affect results in some regions, such as in the Nile basin where macroscale hydrological models generally tend to overestimate flows (which may lead to an underestimation of transgressions). Overall though, our results correspond well with other estimates of withdrawal limits based on EWF. A recent assessment of a wide spectrum of different river basins indicate an average EWF of 37% of mean annual flow (63). An earlier study (122) indicated an EWF range of 30-50% of mean annual flow, with maximum allowed withdrawals of 50-80%.

The number of months when the various thresholds are crossed is of importance in understanding the implications of water withdrawals for ecosystems. Figure S8 displays the data according to how many months each year the water thresholds are exceeded. The upper panel corresponds to the analysis shown in Fig. S7 in the sense that it shows the duration of exceedance of the freshwater withdrawal boundary (MMF – (EWF+0.15*MMF)). The lower panel shows the combination of these features, i.e. duration (number of months) of transgression and severity of transgression, into one index. This map indicates extensive areas where transgression of the freshwater boundary occurs during more than half of the year.

A first analysis applying the river basin-scale boundary approach described above to the global level (6) shows that the proposed boundary of a maximum withdrawal of blue water (25–55% of mean monthly flow) corresponds on average to a global-level withdrawal of 2800 km^3 yr^{-1}, with an uncertainty range of 1100 – 4500 km^3 yr^{-1}. This compares fairly well with the proposed global freshwater boundary of 4000 km^3 yr^{-1} (4000–6000 km^3 yr^{-1}) but also suggests that it may be lower if estimation methods yielding high EWF values are used.

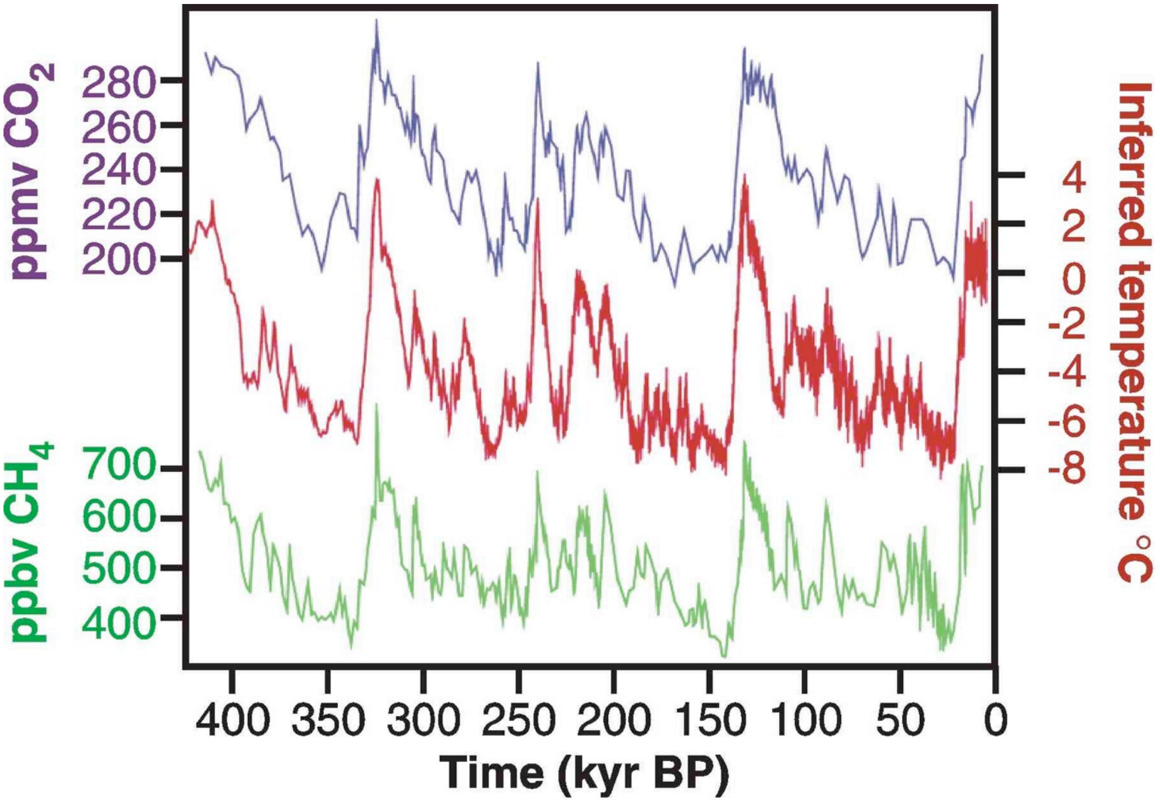

Fig. S1. The 420,000-year Vostok (Antarctica) ice core record, showing the regular pattern of atmospheric CO_2 and CH_4 concentration and inferred temperature through four glacial-interglacial cycles (16, adapted from 133). Anatomically modern humans evolved around 200,000 – 250,000 years ago (134).

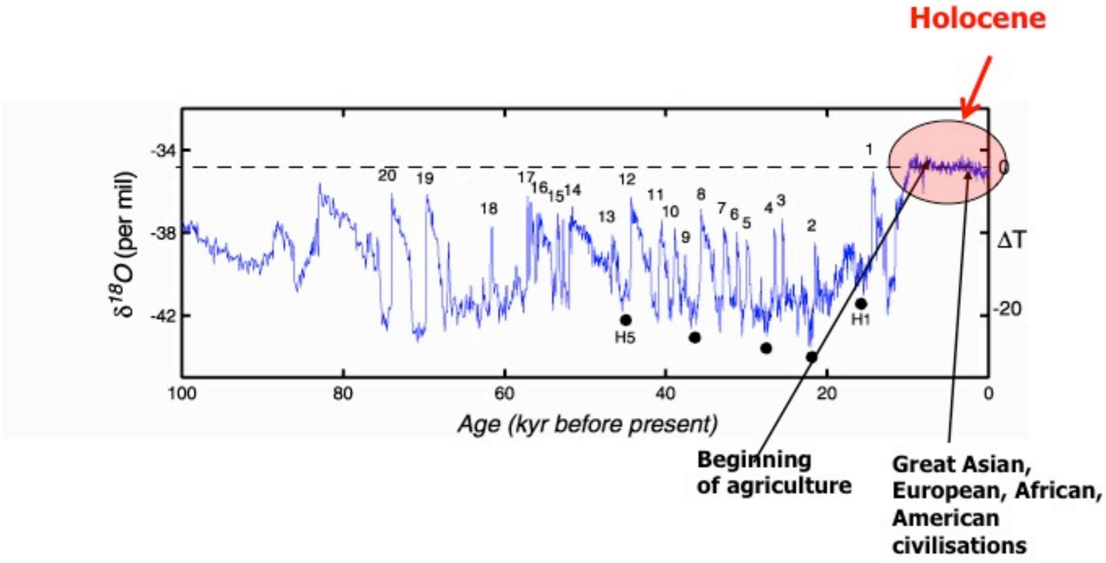

Fig. S2. Record of $\delta^{18}O$ per mil (scale on left) from the Greenland Ice Sheet Project (GRIP) ice core, a proxy for atmospheric temperature over Greenland (approximate temperature range on ^{o}C relative to Holocene average is given on the right, showing the relatively stable Holocene climate during the past ca. 10,000 years and Dansgaard-Oeschger events (numbered) during the preceding colder glacial climate (135). Note the relative stability of temperature for the last 11,700 years (the Holocene) compared to the earlier ice age period.

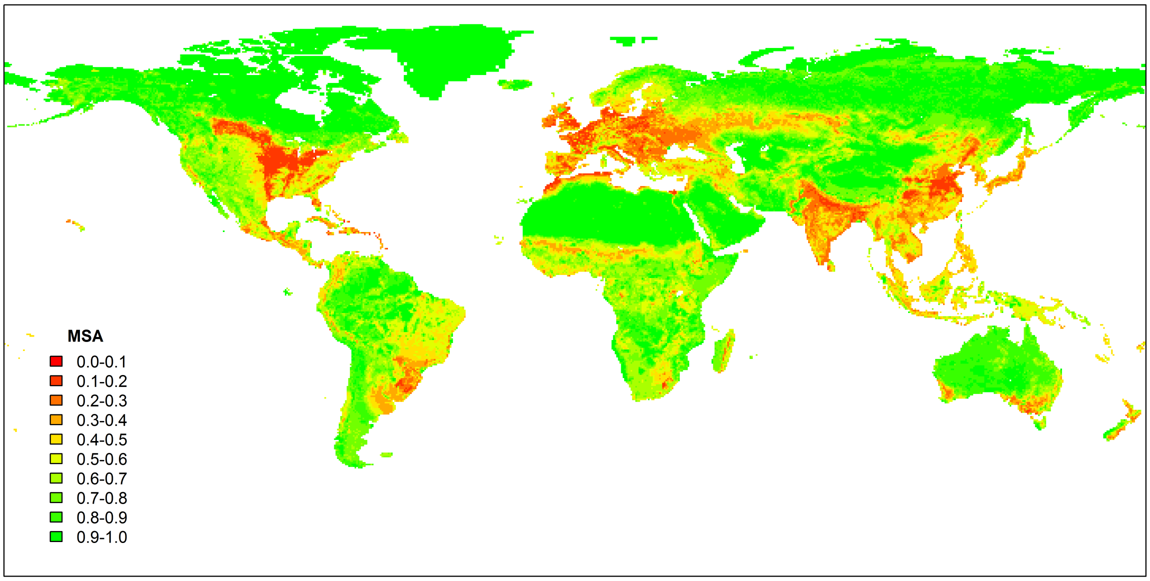

Fig. S3. The global distribution of combined relative mean species abundance of original species (MSA) as an approximation of the aggregated human pressure on the terrestrial biosphere (136).

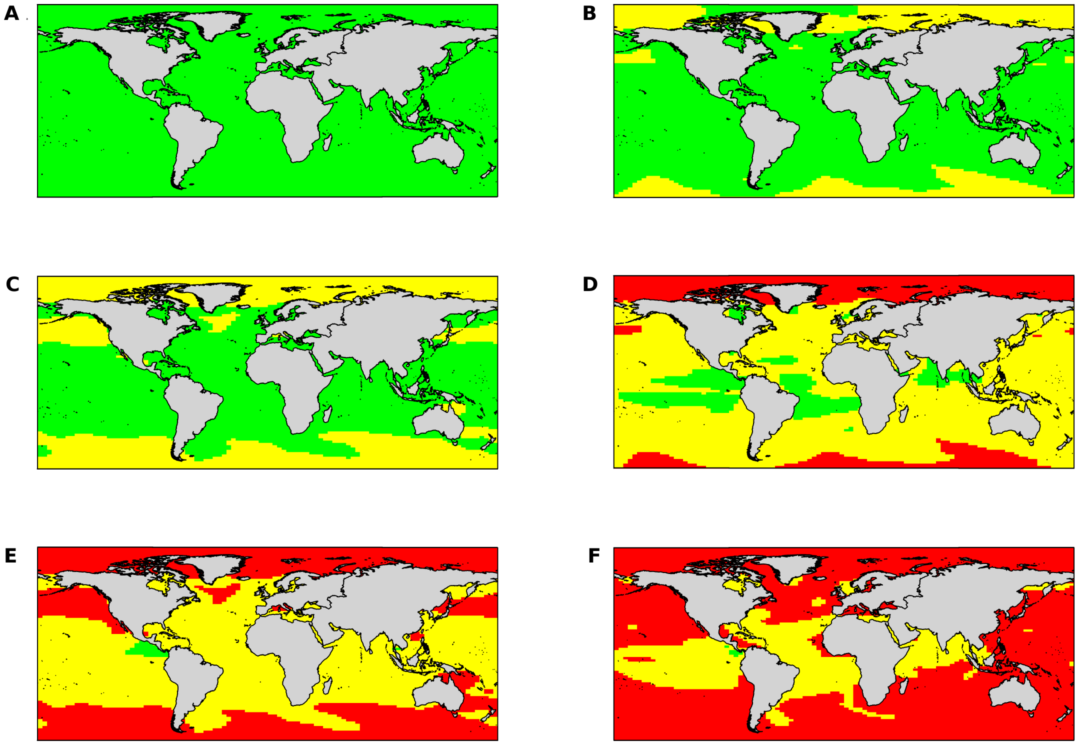

Fig. S4. The ocean acidification boundary: values of the control variable, aragonite saturation state (Ω_{arag}), under (a) 280 (pre-industrial state); (b) 380; (c) 400 (approximately current state); (d) 450; (e) 500; and (f) 550 ppm atmospheric CO_2 concentrations. Green represents regions where Ω_{arag} is below the boundary; yellow where it has transgressed the boundary but is still within the zone of uncertainty; and red where it is beyond the zone of uncertainty. Based on data from (137).

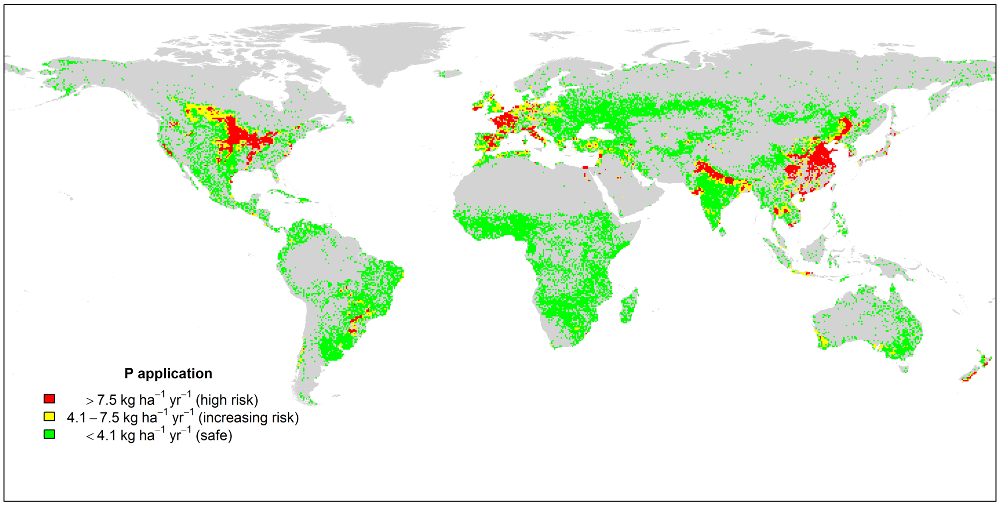

Fig. S5A. Geographical distribution of the control variable for phosphorus for the biogeochemical flows boundary, highlighting large agricultural zones where the P boundary is transgressed. The control variable is expressed as the uniform application rate of P in kg ha^{-1} yr^{-1} (see 33). Green represents regions where the application rate is below the boundary; yellow where it has transgressed the boundary but is still within the zone of uncertainty; and red where it is beyond the zone of uncertainty. Only cropland areas are color-coded; non-cropland areas are grey. Application rates of P from (138); cropland area data from (99). The down-scaled boundaries shown here are derived from the global boundary assuming a uniform rate of addition of P; local and regional pollution limits may deviate significantly from these boundaries.

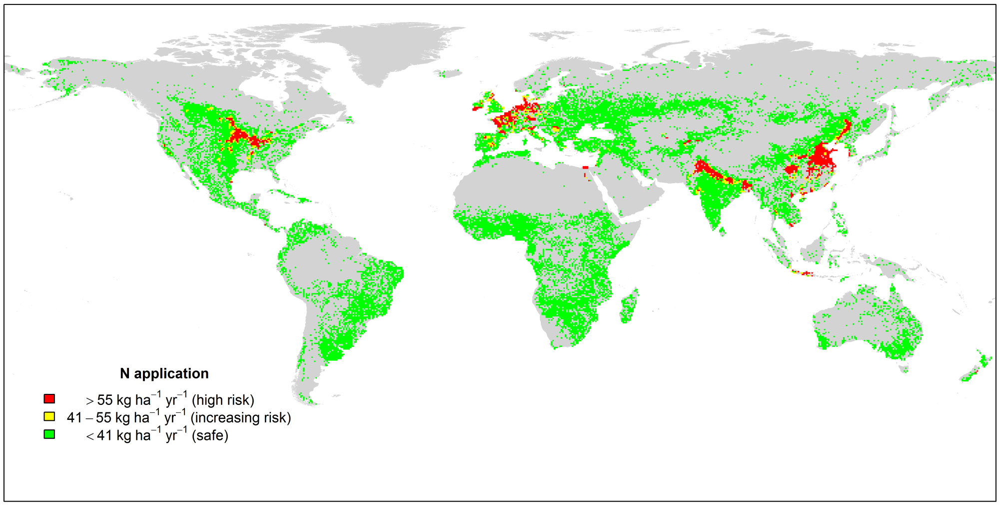

Fig. S5B. Geographical distribution of the control variable for nitrogen for the biogeochemical flows boundary, highlighting large agricultural zones where the N boundary is transgressed. The control variable is expressed as the uniform application rates of N in kg ha^{-1} yr^{-1} (see 33). Green represents regions where the application rate is below the boundary; yellow where it has transgressed the boundary but is still within the zone of uncertainty; and red where it is beyond the zone of uncertainty. Only cropland areas are colour-coded; non-cropland areas are grey. Application rates of N are from (138); cropland area data are from (99). The down-scaled boundaries shown here are derived from the global boundary assuming a uniform rate of addition of N; local and regional pollution limits may deviate significantly from these boundaries.

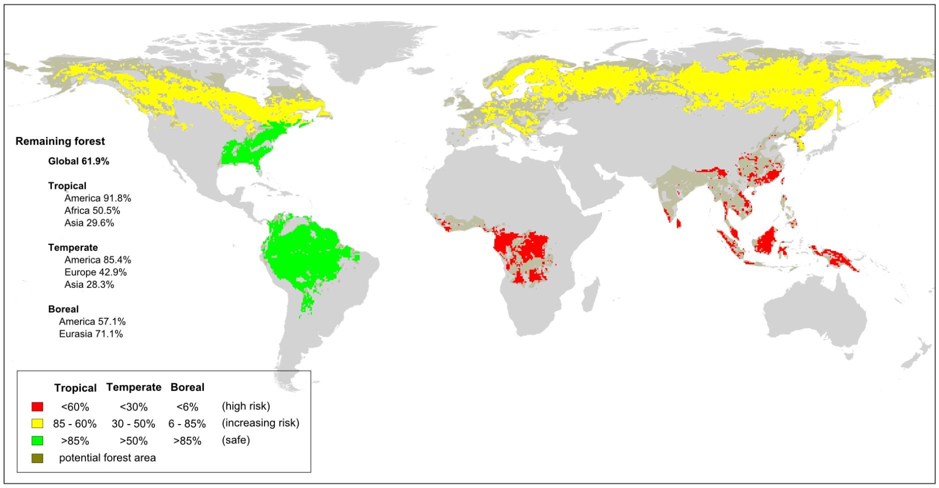

Fig. S6. Area of forest cover remaining in the world's major forest biomes compared to the potential forest cover, color-coded to show the position of the control variable (area of forest land remaining) with respect to the boundary. Areas not covered by major forest biomes are shown in grey. The lighter-colored background areas represent the area of potential forest biomes as estimated by (139). Only large, contiguous areas of forest have been used here to define the major biomes. Much smaller, isolated areas of forest (e.g., temperate forests in the northwest of the USA or along the east coast of Australia) have not been included in the analysis. The area of forest remaining in each of the biomes is represented by the deeper colors overlain on the light background. These areas have been calculated from the ESA GlobCover 2009 project database (111).

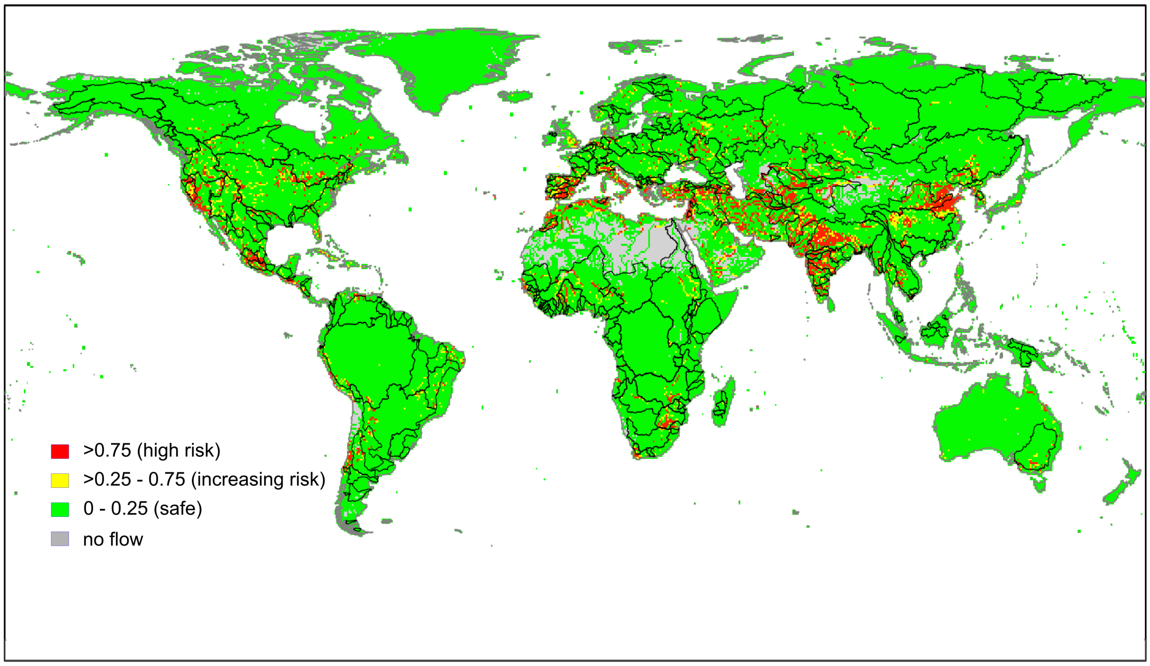

Fig. S7. Transgression of the allowed monthly water withdrawals defined by EWF, plotted as the degree of exceedance (fraction of maximum allowed level) during months that show such an exceedance. For example, green (within safe space) means that average exceedance in the respective months is still below the uncertainty range. The results are shown for all river stretches on a global 0.5° spatial grid, computed for this study with the LPJmL model based on 1981–2000 monthly averages of MMF, EWF (VMF method from (63) ± an uncertainty range to account for other methods) as well as agricultural, industrial and domestic water withdrawals (see 33). Major river basins are delineated.

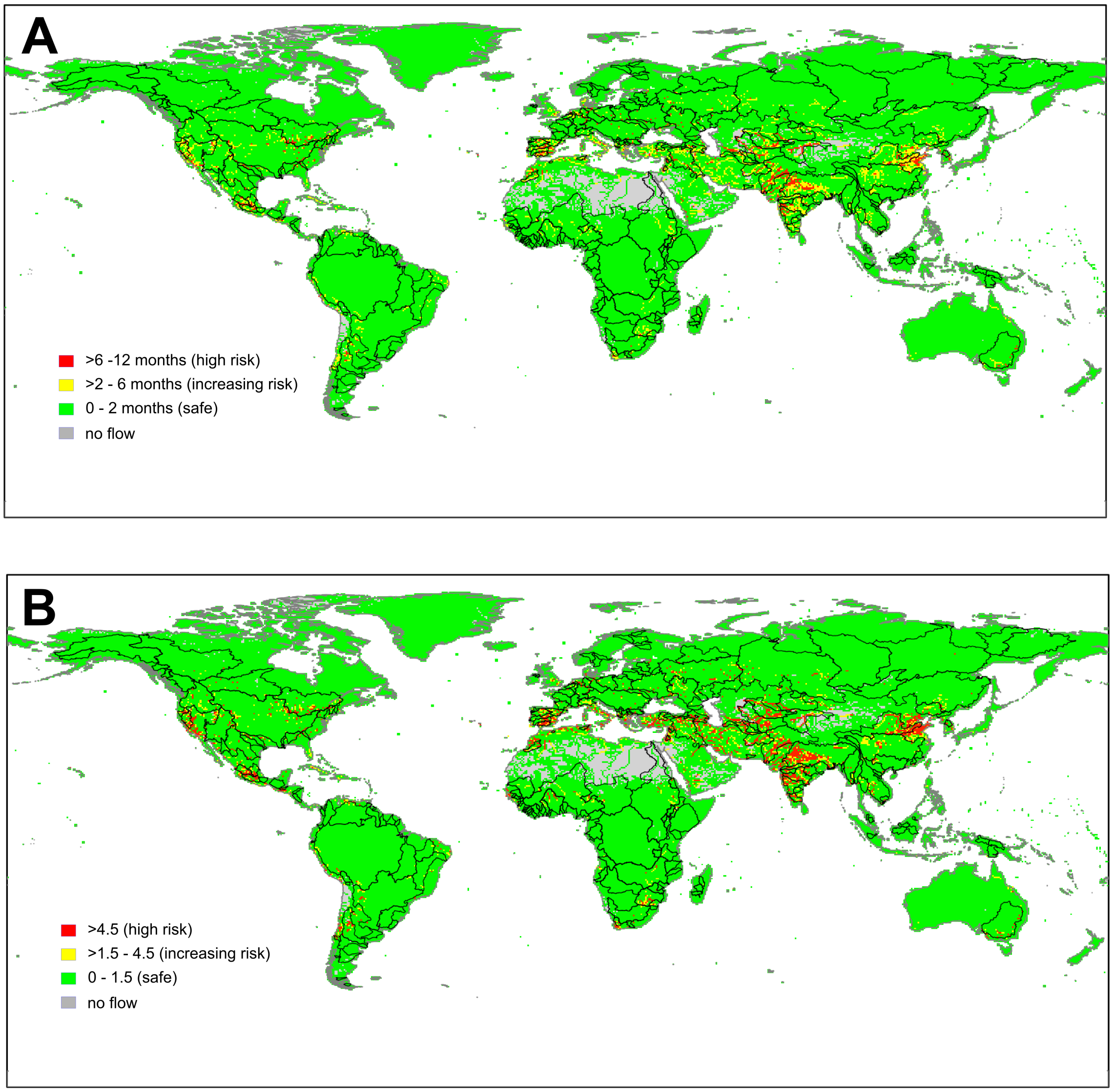

Fig. S8. Upper panel: Number of months per year with a transgression (by any degree) of allowed water withdrawals, corresponding to Figure S7. Lower panel: Risk index, defined as the product of duration and severity of transgression. EWF is estimated according to the VMF method by the method of Pastor et al. (63), here based on a different model setup and a new risk metric (see 33 for details).

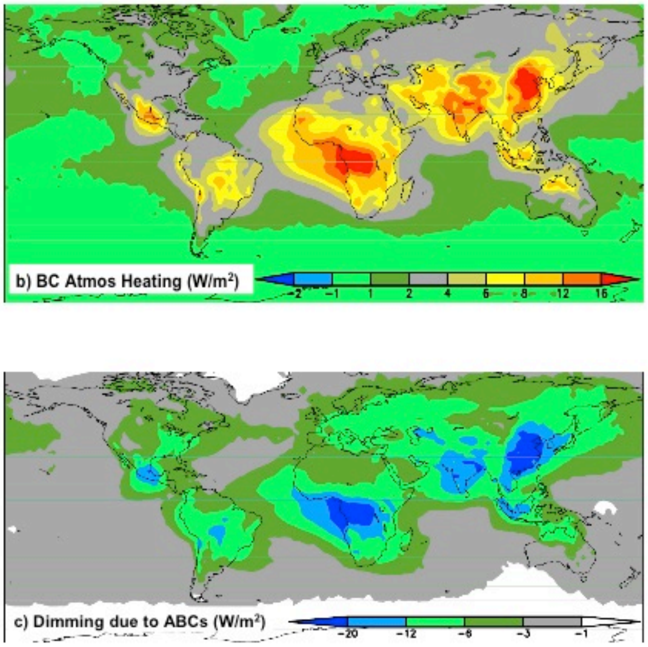

Fig. S9. Heating of the air by black and brown carbon (top panel) and dimming of the surface by all aerosols, including co-emitted aerosols (bottom panel). The impacts of human emissions of aerosols include weakening the monsoons and melting Himalayan/Tibetan glaciers. From (140).

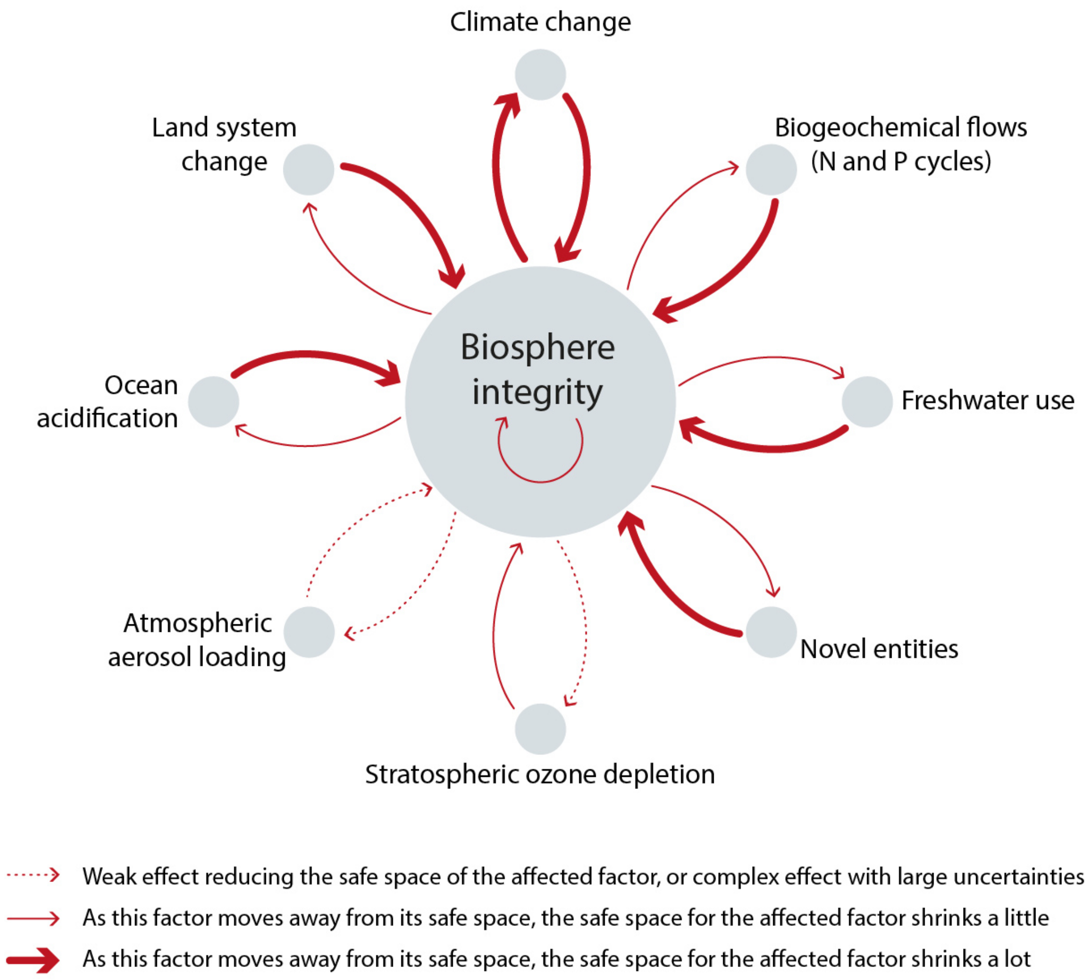

Fig. S10. The interaction between the biosphere integrity planetary boundary and other planetary boundaries. As a given factor (i.e. boundary type, such as biosphere integrity or climate change) moves further away from its own safe space, the arrows indicate changes in the factor (another boundary type). In all cases positive feedbacks exist, so a change in the factor away from the safe space will also move the affected factor away from the safe space. Thicker arrows denote stronger and more closely related effects. Thinner arrows indicate weaker and less closely related effects while dashed arrows indicate a weak and/or complex effect with large uncertainties. Adapted from (7).

Table S1: Transgression of one or more of the six of the PBs at the sub-global level would have consequences for the functioning of the Earth System at the global level (adapted from 50).

Planetary boundary	**Regional impacts with global implications if the boundary is transgressed**
Biosphere Integrity	The loss or degradation of entire biomes (e.g., coral reefs), or of the biodiversity components associated with large-scale ecological processes (e.g. predation, nutrient cycling) would have substantial impacts on regional and distant social/ecological systems (141,142). Changes in these biospheric processes could be large enough to compromise the Earth's ability to sustain human societies as we know them, especially through impacts on ecosystem goods and services, such as food production and climate regulation.
Novel entities	Chemical pollutants can damage health and disrupt ecosystem functioning over large areas which can result in global scale impacts (80,143-145), or affect abiotic processes such as the greenhouse effect (18) or stratospheric ozone chemistry (146)
Biogeochemical flows (P and N cycles)	Widespread eutrophication of freshwater bodies affects the freshwater boundary through reduced availability of water that is fit for human use, which drives further modification of the global hydrological cycle (3,5,147). Coastal eutrophication creates dead zones and harmful algae blooms that disrupt food webs and fisheries (148).
Land-system change	Deforestation of the Amazon basin has teleconnections to global climate (56,103-105,149); regional land-system change affects rainfall patterns at the continental scale (150).
Freshwater Use	Human diversion of (i) water vapor (green water) flows disrupts climate regulation (103,151) and (ii) liquid (blue) water flows induces collapse of aquatic ecosystems (152).
Atmospheric aerosols	Aerosol loading alters the hydrological cycle, radiative balance, albedo, and biosphere processes. Aerosol loading over the Indian sub-continent can trigger an abrupt shift of the Indian monsoon to a drier state, influence Asian monsoon circulation, and could also accelerate the melting of the Himalayan glaciers (67,153-157).

Table S2. Environmental water flow (EWF) requirements (% of mean monthly runoff) for different flow regimes (low flow, intermediate and high flow), and the associated maximum allowed withdrawals. The river basin-scale water boundary is placed at the lower end of the uncertainty range (marked in the table in grey cells). The average values are based on the VMF method (63), while the uncertainty range approximates the uncertainty among different EWF calculation methods. That is, for the low flow regime, for example, the uncertainty range for an EWF of 60% (45-75%) gives a range of maximum allowed withdrawals of 25-55%, an average maximum allowed withdrawal of 40%, and a boundary set at 25% (lower end of uncertainty range).

Flow Regime	**EWF**	**Maximum Allowed Withdrawal**		
		Average	Uncertainty Range	
			Low	High
Low Flow	60%	40%	25%	55%
Intermediate	45%	55%	40%	70%
High Flow	30%	70%	55%	85%

Table S3: Examples of significant interactions between both of the core boundaries – climate change and biosphere integrity – and all of the other boundaries.

Earth System process	**Interaction with Climate Change boundary**	**Interaction with Biosphere Integrity boundary**
Climate change	N/A	Many changes in ecosystem functioning at many scales from changes in temperature, rainfall patterns, extreme events and other changes in the physical climate system. Large-scale changes in the distribution and composition of biomes. Projected large increases in extinction rates of many taxa from rapid climate change. In the other direction, biospheric sinks of carbon are important in reducing radiative forcing due to human activities
Biosphere integrity (earlier "biodiversity loss")	Erosion of resilience in both terrestrial and marine ecosystems results in higher risk of climate-induced tipping points in ecosystems, and hence reducing their capacity to act as carbon sinks (e.g. loss of methane from melting permafrost)	N/A
Novel entities (earlier "chemical pollution")	CFCs and some of their replacements like HFCs are strong GHGs	Many adverse effects on organisms – e.g., toxicity, population declines, increased rate of biodiversity loss (POPs, EDCs, organometallics, radiation etc.) Flow-on effects of species alterations and loss to ecosystem functioning.
Stratospheric ozone depletion	Affects atmospheric circulation in the southern hemisphere, with consequences for storm tracks and rainfall patterns; possible implications for uptake of	Increases UV-B at Earth's surface, especially in southern high latitudes in austral spring; impacts on the functioning and composition of marine ecosystems

	CO_2 in the southern ocean; cools the surface and the stratosphere	
Ocean acidification	Weakening of marine carbon sink; increases airborne fraction of CO_2, amplifying feedback to warming	Threat to coral reefs and other calcifying organisms; likely flow-on effects up marine food chains
Biogeochemical flows: interference with P and N cycles	Atmospheric N species affect radiative forcing: N_2O is a strong, long-lived GHG; NH_3/NH_4^+ and NO_x contribute to aerosol formation, and alter hydrological cycling	Impacts on ecosystem functioning through the increase and redistribution of many important nutrients, especially N and P. Implications for biodiversity distribution on land and ocean (habitat change). The biosphere also absorbs and transforms many P and N compounds, decreasing the perturbation in flows. Eutrophication reduces positive effects of biodiversity on ecosystem stability (158)
Land-system change	Deforestation, forest degradation and agricultural practices can all emit CO_2 (and CH_4 and N_2O) to the atmosphere, amplifying warming. Conversely, forest preservation, reforestation and better agricultural practices can reduce emissions and absorb C from the atmosphere into vegetation and soils. Historically 15-20% of GHG emissions come from land system change.	Conversion of natural to human-dominated ecosystems changes functioning and, in general, leads to less resilient ecosystems. Habitat fragmentation and conversion of habitats for human use is historically the largest driver of biodiversity loss in terrestrial ecosystems. There can also be indirect effects through changes in disturbance regimes, alteration of water vapour flows at continental scales, introduction of invasive species, etc.
Freshwater use	Reduction of growth in natural ecosystems, reducing carbon sink in standing vegetation and soils. Increase in CH_4 emissions from pondages and irrigation;	Changes in functioning and species loss in river, wetland and lake ecosystems through diversion of water for human use. This lead to losses in regulating and other

	decrease in carbon transport from land to ocean via rivers.	ecosystem services, such as buffering during extreme events.
Atmospheric aerosol loading	Affects radiative forcing in complex ways (mainly cooling, but black and brown carbon cause warming). Alters tropical atmospheric circulation. Also affects precipitation amounts (e.g., cooling aerosols reduce global precipitation) and patterns, and hence land C sink strengths. Black and brown carbon deposited on snow and ice cause melting of glaciers and sea ice	All aerosols, natural and anthropogenic, cause surface dimming and thus slow the hydrological cycle. Acidic aerosols (sulfate, nitrate) can damage freshwater ecosystems and soil biota. Heavy smoke from excessive biomass burning and other combustion can be harmful and toxic to plants and animals; Dust loadings alter the distribution of nutrients and light availability, affecting primary production. The biosphere can also remove many aerosols from the atmosphere

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