Article

Keeping the global consumption within the planetary boundaries

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The disparity in environmental impacts across different countries has been widely acknowledged[1,2]. However, ascertaining the specific responsibility within the complex interactions of economies and consumption groups remains a challenging endeavour[3–5]. Here, using an expenditure database that includes up to 201 consumption groups across 168 countries, we investigate the distribution of 6 environmental footprint indicators and assess the impact of specific consumption expenditures on planetary boundary transgressions. We show that 31–67% and 51–91% of the planetary boundary breaching responsibility could be attributed to the global top 10% and top 20% of consumers, respectively, from both developed and developing countries. By following an effective mitigation pathway, the global top 20% of consumers could adopt the consumption levels and patterns that have the lowest environmental impacts within their quintile, yielding a reduction of 25–53% in environmental pressure. In this scenario, actions focused solely on the food and services sectors would reduce environmental pressure enough to bring land-system change and biosphere integrity back within their respective planetary boundaries. Our study highlights the critical need to focus on high-expenditure consumers for effectively addressing planetary boundary transgressions.

Over the past century, human pressures have driven the planet rapidly away from the stable state of the Holocene[6–8]. These changes are primarily due to the consumption of goods and services, unsustainable production and resource extraction, which have led to the transgression of many planetary boundaries (PBs)[9–11]. The unequal distribution of wealth and income results in unequal consumption and environmental footprints[3–5], causing considerable variations in the contribution to PB transgression among different expenditure (income) groups across countries.

A critical question is how the environmental footprints of consumption and responsibilities for PB transgression are distributed across different expenditure (income) groups globally. Understanding this is instrumental for policymakers to formulate sustainable solutions and ensure fair budget allocation within PBs. Although a number of pioneering studies have highlighted that the consumption of affluent countries, such as the European Union countries and the United States, is the major contributor to PB transgression[1,2,12–16], they often overlook substantial within-country differences. This oversight underestimates inequalities and the contributions of affluent individuals in developing countries[17]. Therefore, it is essential to consider these internal disparities when discussing PB transgression.

Research has investigated the environmental footprints of various consumer (income) groups within certain countries, yielding valuable regional insights[4,5,18]. However, these studies often lack comparability owing to differences in research scopes, environment indicators and the regional coverage. For example, categorizing consumer (income) groups by national standards limits comparability, as the top 10% in Luxembourg and the Congo have vastly different consumption levels and environmental footprints[2]. In addition, most studies considering within-country heterogeneity address only a minority of PB indicators and cover a limited number of countries[4,19–22]. Even comprehensive studies examining carbon footprints across 116 countries[5,21] still miss many developed nations and other PB indicators. Therefore, a globally unified and comparable framework is urgently needed to provide detailed insights into the distribution of key environmental footprints and the responsibility of consumers at different expenditure levels for transgressing PBs. This framework would support the development of targeted and effective mitigation strategies across geographical and socioeconomic scales.

To address this important demand, we first investigate the distribution of environmental footprints of consumption and quantify the disparate responsibilities for the transgression of PBs across different global consumption groups. We then assess the environmental mitigation effects of plausible consumption-reduction and efficiency-improvement options that target high-end consumers. By integrating a highly detailed expenditure database covering 201 consumption groups in 168 countries (98% of the global population) with an environmentally extended multi-regional input–output

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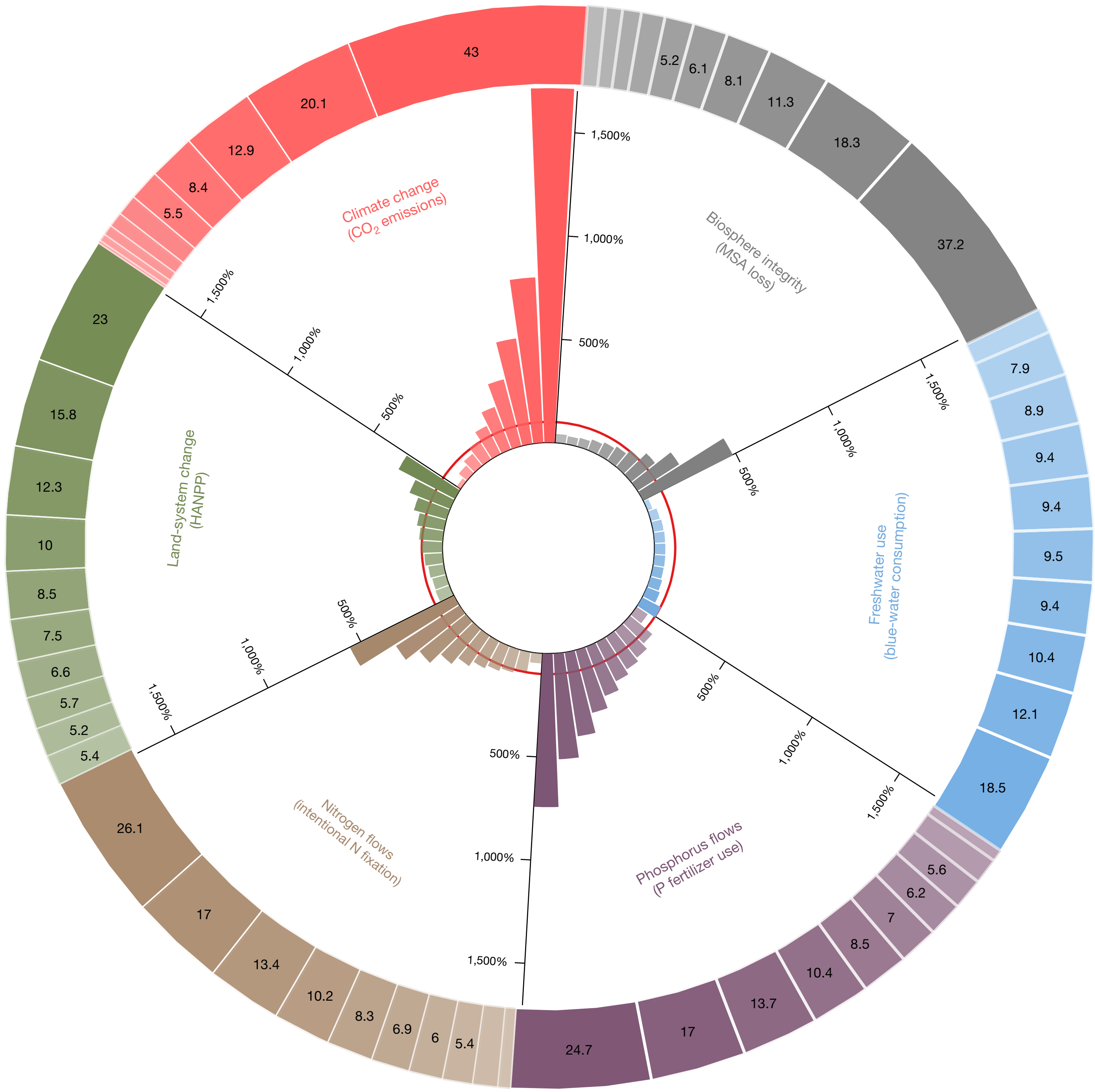

Fig. 1 | The footprints of the six environmental indicators and the shares of each global expenditure decile in the total footprints in 2017. Bar and doughnut pie chart refers to the per capita footprints and the percentage share of each global decile in the total footprints, respectively. The expenditure level of each decile group increases as the colour deepens. The red circle represents the level of per capita boundaries.

(EE-MRIO) model, our study maps the environmental footprints and PB transgression responsibilities across consumer percentiles classified by expenditure levels (Methods). We downscale six proxy indicators (carbon dioxide (CO_2) emissions, human appropriation of net primary productivity (HANPP), intentional nitrogen (N) fixation, phosphorous (P) fertilizer use, blue-water consumption and mean species abundance (MSA loss)) related to the budgets of five PBs (climate change, land-system change, biogeochemical flows, freshwater use and change in biosphere integrity) to per capita equivalents. Instead of comparing these with national averages, we assess them against specific-expenditure footprints (Methods). Our findings highlight the contributions of consumption to PB transgression by economic sectors and expenditure levels, informing targeted mitigation strategies to maintain consumption within PB limits.

Unequal environmental footprints

Figure 1 shows that the world's wealthiest 10% of consumers was responsible for 43% of carbon emissions, 23% of HANPP, 26.1% of nitrogen fixation, 24.7% of phosphorus fertilizer use, 18.5% of blue-water consumption and 37.2% of MSA loss in 2017. By contrast, the poorest 10% contributed marginally: 5.4% to HANPP, 4.4% to blue-water consumption

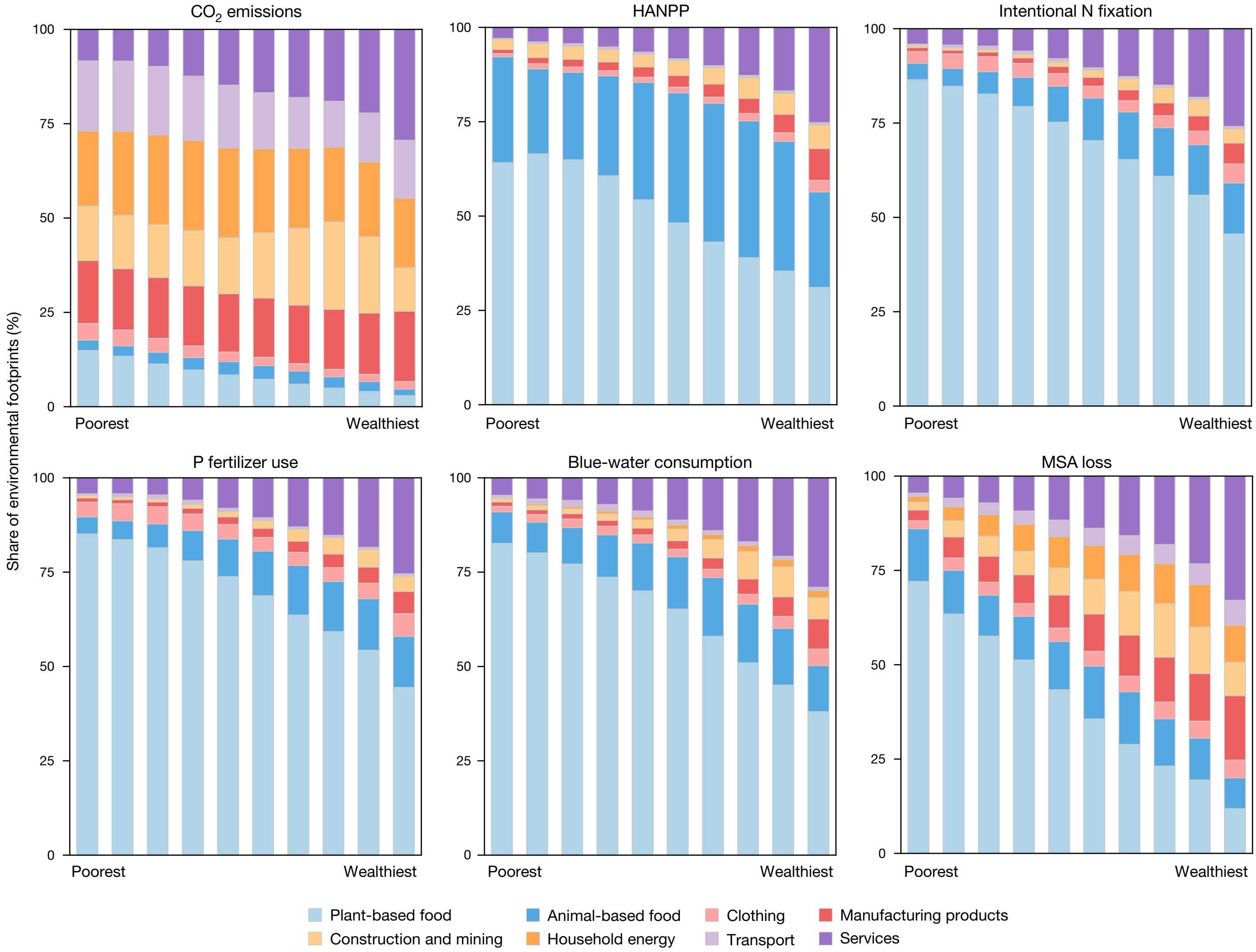

Fig. 2 | Sectoral composition of the six environmental footprints across global consumer deciles in 2017. The consumer deciles are classified by expenditure strata.

and less than 3% to the other footprints. On a per capita basis, the environmental impacts of the top 10% were 4.2 to 77 times that of the bottom 10%, with the most notable disparities in carbon emissions and MSA loss. Extended Data Fig. 1 depicts this inequality through footprint Lorenz curves and Gini coefficients, with carbon emissions (0.58) and MSA loss (0.46) showing considerably higher inequality than other indicators, although still below the expenditure Gini coefficient at 0.69. When compared with per capita PB thresholds (Fig. 1), the environmental footprints of most people in 2017 were excessively high. The top 10% exceeded all per capita PB thresholds across the 6 key environmental indicators, with their footprints ranging from 110% to 1,700% above the PB limit, whereas the bottom 10% remained within all thresholds.

Extended Data Fig. 2 compares the environmental loads of the world's top 1%, next 9%, middle 40% and bottom 50% of consumers. The consumption of the top 1% contributed 14% of carbon emissions, 6% of HANPP, 7% of N fixation, 6% of P fertilizer use, 5% of blue-water consumption and 11% of MSA loss. It is evident that the per capita footprints of the global top 1% were immensely larger, far surpassing those of the next top 9% and reaching 6–70 times that of the bottom 50%. Meanwhile, the middle 40% accounted for 41–47% of global total environmental footprints, also exceeding the per capita PBs, except for the blue-water consumption.

The uneven distribution of the environmental footprints is noticeable at the national level as well (Supplementary Figs. 1–6). Even within many affluent nations such as the United States where the footprints of majority indicators surpassed the per capita PB limits, the national top 10% had footprints that were disproportionately larger compared with the national bottom 10%. By contrast, for some countries in sub-Saharan Africa, such as Burundi, the footprints of the national top 10% remained within the per capita PBs. This contrast underscores the variability in consumption patterns and environmental impacts both within and between nations.

Figure 2 shows the sectoral composition of the six environmental footprints of the global expenditure deciles. It indicates that food consumption, particularly animal-based food, was a dominant driver of environmental pressure for all consumption segments in HANPP, N fixation, P fertilizer use and blue-water consumption. Wealthier groups had higher shares of animal-based food consumption, whereas poorer groups relied more on plant-based food. For example, in the global bottom 10%, 64–87% of their total footprints in these 4 indicators came from plant-based food consumption. For CO_2 emissions and MSA loss, the global wealthier groups had high shares in services and manufacturing products, whereas poorer groups' consumption was mainly focused on their daily necessities such as food, particularly in the context of MSA loss (more discussion in Supplementary Information sections 1.1 and 1.2 and Supplementary Figs. 7 and 8). Despite differences in consumption structures, the wealthier groups consumed considerably more in almost all categories, leading to substantially greater environmental pressure.

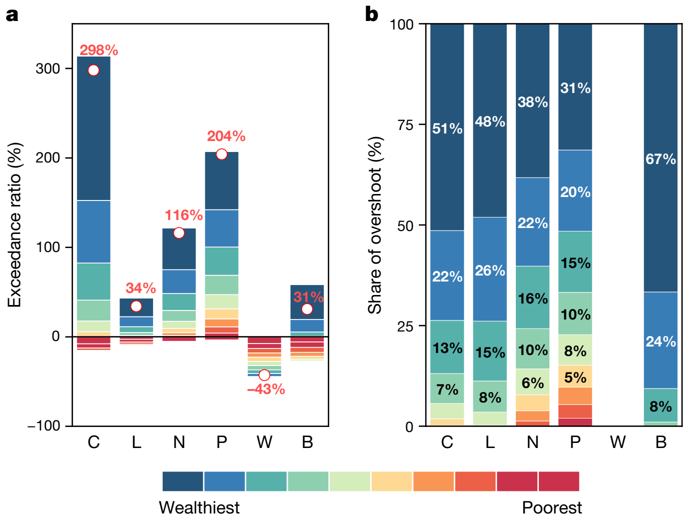

Fig. 3 | The performance and responsibility of global expenditure deciles with respect to the transgression of PBs. a, Exceedance ratio. Red circles and the associated values refer to the 'net' exceedance ratio (the sum of positive and negative exceedance ratios across expenditure deciles). B, biosphere integrity; C, climate change; L, land-system change; N, nitrogen flows, P, phosphorus flows; W, freshwater use. **b**, Share of overshoot. Because the exceedance ratio of blue-water consumption is negative, indicating no overshoot, its share of the overshoot is undefined and not depicted.

The responsibility for PB transgressions

Figure 3 shows the performance and responsibility of global expenditure deciles with respect to PB transgression by the exceedance ratio and share of overshoot. The exceedance ratio measures the deviation of per capita environmental footprints from per capita PBs, with positive values indicating excess and negative values meaning non-exceedance. The overshoot share is specified as the percentage share of each consumer group's per capita exceedance in the total population's exceedance. Although the exceedance ratio reveals the severity of transgressing the boundaries, the share of overshoot uncovers the relative responsibility of different expenditure deciles for the transgression of PBs.

Our findings (Fig. 3a) indicate that for five out of the six indicators, their footprints far surpassed the PBs. On the global scale, the exceedance ratios were 298%, 34%, 116%, 204%, −43% and 31% for carbon emissions, HANPP, N fixation, P fertilizer use, blue-water consumption and MSA loss, respectively. The carbon emissions and P fertilizer use showed the highest exceedance ratio, whereas the blue-water consumption was within the boundary. However, the responsibility of global deciles to PB transgressions varied greatly (Fig. 3b). The world's top 10% of consumers were responsible for 51%, 48%, 38%, 31% and 67% of the PB transgressions in terms of climate change, land-system change, N flows, P flows and biosphere integrity, respectively. The second decile contributed 20–26% of the global PB transgressions. These two deciles include individuals from both developed and developing regions (Extended Data Fig. 3). A considerable share of their responsibility for PB transgressions was tied to more luxurious consumptions (Supplementary Information section 1.2 and Supplementary Fig. 9). Meanwhile, the global bottom 50% had a marginal impact, contributing a share of overshoot of 1.8% to climate change, 0.2% to land-system change, 7.8% to N flows, 15% to P flows and 0% to biosphere integrity.

Extended Data Figs. 4 and 5 illustrate the impact of global expenditure deciles on PB transgressions across regions and nations. For climate change, N flows, P flows and biosphere integrity, the global top decile in the developed regions—Europe, the United States and Asia-Pacific developed—were the primary contributors. Notably, China's vast population led to a sizeable contribution to climate change transgression despite a modest per capita exceedance ratio (Extended Data Fig. 6). China's 83% exceedance surpassed the United States at 76% and Europe at 54%. This population effect also made China and India leading contributors to N and P boundary breaches (Extended Data Fig. 4). For land-system change, the global top 10% in Europe and the United States were the main contributors. However, middle- and low-expenditure deciles in Latin America and the Caribbean and sub-Saharan Africa also had notable impacts, with a 12% exceedance ratio. By contrast, freshwater use remained within the boundary in most regions except the United States. It is important to note that per capita boundary assessment might not fully capture the intricacies of regional water scarcity[23].

An effective mitigation pathway

Recognizing the pivotal role that the world's wealthiest and high-expenditure groups play in exceeding the PBs, we present six scenarios focused on reducing environmental impacts among these high-end consumers based on the literature[13,24–29]. These scenarios, detailed in Extended Data Table 1 and Methods, aim to evaluate strategies for 'reducing overconsumption' and 'achieving best consumer performance with existing technology and social norms'.

When the global top 10% of consumers adopt the consumption levels and patterns of the global 10th percentile level (comparable to the European average level; scenario 1), the global environmental pressure would decrease by 9–23% (Fig. 4) and the overshoots would be mitigated by 18–81% (Extended Data Fig. 7). Expanding this approach to the top 20% of consumers (comparable to the threshold of high-income country defined by the United Nations; scenario 2) would lead to a more substantial decrease in global environmental pressure, ranging from 14% to 36% (Fig. 4). This reduction notably allows biological diversity to return within the PB (Extended Data Figs. 7 and 8). In this scenario, the services sector shows the greatest potential to reduce CO_2 emissions and ranks second among the other five environmental indicators, whereas the food sector ranks first among the latter five indicators. We also find that the consumption-reduction scenarios are relatively more effective in addressing the PB challenges of climate change and biological diversity. This can be attributed to the high elasticity of CO_2 emissions and MSA loss in response to changes in consumption amounts compared with other PB indicators (Extended Data Table 2).

Lowering the environmental intensity of the consumption of the global top 10% group to the lowest level within this group, which is statistically observable at the country level (scenario 3) could decrease the global environmental pressure by 10–23% (Fig. 4) and the overshoots by 22–79% (Extended Data Fig. 7). The same action if taken by the top 20% (scenario 4) would result in reductions of the global environmental pressure by 19–35% (Fig. 4). The service and food sectors are still the frontrunners in these two efficiency-improvement scenarios, accounting for the majority percentage points of the mitigation effects in HANPP, N fixation, P fertilizer use, freshwater and MSA loss (Fig. 4). Compared with the consumption-reduction scenarios, the efficiency-improvement scenarios are more effective in reducing the global environmental pressures for land, nitrogen, phosphorus and water (Fig. 4 and Extended Data Fig. 7). This outcome underscores the feasibility and necessity of more efficient provisioning systems and environmentally friendly consumption patterns.

Finally, the two synergistic scenarios have more remarkable effects. If the global top 10% of consumers simultaneously reduce their consumption and environmental intensity to the lowest levels within their group (scenario 5), the global environmental pressure could decrease by 15–33%. When this approach is extended to the top 20% of consumers (scenario 6), the mitigation rates would increase to

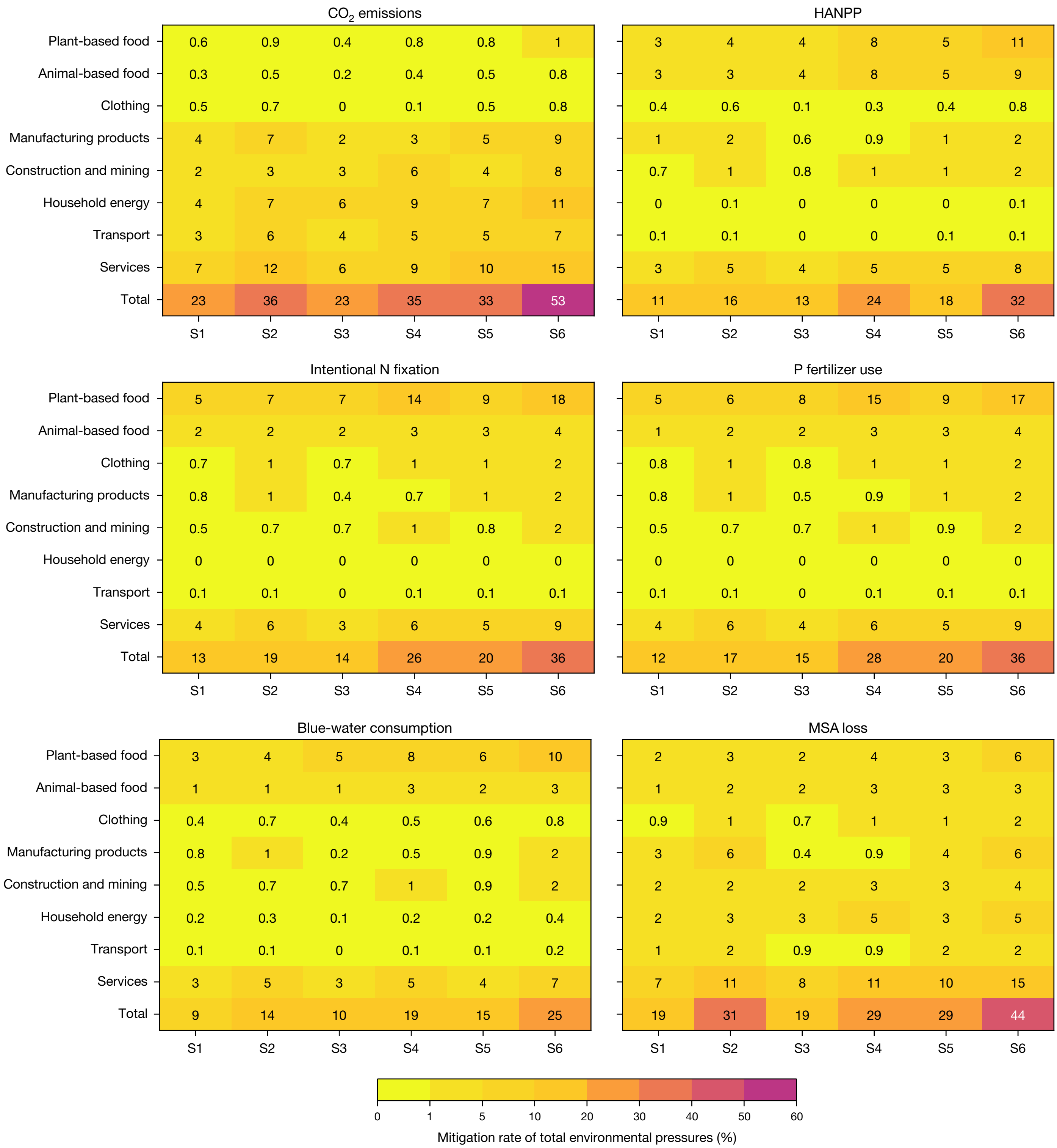

Fig. 4 | Impacts of the plausible consumption reduction and efficiency improvement by the top-two deciles of consumers on environmental pressure. 'Total' is the sum across sectors (that is, column sum). Scenario 1 (S1): the global top 10% of consumers reduce their per capita consumption quantities and adjust consumption patterns to those at the global 10th percentile level. Scenario 2 (S2): the global top 20% of consumers reduce their per capita consumption quantities and adjust consumption patterns to the global 20th percentile level. Scenario 3 (S3): the global top 10% of consumers lower their environmental intensity of consumption to the lowest observed level within their group. Scenario 4 (S4): the global top 20% of consumers lower their environmental intensity of consumption to the lowest observed level within their group. Scenario 5 (S5) is a combination of scenarios 1 and 3. Scenario 6 (S6) is a combination of scenarios 2 and 4.

25–53% (Fig. 4), with a 53% decrease in carbon emissions pressure. More importantly, in scenario 6, actions focusing solely on the food and services sectors would bring land-system changes and biological diversity back within their respective PBs (Extended Data Figs. 7 and 8).

Our analysis decisively demonstrates that both reducing consumption and improving efficiency among high-end consumers are critical and effective strategies for substantially reducing environmental pressures.

Implications for a just future

By integrating an exceptionally detailed expenditure database of 168 countries with an EE-MRIO model, our study provides quantitative insights into the disparate distributions of 6 key environmental footprints and the responsibility of consumers at different expenditure levels for the transgressions of PBs. Our analysis reveals extreme inequality in environmental footprints, highlighting the disproportionate responsibility of affluent groups in both developed and developing countries. Our study contrasts with existing literature by offering a globally unified and comparable framework (more discussion in Supplementary Information section 2.1).

Our findings suggest that considerable environmental pressures are caused by overconsumption, particularly beyond the affluent level typically in high-income countries. Reducing consumption among the global top 10% or top 20% to these levels can generate huge environmental benefits, especially in the food and services sectors (more discussion in Supplementary Information section 2.2). This supports the implementation of sustainable consumption corridors or a floor-and-ceiling framework[13,28]. Our results challenge the pessimistic view that reducing consumption requires a return to primitive lifestyles[25,26], showing instead that substantial environmental benefits can be achieved by moderating the consumption of the affluent.

The lowest observed environmental intensity of consumption within the affluent group demonstrates the potential for efficiency improvement with existing technology and social norms[2,13]. However, targeting affluent groups with mitigation measures may face resistance owing to their political power (more discussion in Supplementary Information section 2.2). Bottom-up actions, which play a crucial role in cultural and value changes[26,27], are vital for pushing top-down changes and establishing maximum consumption thresholds through democratic decision-making.

Although our findings demonstrate the effectiveness of reducing consumption and improving efficiency among affluent consumers in mitigating environmental pressures, the practical implementation of these strategies requires careful consideration of their broader economic and social impacts. Reducing consumption among high-end consumers could lead to a decline in market demand, potentially affecting investment and employment (more discussion in Supplementary Information section 2.2). To mitigate these effects, it is essential to adopt targeted approaches. Numerous studies have shown that implementing progressive taxes on luxury goods and services can reduce excessive consumption among the affluent while generating revenue for social and environmental programmes[25,26,30]. In addition, providing incentives for adopting sustainable consumption and production practices can encourage behavioural changes without causing abrupt economic disruptions. We also argue that although there may be short-term challenges, the long-term benefits of reducing environmental pressures and transitioning to a more sustainable economy can outweigh the initial difficulties.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-024-08154-w.

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Methods

To analyse the inequality of global environmental footprints, we calculated the expenditure-specific footprints of 6 environmental indicators—CO_2 emissions, HANPP, intentional N fixation, P fertilizer use, blue-water consumption and MSA loss—for 168 countries. This was achieved by linking detailed expenditure data with an EE-MRIO model. Following the principle that the resources and ecosystems of our planet are the global commons and all people on the planet are entitled to an equal sustainable share of them[3,13], we downscaled the boundary allowances of these six proxy indicators to per capita equivalents. We compared these with footprint indicators and determined the contributions of different countries and consumption segments to the transgression of PBs.

EE-MRIO model

The EE-MRIO model was used to estimate the environmental footprints of different consumption segments in this study. The EE-MRIO model has been widely used to estimate the global environmental impact of consumption and trade[31,32]. A particularly frequent application is the analysis of environmental footprints of consumption, such as water, carbon and biodiversity footprints[32–35]. One great virtue of this method is that it can model both direct and indirect footprints of consumption, including direct environmental impacts stemming from consumption and indirect environmental impact across the supply chains[36–38]. The EE-MRIO model uses the economic multi-region input–output (MRIO) table to describe the monetary flows and their correlation among economic sectors in international and regional economies[39–42]. The environmental satellite accounts add an environmental dimension, making it possible to quantify the environmental impacts of consumption. Combined with the MRIO table, the calculation equation can be expressed as:

$$\mathrm{EF}_{i,q,c} = E_c\,(I - A)^{-1} y_{i,q} \tag{1}$$

where $(I - A)^{-1}$ is the Leontief inverse matrix and $y_{i,q}$ is the final demand vector of consumption segment (q) in country (i). The environmental emissions and resource usage intensity (E_c) of environmental indicator (c) is a row vector by industry sector for each country, which can be obtained by dividing the environmental emissions and resource usage of the production industry sector and country by the total input of the industry sector and country. $\mathrm{EF}_{i,q,c}$ is the environmental footprint of consumption segment (q) in country (i) for environmental indicator (c). Notably, it is also necessary to include direct household emissions when calculating the carbon footprint[43,44].

PBs and the corresponding proxy indicators

Since the PBs framework was proposed in ref. 6, it has undergone intense debates and multiple updates[6,9–11]. Today, the concept of PBs, including the selection and quantification of proxy indicators, remains a hot topic in the literature[45]. This study does not aim to explore alternative boundaries or their limits. In other words, we do not attempt to revise the PB framework. Our study focuses on quantitative accounting based on the current PB framework. Five PBs were considered in this study: climate change, land-system change, biogeochemical cycles, freshwater use and biosphere integrity. The PB for novel entities was not selected because their impacts on the Earth system as a whole remain largely unstudied, and quantitative evaluation methods on a global scale are still lacking[10,46]. The ocean acidification PB was not included as a separate boundary as it is driven by climate change, and the corresponding pressure indicator has been included in our study. After the Montreal Protocol in 1987, many ozone-depleting substances were phased out. Owing to the decreased human perturbation of the stratospheric ozone depletion, the stratospheric ozone depletion PB was not selected in this study. Atmospheric aerosol loading is controlled by multiple factors and it is difficult to quantify from a consumption-based perspective. In addition, ref. 10 pointed out that this PB is still within the safe operating space. Thereby, it was not selected in this study.

The PB framework includes a series of proxy indicators that represent the 'state' of PBs, such as atmospheric CO_2 concentration. In this study, we define a proxy indicator and a global yearly budget for each selected PB. Notably, the selection of indicators for PBs is based on a comprehensive consideration of the existing PB literature, data availability and the computability of human environmental footprints. Therefore, the selected indicators and related global budgets are not necessarily identical to those in refs. 1,10,47,48. For five selected PBs in our study, proxy indicators and corresponding global budgets were set according to the literature. Specifically, CO_2 emissions, HANPP, N fixation, application of P fertilizers, blue-water consumption and MSA loss, as well as their global yearly budget limits, were used to represent the PB categories of climate change, land-system change, biogeochemical cycles, freshwater use and biosphere integrity, respectively[1,10,11,13]. Owing to biogeochemical cycles being represented by two indicators (N and P), six indicators were included in our analysis. Notably, all global budgets of the six indicators were annual, and the cumulative budget of certain indicators was converted to the annual budget in a linear manner[2,13]. For example, we assumed that the budget consistent with 1.5 °C warming would be used up with an equal annual distribution of the CO_2 emission budget over 2011–2100, in line with the common practice recommended in the literature[1,49]. The following sections provide a detailed description of the PBs and the corresponding proxy indicators. Supplementary Table 1 also presents the global performance of the six key environmental indicators concerning per capita PBs.

Climate change. The proposed measurements in the PB framework for climate change include anthropogenic radiative forcing threshold and the maximum atmospheric CO_2 concentration. This is translated into maximum allowable global temperature increase in the documents of international policy and reporting[11], with the goal set by Paris Agreement at 1.5 °C or 2 °C (ref. 50). Some literature has strengthened the target to 1 °C for fairness and local considerations[9,10]. The set of actionable targets for climate change mitigation is always one of the defining discourses in climate research and international policy[51–53]. In this study, the CO_2 concentration consistent with the global budget on the strict Paris Agreement goals (1.5 °C) is selected. As there is an almost one-to-one link between the maximum allowable global temperature increase and the cumulative CO_2 emissions, the latter is thus selected as the proxy indicator to represent the climate change boundary.

The literature puts the estimation of the global cumulative CO_2 emission budget consistent with 1.5 °C at 860 $GtCO_2$ equivalent from 2011 to 2100 (ref. 54). There are many methods to achieve the transformation from the cumulative budget to the annual budget, and each has specific pros and cons and relies on varying assumptions. We adopt the frequently used method that the CO_2 emission budget would be used up with an equal annual distribution between 2011 and 2100 (refs. 1,13,49). In addition, previous accounting has shown that the budget of about 290 $GtCO_2$ emissions has been used up globally from 2011 to the end of 2017 (ref. 55). Considering that our research year is 2017, a global budget of 570 $GtCO_2$ from 2018 onwards is used in this study, resulting in an annual CO_2 emission budget of approximately 7 $GtCO_2\,yr^{-1}$. This budget results in approximately 0.95 tCO_2 per capita when given a population of 7.3 billion.

It is worth noting that many factors, including political and technological, have the potential to either expand or reduce this budget. For example, the implementation of negative emission technologies could potentially increase this budget. However, such technologies also have inherent flaws, potentially leading to biophysical, technical and economic risks[56]. Numerous studies have also highlighted that substantially increasing the CO_2 emission budget may be unrealistic, given current constraints and technological limitations[50]. However, the per capita boundary may contract owing to population growth. A recent study also pointed out that the remaining carbon budget for keeping warming to 1.5 °C was only around 250 $GtCO_2$ as of 2023 with a 50% chance[57]. Although there are large uncertainties in the remaining carbon budgets, this estimate suggest that the budget we used in this research may be a very optimistic estimate and that the actual situation may be even worse. However, compared with the figure of 1.61 tCO_2 per capita as suggested in a previous study[13], the budget in this study is already strict.

Only energy- and industry-related CO_2 emissions were considered, excluding other non-CO_2 greenhouse gases. Therefore, the estimate of the consumption-based carbon footprint and the overshoot of climate change is optimistic, and the actual situation may be worse. Previous literature has indicated that the net emissions of land-use change over the 2010–2100 period is projected to be close to zero[50]; therefore, we did not consider emissions related to land use. The CO_2 emissions data for 2017 for footprints estimation were obtained from the Global Trade Analysis Project (GTAP) 11 database.

Land-system change. Initially, the proxy indicator utilized in the PB framework for land-system change was the percentage of global land cover converted to cultivated land[6]. Subsequent updates have shifted the emphasis towards the biophysical processes within the land system, advocating for the amount of forest cover as a proxy measurement[10,11]. However, measuring the area of forested land associated with the consumption of goods and services is challenging. After ref. 6 proposed the PB framework, many studies have suggested that the HANPP could serve as an alternative PB. HANPP integrates various boundaries[58–60], including land-system change, biosphere integrity[61,62], freshwater use and biogeochemical cycles, owing to its comprehensive approach to assessing human impacts on ecosystems. Consequently, HANPP has been widely applied as an indicator for PBs, particularly for land-system change[2,13,63–65].

Although ref. 10 recently assigned HANPP to biosphere integrity, we selected HANPP as the indicator for the land-system change PB. This decision is based on the multi-representativeness and consumption-based quantifiability of HANPP for PBs[10,13,59,62]. We argue that this selection does not undermine the main findings of our study. As emphasized, our aim is not to revise the PB framework but to make a comprehensive selection based on the literature and data availability. According to ref. 10, the global potential natural vegetation of HANPP was estimated to be 53.7–54.6 GtC yr^{-1} between 2000 and 2020, with a threshold set at 20% HANPP, equivalent to 10.8 GtC yr^{-1}, to maintain Earth's balance and sustainability. This translates to 1.47 tC per capita in 2017.

We have constructed a long-time-series HANPP environmental account based on the Lund–Potsdam–Jena dynamic global vegetation model (LPJ-DGVM), which has been well matched with the GTAP model in our previous studies. More details can be found in refs. 65,66.

Biosphere integrity. It is challenging to select indicators and set boundaries for biosphere integrity from an Earth system perspective. Initially, ref. 6 used the species extinction rate (rate of biodiversity loss) as a provisional indicator. Reference 11 later incorporated both the global extinction rate and the Biodiversity Intactness Index (BII) as interim indicators for this boundary. However, some studies have pointed out that the BII cannot be directly linked to establishing an Earth system state. Reference 10 retained the extinction rate and introduced HANPP as an alternative indicator to replace BII. Reference 9 also proposed two complementary indicators of biodiversity: the area of largely intact natural ecosystems and the functional integrity of all ecosystems.

In this study, we used the rate of biodiversity loss as the key indicator for biosphere integrity, in line with the PB framework. However, instead of using the extinctions per million species-years metric recommended by the original PB framework, we used MSA loss, as developed in ref. 67. MSA loss measures the average abundance of original species in a disturbed environment relative to their average abundance in an undisturbed reference environment. A notable advantage of the MSA indicator is its integration into footprint calculations, which help clarify the relationship between human activities and their impacts on biodiversity across various pressures[67]. We chose MSA loss for its quantifiability and practical application in assessing biodiversity impacts[1,68].

Given the existence of better quantitative indicators for the biosphere integrity PB, HANPP was assigned to represent another PB: land-system change. According to ref. 1, the limit for MSA is set at 3,724 million MSA-loss ha per year, which can be converted to 0.51 MSA-loss ha per capita per year.

The MSA-loss environmental account, consistent with the GTAP model, was formulated using the methodology of ref. 67. We applied the MSA-loss account utilizing transparent methodologies and data provided by refs. 1,67, ensuring a comprehensive and accurate representation of MSA-loss within our study framework.

Biogeochemical cycles. The planetary framework outlines two sub-boundaries for biogeochemical flows, specifically focusing on the biogeochemical cycles for N and P (ref. 11). For the N cycle, the proposed proxy indicator is the intentional N fixation, which includes N fixation in fertilizer and from crop fixation. For the P cycle, the proposed proxy indicators include the P flow from fertilizers to erodible soils and the P flow from fresh water into the ocean. However, quantifying the amount of P transitioning from fresh water to the ocean is fraught with considerable uncertainty, and comparing this quantification with the consumption-based environmental footprints poses great challenges. Consequently, the intentional N fixation and P fertilizer use were selected as the proxy indicators for the N and P cycles, respectively[1,2]. According to the most recent research by ref. 9, the updated budgets are 62 TgN yr^{-1} and 4.5–9.0 TgP yr^{-1}, respectively. By synthesizing the findings from refs. 9–11, this study adopted 62 TgN $yr^{-1}$and 6.2 TgP yr^{-1} as the budgets for the N and P cycles, respectively. Correspondingly, the per capita N and P budgets were 0.85 kgP yr^{-1} and 8.5 kgN yr^{-1}, respectively.

The intentional N fixation and P fertilizer use accounts were built with the bottom-up method. Both N fertilizer usage and biological N fixation were considered in N fixation. The national N fertilizer usage data were obtained from the Food and Agriculture Organization. The N fertilizer usage data for 13 crops in each country were obtained from the International Fertilizer Industry Association. We allocated the national N fertilizer usage values to eight agricultural sectors in GTAP. For biological N fixation, we obtained the N fixation coefficient (per kg of crop yield) for nitrogen-fixing crops from refs. 12,69. Finally, the biological N fixation was allocated to the specific agricultural sectors in GTAP.

Like the account-building process of N fertilizer usage, we obtained the P_2O_5 fertilizer usage from the Food and Agriculture Organization and allocated it to the eight agricultural sectors of GTAP based on the International Fertilizer Industry Association data. Multiplying the amount of P_2O_5 fertilizer usage by the chemical factor content of P (approximately 62/142) generated the quantity of P fertilizer use.

Freshwater use. The PB for freshwater use represents the maximum quantity of freshwater that can be appropriated by humans[70]. Typically, the available amount of consumptive runoff, or blue water, serves as the proxy indicator for freshwater use. Recently, ref. 10 proposed an alternative: the percentage of annual global ice-free land area with deviations in streamflow and root-zone soil moisture from preindustrial levels. Reference 9 refined this by introducing two sub-boundaries: a flow alteration boundary for surface water and a drawdown boundary for groundwater, each with its respective boundary threshold[9].

A substantial portion of blue water is inaccessible for human use[23], and integrating this refined indicator into consumption accounting poses substantial challenges. Consequently, this study opted for global consumption of blue water as the proxy indicator for this PB[11].

We noticed that the threshold for freshwater use is a matter of ongoing debate, with discrepancies between estimates of global blue-water consumption derived from bottom-up and top-down methods, the former usually yielding lower estimates[13]. Given these limitations and adhering to the precautionary principle, this study adopted a more stringent budget, setting the threshold for blue-water consumption at 2,800 $km^3\ yr^{-1}$, as defined by ref. 71, to navigate the complexities and uncertainties surrounding freshwater use and ensure a conservative approach to managing this critical resource[11,13]. This translated to a per capita budget of 384 $m^3\ yr^{-1}$.

The blue-water consumption account was also built with the bottom-up method. We considered crop farming, husbandry and other sectors separately. Blue-water consumption coefficients were adopted from ref. 72, and 2017 crop production data of 161 crops from the Food and Agriculture Organization were used to calculate blue-water consumption in crop farming. The results were allocated across the eight agricultural sectors defined in GTAP. For husbandry, country-specific blue-water consumption data provided by ref. 73 were used. For other sectors, the water use coefficient from GTAP-2014 was used. This allowed us to obtain the blue-water consumption estimates for husbandry and other sectors in 2017.

Discrepancies exist between estimates of global blue-water consumption derived from the bottom-up and top-down methods, with the former typically yielding lower estimates[13]. Consequently, our global pressure estimates of blue-water consumption were lower than those presented in ref. 11 but align closely with the findings of ref. 74. Regardless of the estimates considered, global blue-water usage is well within the PBs. However, regional water security issues continue to pose great challenges[10,75,76].

PB downscaling

Various methods exist for downscaling PBs, each reflecting alternative views on distributive fairness[77–80]. Some studies have advocated for a multiscale method, arguing that considering regional background heterogeneity is more appropriate for PBs owing to the diverse ecological contexts found globally[49,81,82]. Other studies have supported a top-down allocation approach, asserting its appropriateness based on general concepts of distributive fairness[13,48,83]. Many top-down methods have been proposed in this context, including grandfathering (a right-based approach), equal per capita (emphasizing equal individual rights), ability to pay (a duty-based approach) and accounting for cumulative emissions (addressing historical responsibility)[1,13]. Although we recognize the practical suitability of the multiscale method for managing resource use, our study used a top-down approach, utilizing the equal-per-capita method to allocate the global budget. This choice aligns with our research focus on examining the contributions of various consumption segments to global transgressions of PBs. We operated under the premise that every individual has equal rights to access natural resources, and thus we allocate the global budget of PBs using the equal-per-capita approach[3,13,84]. Consequently, the PB for each proxy indicator is evenly distributed among the global population. In this way, we obtained the per capita equivalents of five PBs, providing a fair and equitable basis for analysing resource use and environmental impact across diverse populations.

Responsibilities quantifying

Our responsibility allocation is based on a 1-year scale in alignment with the current PB framework and the accounting feasibility. However, from the perspective of historical responsibility, high-end consumer groups and countries bear a greater responsibility for ecological breakdown[51,52,85,86]. More discussion in this regard can be found in Supplementary Information section 1.1.

The exceedance ratio measures the severity of transgressing the PBs, which is calculated as follows:

$$\text{Exceedance ratio}_q = \frac{\text{EF}_q - \text{Share}_q}{\text{Share}_q} \tag{2}$$

in which EF_q and Share_q refer to the environmental footprint and the fair share of consumption segment q. The fair share is determined according to the equal-per-capita approach discussed above.

The share of overshoot represents the relative responsibility of different groups for the transgressions of PBs. Following ref. 3, we posit that the undershoot of one group does not offset the overshoot of another. Consequently, the exceedance ratio for a group in undershoot is assigned a value of zero in the responsibility calculations. Thus, the share of overshoot for group q can be calculated as follows:

$$\text{Share of overshoot}_q = \frac{\text{Exceedance ratio}_q}{\text{Exceedance ratio}_{q\_\text{total}}} \tag{3}$$

Moreover, we also quantify the responsibilities for PB transgressions associated with necessary versus discretionary consumptions based on the expenditure elasticity theory[22,30,87]. Discretionary goods are defined as having an expenditure elasticity greater than 1, whereas necessities have an expenditure elasticity less than 1. This approach helps identify the consumption attributes by distinguishing expenditure types (see Supplementary Information section 1.2 for details).

Inequality measurements

The Gini coefficient was used to measure expenditure and footprint inequalities. It ranges from 0 (perfect equality) to 1 (perfect inequality)[88–90]. The basic income Gini coefficient is calculated by:

$$G = \sum_{i=1}^{n} P_i Y_i + 2\sum_{i=1}^{n} P_i (1 - C_i) - 1 \tag{4}$$

where G refers to income Gini coefficient, P_i, Y_i and C_i are the population share, income share and cumulative income share of income group i, respectively, and n is the number of groups. Similarly, the environmental footprints inequality (EF-Gini) can be calculated by replacing the income with the environmental footprint in the equation[89], and using Y_i and C_i to represent environmental footprint and the accumulated footprints of consumption segment i.

We also used the Lorentz curve to show the expenditure and environmental footprint inequality, which is the ordered distribution of the cumulative share of population against the cumulative share of expenditure and environmental footprints.

Scenarios setting

The term 'overconsumption' is widely discussed in both the scientific literature and the mass media[26,91–94], but there is no clear definition of the standards for overconsumption. Rather than attempting to define overconsumption, we set scenarios to quantify the mitigation effect of (1) reducing consumption by the affluent groups to a more sustainable level acceptable within their own group and (2) achieving the best consumer performance with existing technology and social norms within their group[13,24,26–28,95]. The global 10th percentile level of final demand is about US$27,000 per year, equivalent to the European average in 2017. The global 20th percentile level is about US$12,000 per year, comparable to the threshold of high-income countries defined by the United Nations in 2017. These two thresholds represent typical levels of affluent consumption where high living standards are maintained, as frequently referenced in the mass media, government reports and academic literature. Our analysis considers the lowest observed environmental impact intensity of consumption within each of these two groups as the 'best performance' achievable under existing technology and social norms within the group[13,96,97]. To explore the potential impact of these behavioural adjustments, we set six scenarios as detailed in Extended Data Table 1.

Data sources and process

The MRIO table was taken from the GTAP 11 database[98,99]. GTAP 11 is a global detailed MRIO database developed by harmonizing and detailing supply use and international trade tables for 141 countries and regions. It provides a detailed classification with 65 sectors and the corresponding household final demand. In this study, GTAP 11 covering the year 2017 was used.

The household expenditure data used in this study are a composite dataset[100–102], sourced from the World Bank Global Consumption Database (WBGCD)[5,103], the Eurostat Household Budget Survey (HBS), the Japanese Family Income and Expenditure Survey (FIES), the Canada Survey of Household Spending (SHS) and the Australia Household Expenditure Survey (HES). The WBGCD data provide a comprehensive description of household and consumption characteristics, featuring detailed information on 33 categories of consumption items and 201 expenditure levels across 116 countries for the year 2011. The HBS delineates household and consumption characteristics across 12 major categories and 47 sub-categories for 5 quintiles in 32 European countries for the year 2015. The FIES details household and consumption characteristics across 23 categories for 10 deciles in Japan for the year 2017. The SHS provides data on 358 consumption categories for 5 quintiles in 2017. The HES data cover 12 major categories and 46 sub-categories for 5 quintiles in 2015.

The household expenditure survey data have to be bridged and matched to GTAP to calculate the environmental footprints among expenditure groups. First, considering that WBGCD has the broadest geographical coverage, we used the consumption shares of each sector by expenditure bins in WBGCD as the basis, updating them with other national expenditure survey data where available. For countries lacking data, we approximated the expenditure distribution structure using neighbouring countries with comparable levels of development. Given the constraints of data availability, this approach was deemed appropriate[87]. As a result, the refined expenditure dataset encompasses 33 sectors, 201 bins and 168 countries. Next, we constructed a bridging matrix to link these 33 sectors to the 65 sectors in the GTAP MRIO table, adhering to the sector definitions provided in refs. 5,104. This matrix enabled the derivation of consumption shares in each sector by expenditure bins for the 65 sectors in the GTAP MRIO table. This means that our analysis was consistently based on basic prices (producer price), and the information we retrieved from the expenditure data pertained to the expenditure shares, not the monetary values of expenditure. This process yielded household final demand data, which are consistent with the GTAP classification and across different consumption segments[105]. In addition, we updated the 2011 population data in the expenditure survey data to 2017, using population statistics from the World Bank and maintaining the original dataset's population distribution between expenditure bins. It is worth noting that to ensure comparability in discussing the PB, we assumed that the final demand from government and the investment of different consumption segments would follow the same distribution as the household consumption, in the absence of additional pertinent information[5]. Further discussion on the uncertainties and limitations of the methods and data are provided in Supplementary Information section 3.

Data availability

The MRIO table used in the paper is derived from the GTAP-v11 database (https://www.gtap.agecon.purdue.edu/). For household expenditure data, the World Bank Global Consumption Database (WBGCD) is available at the database website (https://datatopics.worldbank.org/consumption/). The Household Budget Survey (HBS) for European countries is obtained from Eurostat (https://ec.europa.eu/eurostat/web/household-budget-surveys). The Family Income and Expenditure Survey (FIES) for Japan is provided by the Statistics Bureau of Japan (https://www.stat.go.jp/english/data/sousetai/1.html). The Survey of Household Spending (SHS) for Canada is provided by Statistics Canada (https://www.statcan.gc.ca/en/survey/household/). The Household Expenditure Survey (HES) of Australia is provided by Australian Bureau of Statistics (https://www.abs.gov.au/statistics/economy/finance/household-expenditure-survey-australia-summary-results).

Code availability

The code was developed in MATLAB to calculate the environmental footprints of expenditure groups, which is available on Zenodo at https://doi.org/10.5281/zenodo.13788196 (ref. 106).

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Additional information
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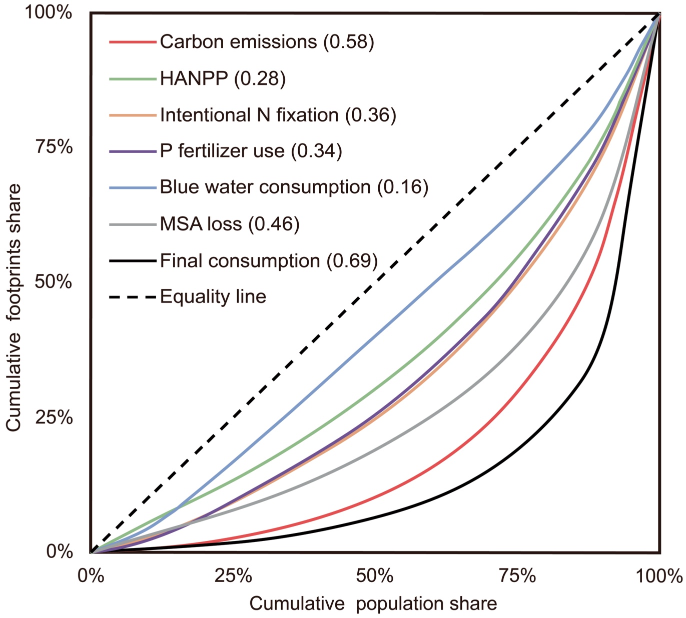
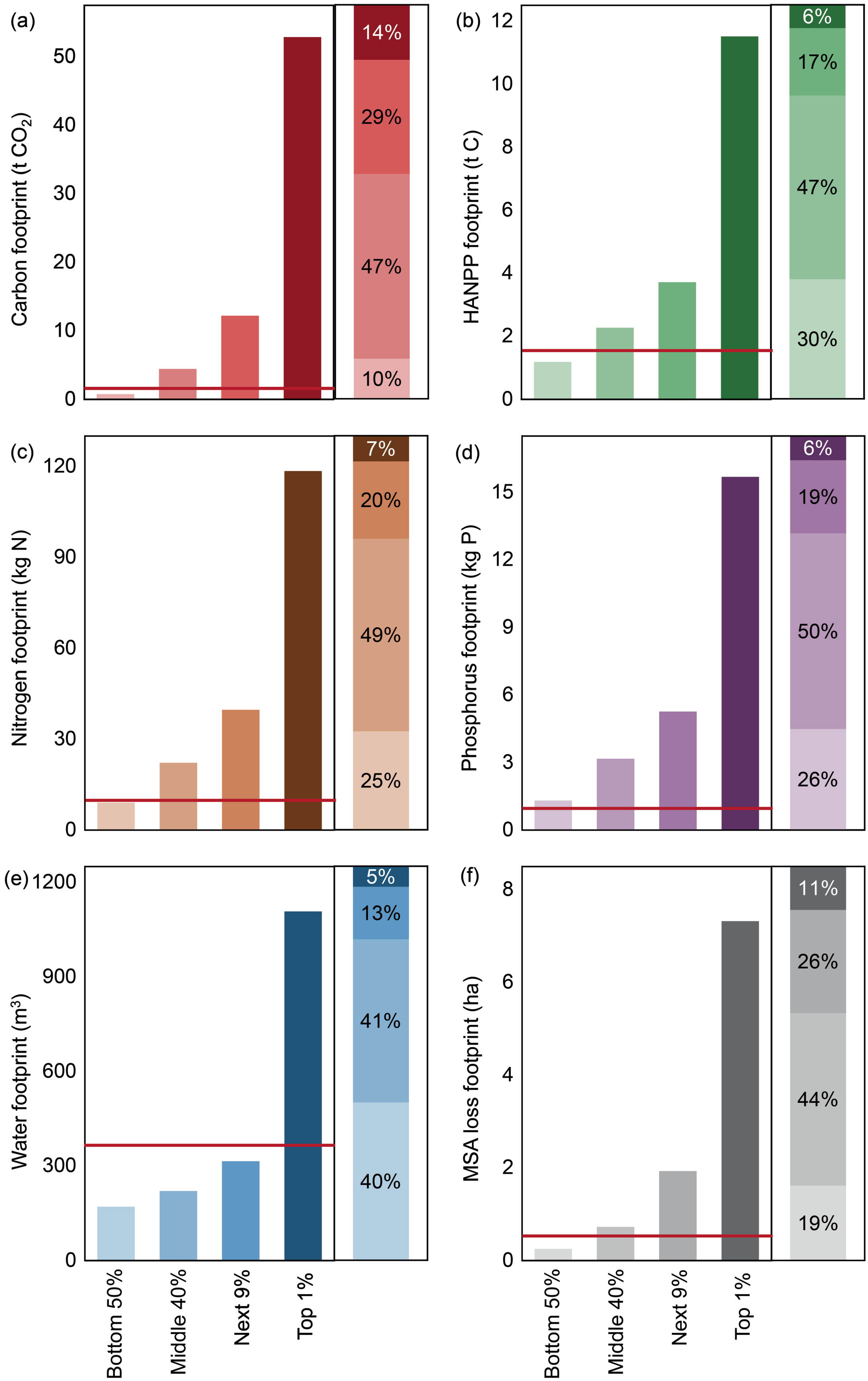
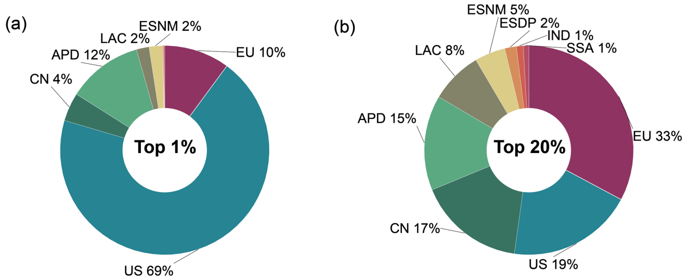


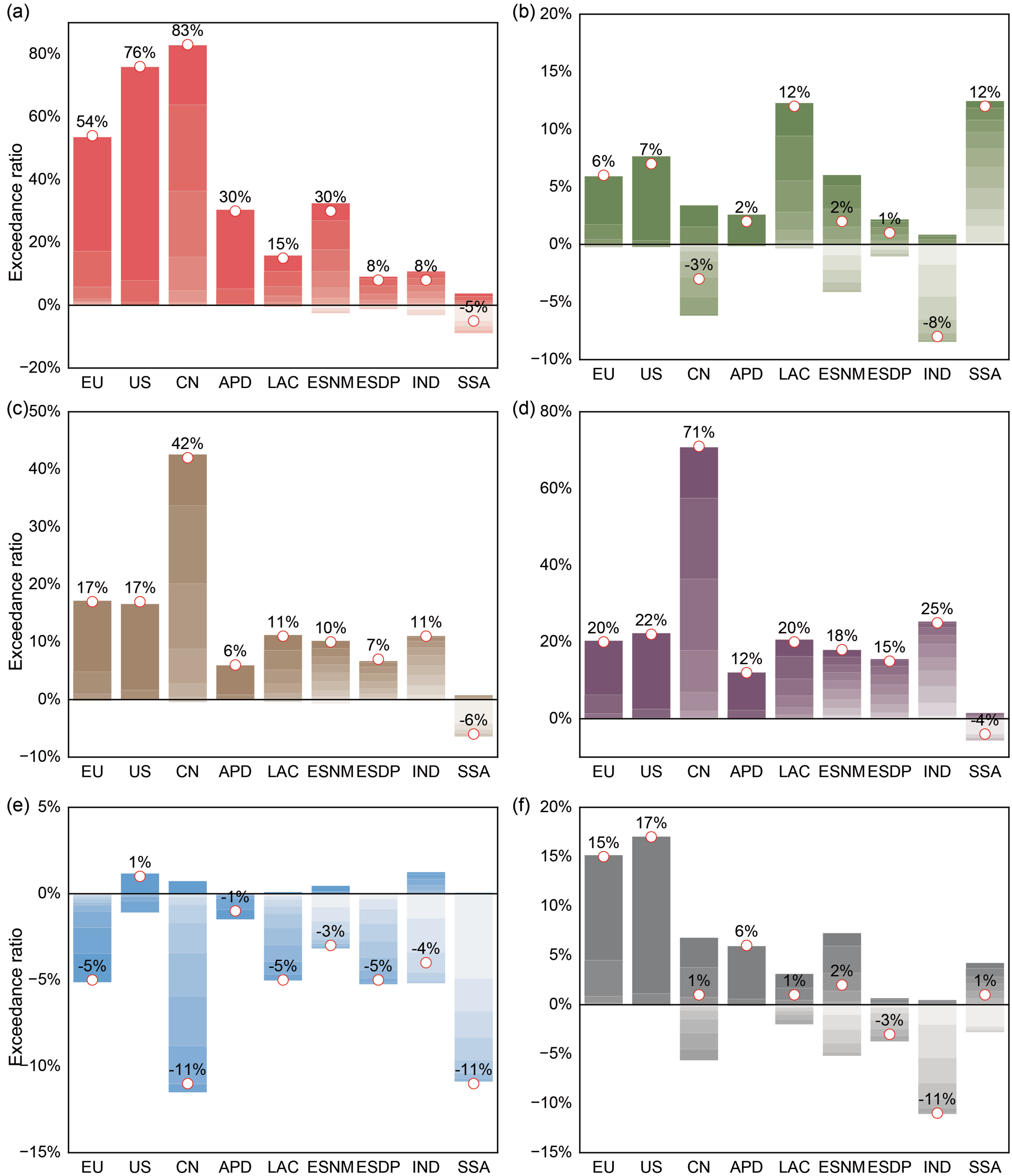
Extended Data Fig. 1 | Lorenz curve for the footprints of the six environmental pressure indicators at the global scale in 2017. The numbers in the legend represent the Gini coefficients for each of the six environmental pressure indicators.



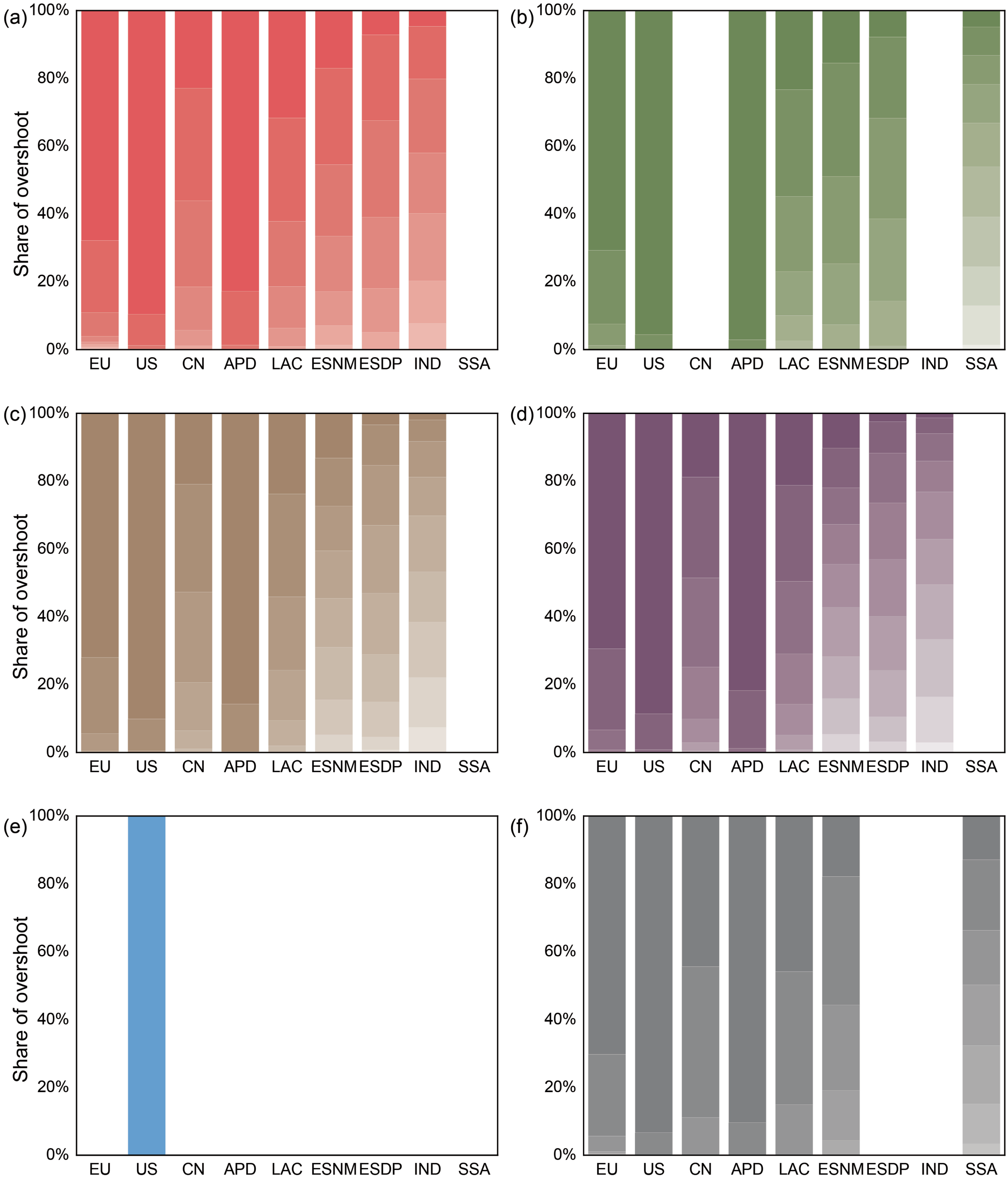
Extended Data Fig. 2 | The footprints of six environmental indicators by the wealthiest top 1%, next 9%, middle 40% and bottom 50% of the global population, and the corresponding shares in the total footprint. The global percentiles of consumers are classified by expenditure level. The red line represents the level of per capita boundaries.



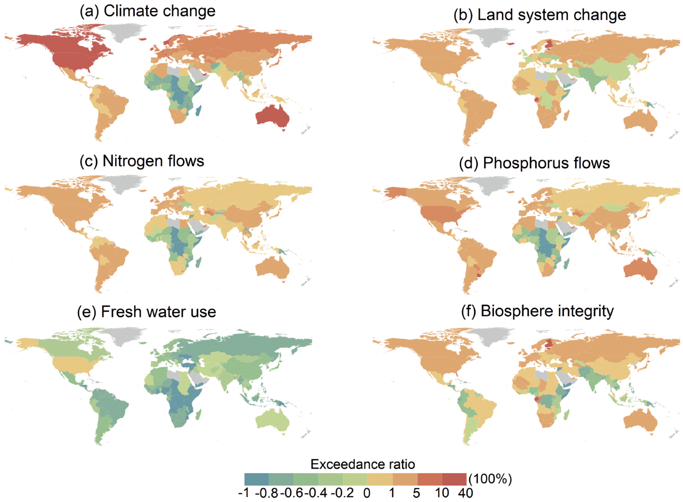
Extended Data Fig. 3 | The geographical distribution of global top 1% and 20% affluent consumers. The global percentiles of consumers are classified by expenditure level. EU, US, CN, APD, ESDP, LAC, IND, and SSA represent Europe, the US, China, Asia-Pacific Developed, East Asia and Developing Pacific, Latin America and Caribbean, India, and Sub-Saharan Africa, respectively. The ESNM represents the Eurasia, Southern Asia, North Africa, and the Middle East, respectively. The region classification is presented in Supplementary Fig. 10.



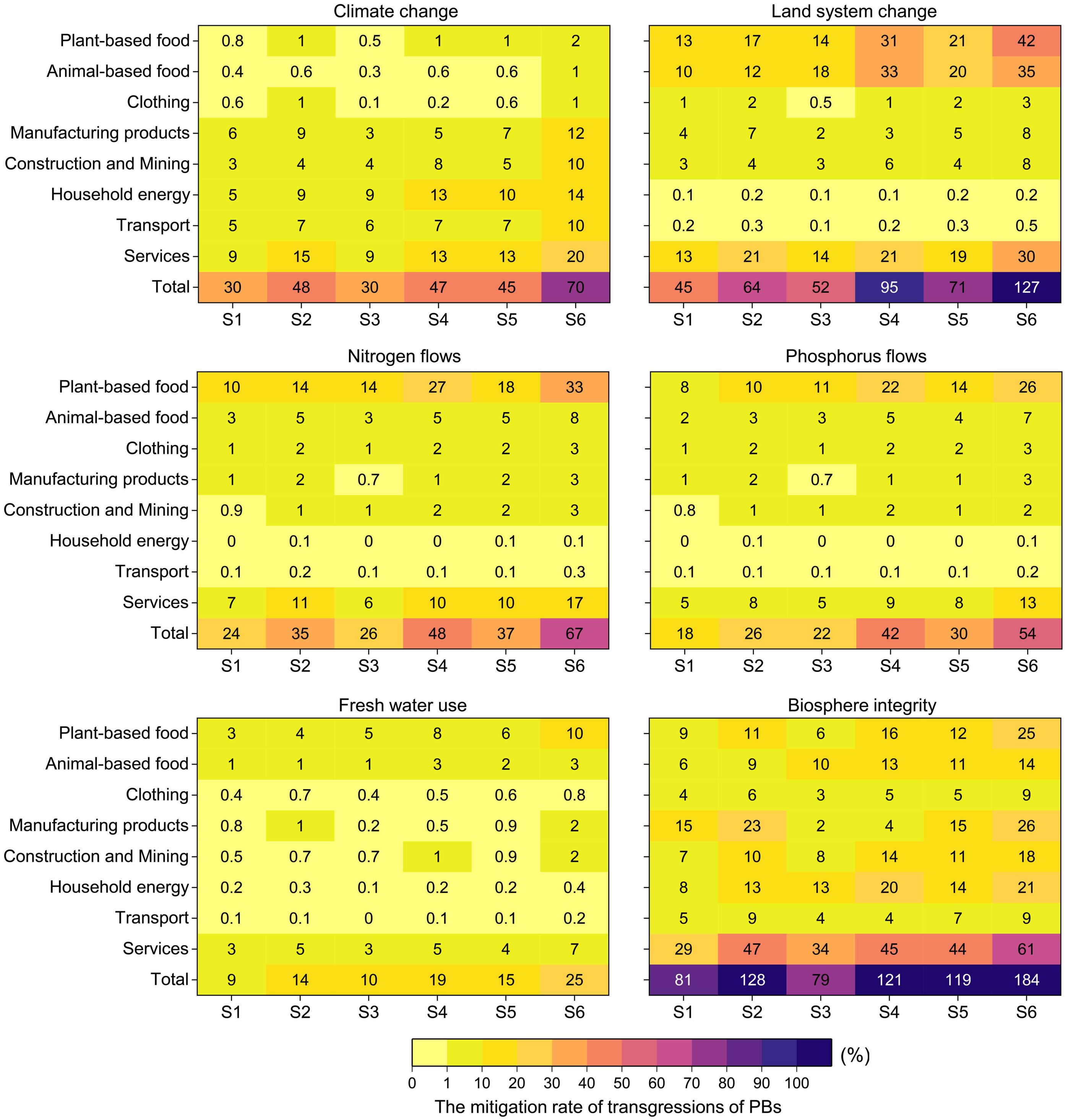
Extended Data Fig. 4 | The exceedance ratios of global expenditure deciles in different regions. The sum of regional exceedance ratio is the global exceed ratio (Fig. 3). These deciles are formed on a global scale, increasing as the color deepens. (a)-(f) refer to climate change, land system change, nitrogen flows, phosphorus flows, freshwater use, and biosphere integrity, respectively. EU, US, CN, APD, ESDP, LAC, IND, and SSA represent Europe, the US, China, Asia-Pacific Developed, East Asia and Developing Pacific, Latin America and Caribbean, India, and Sub-Saharan Africa, respectively. The ESNM represents the Eurasia, Southern Asia, North Africa, and the Middle East. The distribution of global deciles of consumers is presented in Supplementary Fig. 11.



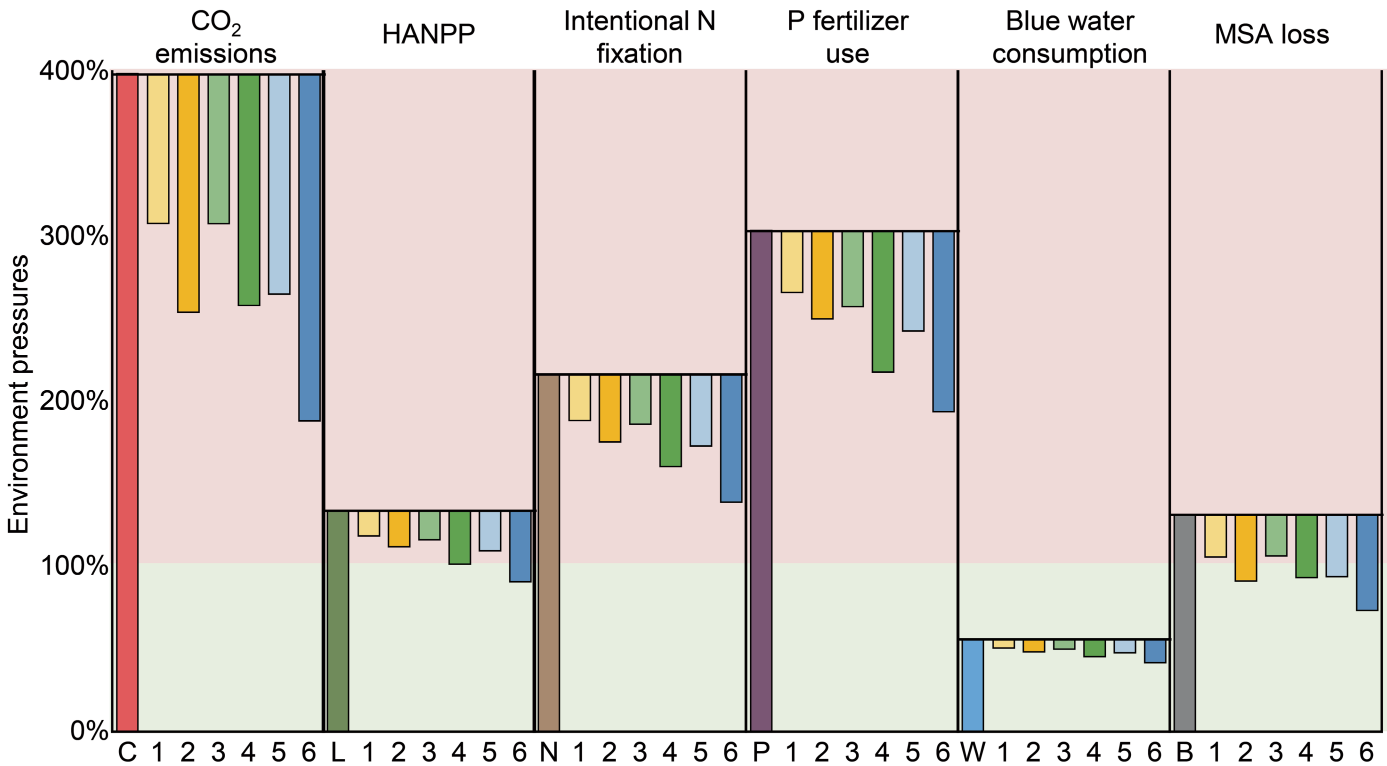
Extended Data Fig. 5 | The contribution of global deciles of consumers to the transgressions of planetary boundaries in different regions. (a)-(f) refer to climate change, land system change, nitrogen flows, phosphorus flows, freshwater use, and biosphere integrity, respectively. The expenditure level of decile groups increases as the color deepens. EU, US, CN, APD, ESDP, LAC, IND, SSA represent Europe, the US, China, Asia-Pacific Developed, East Asia and Developing Pacific, Latin America and Caribbean, India, Sub-Saharan Africa, respectively. The ESNM represents the Eurasia, Southern Asia, North Africa, and Middle East.



Extended Data Fig. 6 | National performance in the transgression of planetary boundaries. The performance is measured by the exceedance ratio.



Extended Data Fig. 7 | Impacts of the plausible consumption reduction and efficiency improvement by the top two deciles of consumers on the overshoots of planetary boundaries. The mitigation rate of transgressions of one PB is the ratio of the pressure reduction under the scenario to the total overshoot of the PB, with the value > 100% indicating that the environmental indicator is brought back within the PB. "Total" is the sum across sectors (i.e., column sum). Because the blue water consumption remains within the PB limits at the global scale, figures in the heat table of blue water consumption present the mitigation rate of total pressures, rather than that of overshoot. S1-S6 refer to Scenarios 1-6, respectively.



Extended Data Fig. 8 | Impacts of the plausible consumption reduction and efficiency improvement by the top two deciles of consumers on total environmental pressure. When the environment pressures <100%, they are within the PBs' budgets. Note: C: Climate change; L: Land system change; N: Nitrogen flows, P: Phosphorus flows; W: Freshwater use; B: Biosphere Integrity. The 1-6 refer to the scenarios 1-6, respectively.

Extended Data Table 1 | Consumption reduction and efficiency improvement scenarios

Scenarios	Description
Scenario 1 (S1) Consumption reduction of the top 10%	The global top 10% consumers reduce their per capita consumption quantities and adjust consumption patterns to those at the global 10th percentile level. The latter quantity is about 27 thousand dollars per year, comparable to the European average level in 2017.
Scenario 2 (S2) Consumption reduction of the top 20%	The global top 20% consumers reduce their per capita consumption quantities and adjust consumption patterns to the global 20th percentile level. The latter quantity is about 12 thousand dollars per year, comparable to the threshold of high-income country defined by the United Nations.
Scenario3 (S3) Efficiency improvement of the top 10%	The environmental intensity of the consumption of all global top 10% consumers is reduced to the lowest level within this group. This intensity level is statistically observable at the country level and represents the “best performance of top 10%” in terms of efficiency improvement achievable with existing technology and social norms.
Scenario 4 (S4) Efficiency improvement of the top 20%	The environmental intensity of the consumption of all global top 20% consumers is reduced to the lowest level within this group. This intensity level is statistically observable at the country level and represents the “best performance of top 20%” in terms of efficiency improvement achievable with existing technology and social norms.
Scenario 5 (S5) Consumption reduction and efficiency improvement of the top 10%	A combination of Scenarios 1 and 3.
Scenario 6 (S6) Consumption reduction and efficiency improvement of the top 20%	A combination of Scenarios 2 and 4.

Extended Data Table 2 | The global footprint elasticity of consumption for six planetary boundary indicators

Planetary boundary	Indicator	Elasticity
Climate change	CO_2 emissions	0.89
Land system change	HANPP	0.28
Biogeochemical flows	Intentional N fixation	0.46
Biogeochemical flows	P fertilizer use	0.46
Freshwater use	Blue water consumption	0.21
Biosphere integrity	MSA loss	0.54