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Supplementary information

Keeping the global consumption within the planetary boundaries

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Supplementary Information for

Keeping the global consumption within the planetary boundaries

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This Supplementary Information file includes:

1. Responsibility for planetary boundary transgression

1.1 Methods selection for allocating responsibilities

The allocation of responsibility for PB transgression is a controversial and ultimately normative issue, particularly in the context of climate change. Responsibility for climate change and the allocation of remaining carbon budgets have long been points of contention in climate research and international negotiations. There are alternative methods for allocating environmental responsibilities, including income-based, history-based, population-based and other approaches[1]. Historically, developed countries in the Global North bear significant responsibility for climate change. For instance, Hickel et al.[2] pointed out that the Global North is responsible for over 90% of historical excess global CO_2 emissions, whereas many countries in the Global South have stayed within their fair shares. However, the allocation of this responsibility remains controversial, especially when considering changes in national sovereignty (e.g., should current countries be held accountable for emissions during the colonial period)[2].

Apart from climate change, some PB indicators, such as biosphere integrity, biogeochemical flows (P and N cycles), and atmospheric aerosol loading, are defined based on annual pressure in the PB framework[3–6], others like freshwater use are renewable. For these indicators, their operating space and budgets are measured annually. While high-end consumers or developed countries may transgress these yearly PB limits regularly, the cumulative effects of these transgressions remain under-investigated and there is a lack of quantitative evaluation methods for this perspective[3].

While it is widely regarded that cumulative responsibility could provide a more just framework when discussing national environmental impacts, applying this perspective to socio-economic groups can be challenging. The composition of affluent groups is not static; individuals within these groups change over time. This dynamic nature means that current members of affluent groups might argue that they should not be held accountable for the actions of past affluent individuals if they were not affluent at that time. In other words, while holding countries accountable for historical environmental impacts might be justified at the national level, it is less appropriate at the individual level due to the social mobility that causes people to move in and out of different social classes. This makes it unreasonable to hold individuals responsible for the actions of their ancestors.

Our study adopts a future-oriented perspective to allocate responsibility for PB transgressions, focusing on the transgressions of remaining operating space and budgets. This approach aligns with the theoretical framework of PB, which aims to maintain a safe operating space for humanity by ensuring that we do not extract more than what the Earth can regenerate or pollute more than it can absorb. The allocation of remaining space and budget is a mainstream method in the literatures[7–11], where the yearly budget (the upper limit of annual human pressure) is allocated using various methods, each reflecting alternative views on distributive fairness. Lucas et al.[7] have investigated the difference in various allocation methods for remaining PB budgets.

While we recognize the practical suitability of multiscale methods for managing resource use, our study employs a top-down approach, utilizing an equal per capita method to allocate the yearly global budget. This choice aligns with our research focus on how different consumer groups are using and encroaching on the current PB space (budgets). Our study operates under the premise that every individual possesses equal rights to access natural resources, thus allocating the global budget of PBs using the equal per capita approach[8,12].

1.2 The responsibilities of necessary and discretionary consumption for PB transgressions

Distinguishing responsibilities between necessary and discretionary consumption is important for creating effective, equitable, and impactful environmental policies. It ensures that mitigation strategies are targeted and efficient, addresses social justice concerns, focuses on high-impact areas to reduce PB transgressions, and promotes sustainable consumption behaviors. Some environment footprints are generated to meet essential human needs, such as accessing basic food and clean water. Others are discretionary, such as flying long-distance for holidays or driving luxury cars. In other words, some environmental footprints are driven by affluent consumption rather than essential human needs[13]. Thus, it is important to identify the responsibilities of necessary and discretionary consumption for PB transgressions.

However, there is no clear-cut way to classify goods and services as discretionary or necessity. There is a certain subjectivity in any classification and definition, as what is considered discretionary to one individual might reasonably be classified as a necessity to another. In addition, consumption patterns depend on local supply capabilities, culture and other factors. Here, we discuss the responsibilities of necessary and discretionary consumptions responsibilities for PB transgressions based on the expenditure elasticity theory[14,15]. Discretionary goods are typically defined as having an expenditure elasticity greater than 1, while necessities have an expenditure elasticity less than 1. For example, most plant-based foods have an expenditure elasticity of less than 1, indicating that they are necessary goods (Supplementary Fig. 7). In contrast, most services are discretionary (expenditure elasticity > 1), with air transport having the highest elasticity.

To obtain the expenditure elasticity for a given consumption category in a given country, we run a log–log regression of per capita spending on the consumption category by individual expenditure percentile on the total expenditure per capita of the expenditure percentile, mathematically[15–17]:

$$\log D_i = a + b \log W_i \tag{1}$$

where i stands for the expenditure percentile. The coefficient b is the expenditure elasticity of the given consumption category in the given country. The global expenditure elasticity for each consumption category is the population-weighted average of the 168 countries' expenditure elasticities[16].

Based on this classification, we investigate the responsibilities for PB transgressions associated with necessary and discretionary consumption. As can be seen in Supplementary Fig. 8, the wealthier groups tend to have higher shares in discretionary consumption, while poorer groups have high shares in necessary consumption. For the global bottom 10%, the environmental pressure induced by their necessary consumption account for 39%-92% of their total footprints in all six environmental indicators. In contrast, for the global top 10%, this figure ranges from 19% to 64%. Furthermore, Supplementary Fig. 9 shows that the discretionary consumptions of the top two deciles group are the main driving force for PB transgressions in climate change and biosphere integrity, accounting for 60% and 63%, respectively. The shares of discretionary consumptions of these two deciles in land system change, nitrogen flows, phosphorus flows reach 28%, 20%, and 17%, respectively. This analysis underscores the importance of targeting high-end discretionary consumption in mitigation strategies to reduce PB transgressions effectively.

2. Extended discussion on the results

2.1 Discussion on the global unequal environmental impacts

The analysis of global, country and expenditure-specific environmental footprints highlights the striking inequality of per capita environmental impacts and responsibilities for PB transgressions. Our findings confirm the existence of severe global environmental pressures and inequality between countries, as previously reported by Rammelt et al.[18], O'Neill et al.[8], Lucas et al.,[7] and Kickel et al.[19], among others, and further delineate disparities within and between countries.

Our study comprehensively and consistently maps the distribution of six key environmental footprints and their responsibility for the transgression of PBs across consumer percentiles, providing new and more comprehensive insights than existing literatures[16,20–22]. The results indicate that the world's top decile of global consumers have per capita footprints 4.2 to 77 times higher than those of the bottom decile. This gap is significantly wider than that between high-income and low-income countries[18]. Previous studies have also highlighted that most of the inequality in terms of current carbon emission is due to differences between low and high emitters within countries rather than between countries [20]. Therefore, we argue that within-country inequality requires urgent attention in global environmental governance and policy implementation (Supplementary Figs. 1-6), especially considering that mitigation policies are usually formulated on a national or regional basis rather than targeting specific groups[23].

Developing countries may also have global high-end consumers with substantial environmental impacts. Universal mitigation policies, such as carbon taxes, often disproportionately affect low-expenditure consumers, leaving the super-rich relatively unaffected[14,24,25]. Implementing targeted compensation and revenue recycling within countries is becoming increasingly important[25]. This approach could potentially facilitate a reciprocal balance between ecological restoration and the protection of vulnerable social groups, fostering a scenario where environmental sustainability and social equity are mutually reinforced.

In addition, diversified mitigation strategies are also necessary. As we probe into the intricacies of environmental impact and expenditure, it becomes evident that climate change and biosphere integrity are most strongly influenced by expenditure growth[20,21]. Controlling consumption and adopting greener consumption patterns emerge as effective pathways to mitigate the transgressions of PBs[26]. However, other PBs, such as nitrogen and phosphorus flows, while performing better in efficiency improvement scenarios, have footprints derived from the consumption of lower-expenditure groups in developing countries that also exceed the per capita PBs. This implies that the existing provisioning systems associated with nitrogen and phosphorus flows may necessitate comprehensive restructuring to align with the limitations imposed by PBs[27]. Although freshwater use does not breach boundaries, this does not address the critical issue of local water scarcity[8,28]. Previous studies have also shown the asymmetric relationship in water use between the affluent and low-consumption segments at the city scale[29]. Therefore, addressing local water boundary issues may warrant significant attention in future research endeavors, ensuring that strategies are localized and context-specific to address the multifaceted challenges posed by varying environmental pressures.

2.2 Discussion on consumption transition of the affluent consumers

Our study emphasizes the significant environmental benefits of the transition of high-end consumers to more sustainable practices. If the global top 20% of consumers adopt the consumption levels and patterns which have the lowest environmental impacts within their group, global environmental pressure can be effectively alleviated, fully mitigating PB overshoots related to land system changes and biological diversity.

The service and food sectors are the primary focus of mitigation strategies for high-end consumers (Fig. 4 and Extended Data Fig. 7). For the food sector, the health and environmental benefits of dietary changes that reduce red meat consumption and increase vegetable intake have been well-documented. For example, Grummon et al.[30] found that simple dietary substitutions, such as replacing beef with chicken, can significantly improve dietary quality and reduce carbon footprints. Prospective studies, including the EAT–Lancet planetary health diet[31], highlight that a substantial transformation in food consumption is both necessary and achievable.

The most affluent group has a particularly large potential for positive impact, as their dietary habits often have a greater environmental impact and influence consumption norms[13]. Our quantitative assessment and mitigation scenarios show that the tertiary industry, particularly services, should be the next focus for addressing the impact of affluent consumers. Despite being often overlooked in public policy due to perceived lower environmental impact, the significant consumption of services by affluent groups and the extensive supply chains effect of the service sector generate enormous environmental impacts. For example, Lenzen et al. found that global tourism alone contributed to about 8% of global greenhouse gas emissions in 2013[32]. Compared with the food sector, the service sector has more luxury attributes and presents a higher mitigation prospect.

There are challenges in implementing mitigation measures that target the affluent groups. Firstly, reducing consumption in current capitalist economies can sometimes imply widespread economic recession with socially spillover effects, such as unemployment and firm bankruptcies[33]. Theories and methods proposed over the past decades, such as steady-state economy and degrowth[33,34], offer potential solutions beyond the current capitalist model. Hickel[35,36], and Keyßer et al.,[37] as well as Slameršak et al.[38], have suggested viable pathways to limiting global warming to 1.5° C. Some studies[39] based on dynamic macrosimulation suggest that enhanced social security could address these issues. All these studies emphasize the need for an orderly and gradual transition.

Targeted approaches may be more effective. For example, Oswald et al.[15] found that luxury-focused carbon taxation can improve fairness of climate policy. Additionally, as discussed in the Main, affluent groups typically wield greater political power. Bottom-up movements may be crucial in making mitigation measures effective. Proposals targeting the affluent, such as reducing overconsumption, promoting rational consumption patterns, and reducing inequality, often receive support in surveys and citizens' assemblies [40]. Bottom-up social movements have proven effective in pushing for political programs, changing values, and promoting low-carbon consumption cultures. They have played an indispensable role in climate change response decision-making processes over the past decades[41].

Finally, we argue that long-term and systematic solutions are necessary for addressing affluent consumption. Our study reveals the enormous potential of transitioning affluent consumers, providing new quantitative evidence for this debate[2,33,42–44].

3. Limitations and uncertainty

3.1 EEMRIO Analysis

The environmental extended multi-region input-output model (EEMRIO) is widely used to estimate the global environmental impact of consumption and trade, particularly, in analyzing environmental footprints such as carbon, water and biodiversity footprints[45,46]. EEMRIO analysis relies on MRIO tables and environmental extended accounts, which are primary sources of uncertainties. Wiedmann et al.[47] have summarized these possible uncertainties, and subsequent studies[48] have further explored them. Generally, MRIO tables suffer from more uncertainty than single-region IO tables, primarily due to fluctuations in monetary exchange rates, the treatment of aggregated regions, and the combination of different country-specific input-output tables with varying definitions and economic sectors.

In general, the largest contributors to uncertainty in consumption account results are, in descending order of priority: the total of territorial environmental extension accounts, the allocation of environmental impacts to economic sectors, the total and composition of final demand, and the structure of the economy. Aggregating economic activities with different environmental impacts can lead to sector aggregation error[49]. However, previous studies[50] have indicated that aggregation errors are relatively limited in the footprints accounting of households or nations, where footprints are determined by the product of sector multipliers and consumption volumes.

The EEMRIO model cannot differentiate between the quality and quantity of consumer goods (e.g., a cheap car versus a premium car). Higher expenditures typically lead to higher environmental impacts because the Leontief production function is linear in the input–output model[46]. Another source of uncertainty stems from missing data, which necessitates imputation and balancing procedures to ensure consistency. Environmental extended accounts also contribute significantly to uncertainties in consumption-based accounting. Despite these challenges, EEMRIO remains one of the most widely used and mature approaches for estimating the environment impacts of consumption on a macro-scale.

GTAP is one of several well-known MRIO databases widely used worldwide, including Exiobase, Eora, WIOD, EMERGING, and others. Compared to other databases, GTAP has high regional resolution and relatively higher agricultural sector resolution, which is the main source of many PB pressures. Andrew and Peters[51] and Aguiar et al.[52] have described the construction and the uncertainties of GTAP database. Rodrigues et al.[48] reported limited errors between various MRIO databases, further supporting the reliability of our approach.

3.2 Household survey data

There are some limitations and uncertainties in Household survey data (HSD). The first one is the uncertainties of underreporting. The respondents may have some recall bias for the infrequent purchases, may be reluctant to report purchases that are socially undesirable, and may mismatch expenditures to purchased items. In addition, certain bias of sample selection may exist in the survey process, with some groups being hardly incorporated into the survey. Especially, HSD often has shortcomings in capturing rich/wealthy households/individuals[26,53], which may result in an underestimation of inequality. All these factors lead to some gaps between the HSD and household demand in the System of National Accounts (SNA). Previous case studies in Germany have shown that this gap can reach up to 15.3%[54]. Secondly, different sources of HSD with different surveying times from 2011 to 2017 are used in this study based on data availability, including World Bank Global Consumption Database (WBGCD), Eurostat Household Budget Survey (HBS), and Japanese Family Income and Expenditure Survey (FIES). The monetary values of expenditures from various HSD database are reported by different purchaser prices in different years. Finally, when linking the consumer expenditure in HSD to the MRIO database (GTAP), there is an issue of inconsistent classification, where HSDs adopt the classification of individual consumption by purpose (COICOP) with purchaser prices and MRIO tables adopt the classification of economic sector with producer prices.

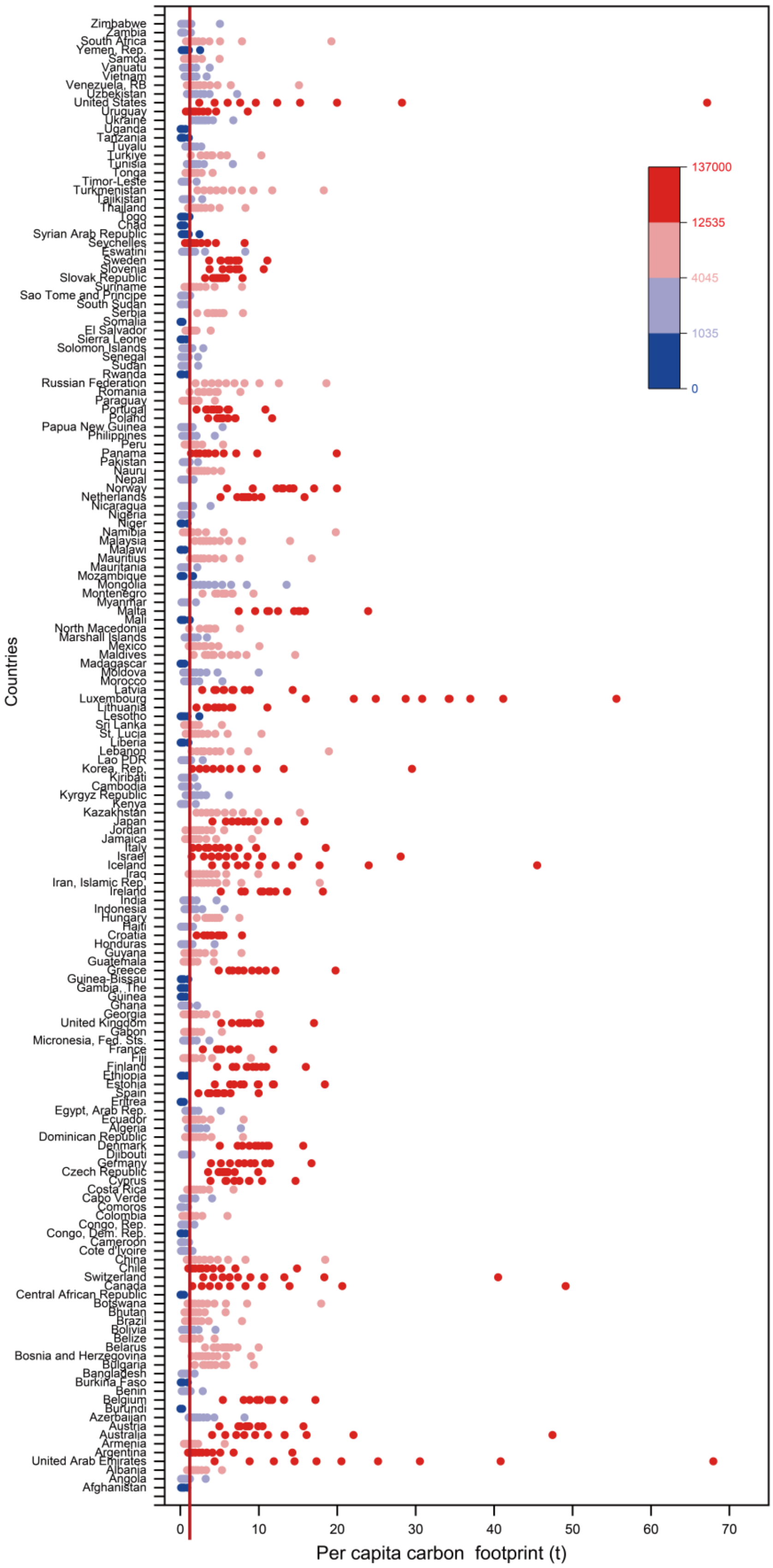
We use the RAS-based method to cope with the inconsistent problem among various HSD data sources as well as between HSD data and MRIO table[16,17,55,56]. In the reconciliation process, GTAP data on household demand is set as the benchmark. Using the concordance matrix of sectors, the household demand vector for each country in GTAP are disaggregated to multiple vectors for expenditure groups. In other words, the information we retrieve from the HSD data is the expenditure shares rather than the monetary values of expenditures and our analysis is still based on basic prices (producer prices) in 2017. It is implicitly assumed that the relative expenditure structures between different expenditure groups remain unchanged from 2011 to 2017. We argue that this assumption is acceptable as the consumption (expenditure) structure changes slowly and the relatively structure between different income (expenditure) groups in each region may be stable due to habit persistence and other social-cultural reasons. This approach has been adopted in many studies when the data is limited[57,25,58].

3.3 Estimation of inequality in environmental responsibility

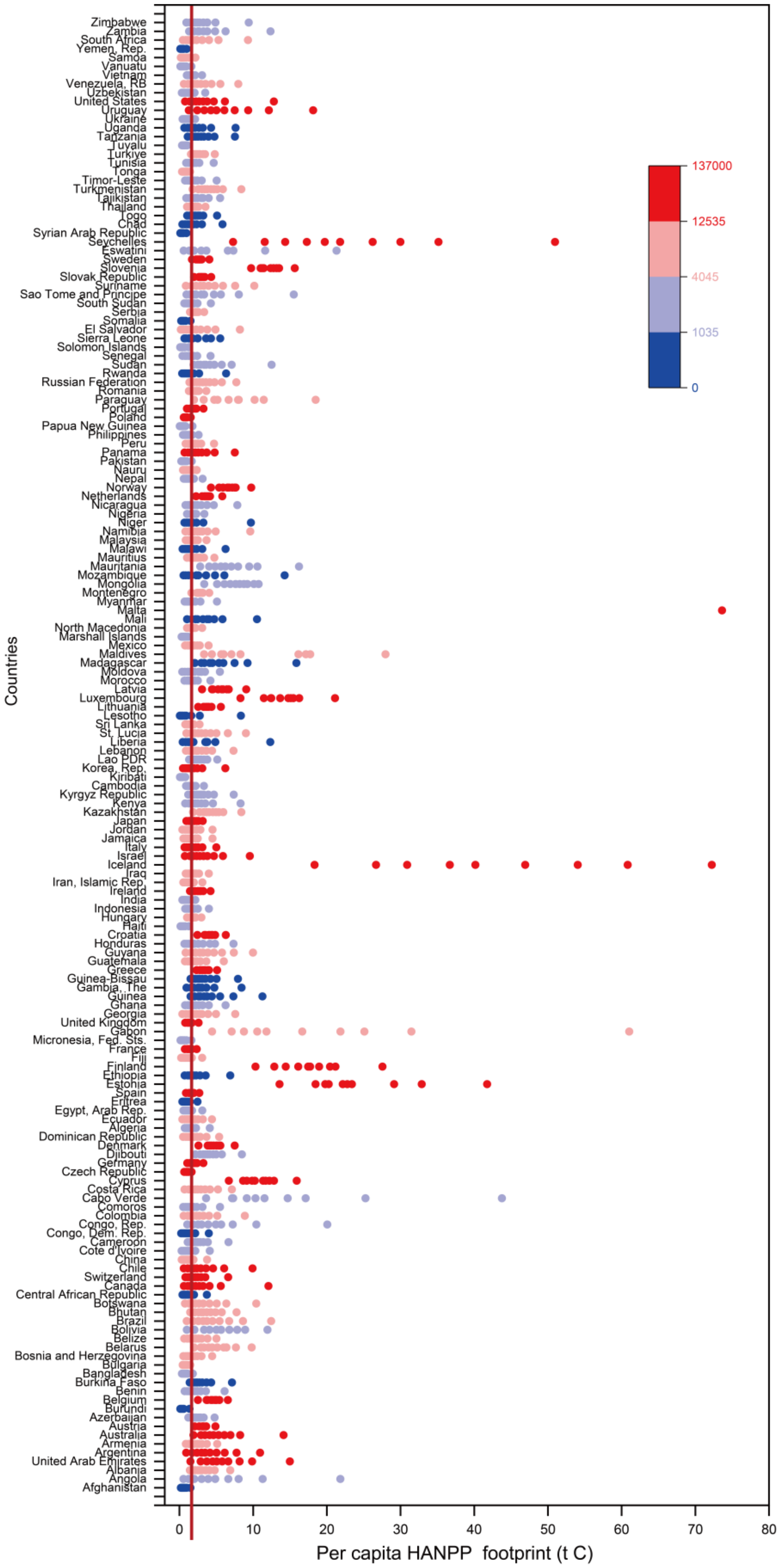
Firstly, there are some uncertainties in using household expenditure survey (HES) data to estimate environmental footprints, as HES data only capture paid items for goods and services. This study does not account for consumption with environmental impacts that are not captured by macro-economic system. For example, subsistence energy sources (e.g., wood, charcoal and solid waste) also cause carbon emissions. Non-market consumption is usually more common in low-income countries and groups[21]. This may lead to an underestimation of environmental footprint of low-income groups. Additionally, there is a certain bias in sample selection in the surveys, and some groups are hardly incorporated. Especially, HES data have limited ability to capture super rich individuals/households, which may lead to an underestimation of actual inequality[26]. We acknowledge that we may underestimate the environmental footprints of global top 1% (Extended Data Fig. 2). Furthermore, as mentioned before, The EEMRIO model cannot differentiate the quality and quantity of consumer goods and services, which may lead to an overestimation of the environmental impacts of expensive products[57].

Secondly, we have to assume that the final demand from government and investment in different consumption segments would follow the same distribution as household consumption, in the absence of additional pertinent information. This means that higher household spending corresponds with higher investments and government spending in a sector. The uncertainties mainly come from the estimation of investment because government spending typically has relatively lower environmental impacts. This assumption may also lead to the underestimation of inequality in environmental footprints among income groups. Chancel [20] pointed out that investment-related carbon emission are far more concentrated among affluent groups compared to consumption expenditure, leading to more unequal estimates of carbon footprints in his study.

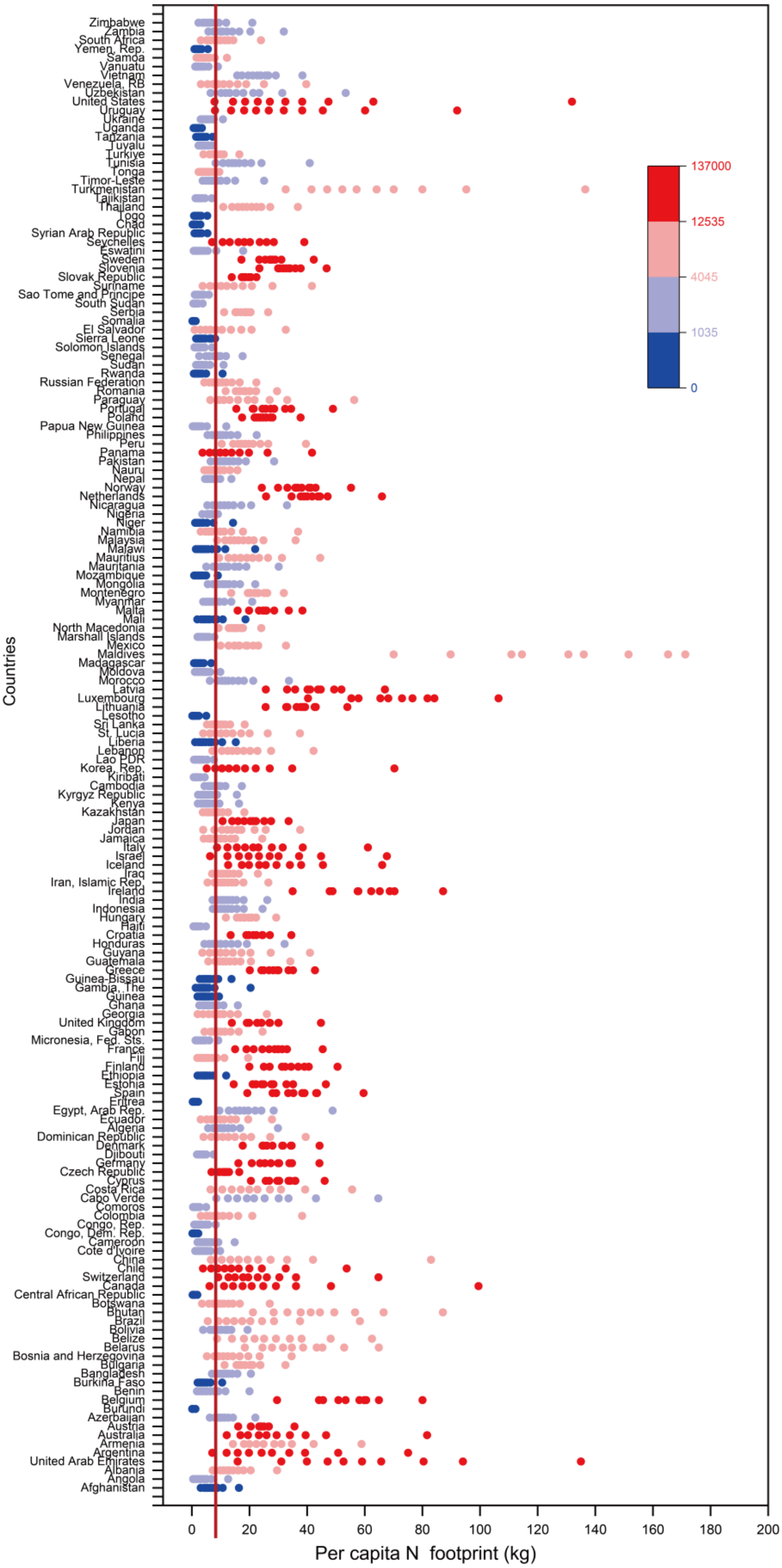
Finally, our analysis of the responsibility for PB transgression is based on the independent analysis of PB indicators, similar to previous studies[7–11,59]. However, it is important to recognize that the indicators representing various PBs interact with each other. For example, changes in the land system can influence climate change, and ocean acidification is almost entirely driven by CO_2 emissions. Lade et al.[60] and Steffen et al.[61] have discussed this issue and found that the interplay between the planetary boundaries can lead to cascades and feedback loops, amplifying human impacts on the Earth system. They argued that the actual safe operating space for future human impacts should be smaller than evaluations based on single indicators suggest. However, due to the complexity of these interactions, it is challenging to quantify these compounded effects with current framework. This complexity indicates that our estimates of ecological overshoot and the responsibility for PB transgression are optimistic, and the actuality may be even worse. Furthermore, from the perspective of historical responsibility, the high-income groups and countries should bear a greater responsibility for ecological breakdown, as they have contributed more significantly to environmental degradation over time.



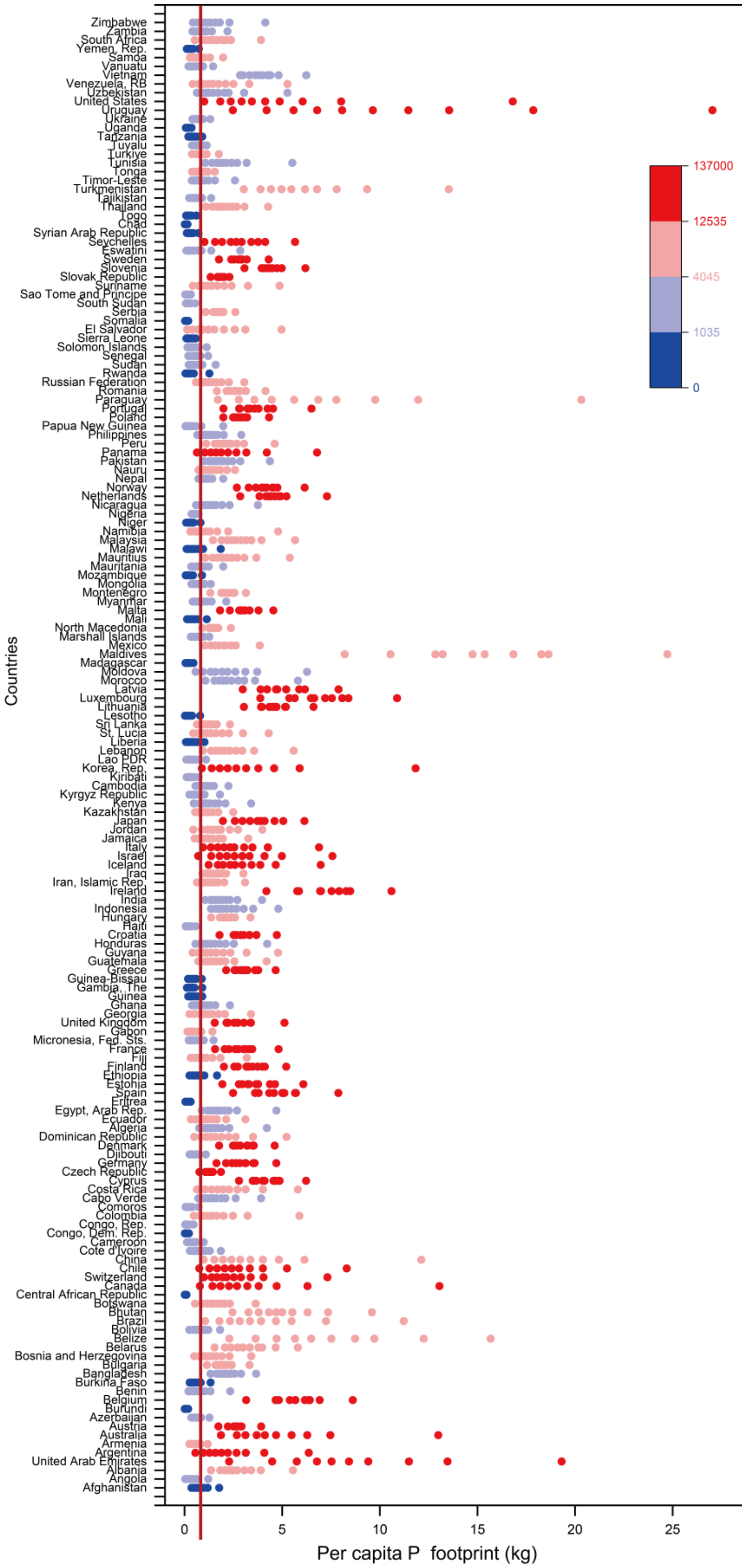
Supplementary Figure 1 Per capita carbon footprints by national decile in 168 countries. The red vertical line is per capita planetary boundary



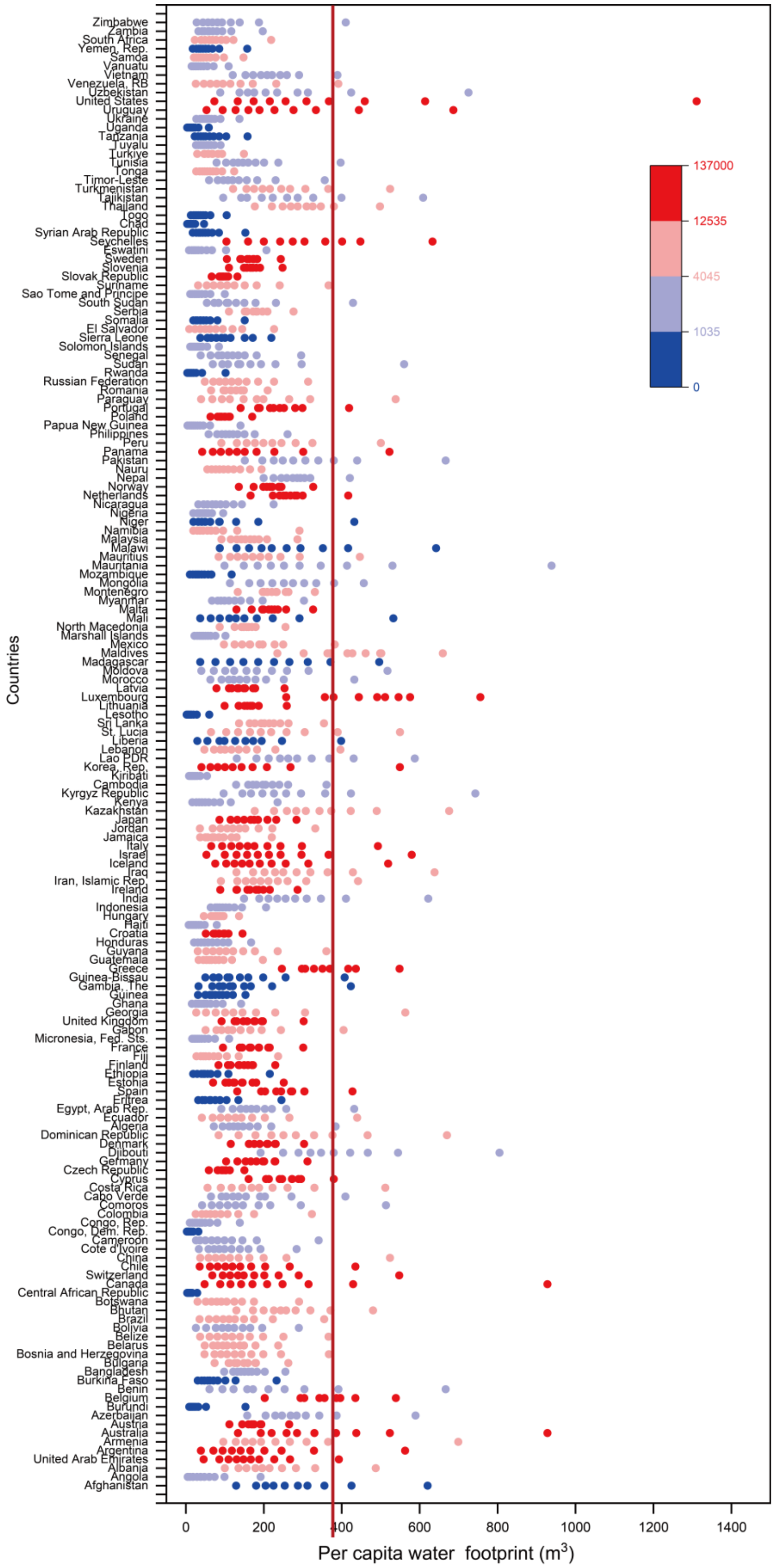
Supplementary Figure 2 Per capita HANPP footprints by national expenditure decile in 168 countries. The red vertical line is per capita planetary boundary



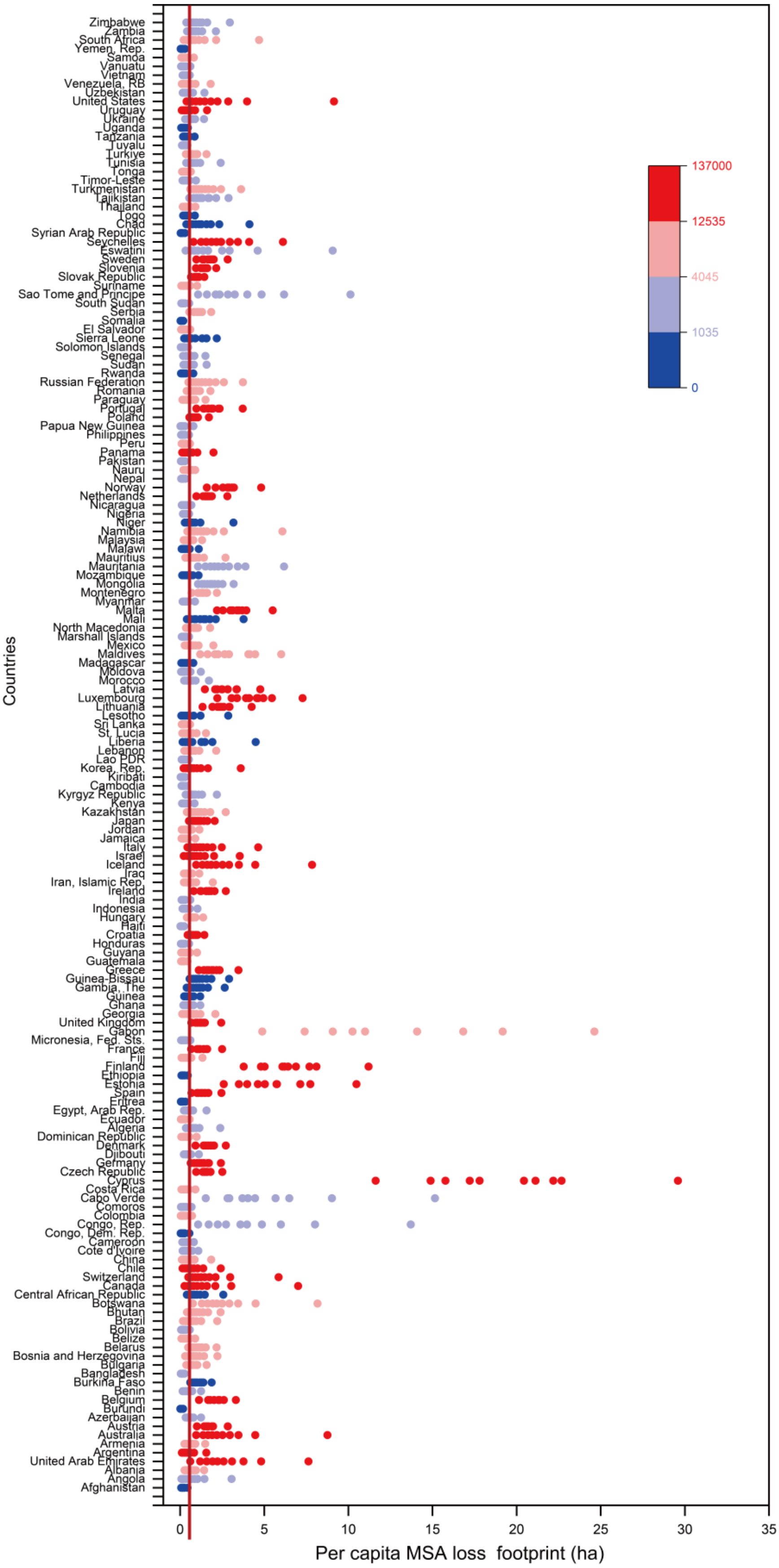
Supplementary Figure 3 Per capita N footprints by national expenditure deciles in 168 countries. The red vertical line is per capita planetary boundary



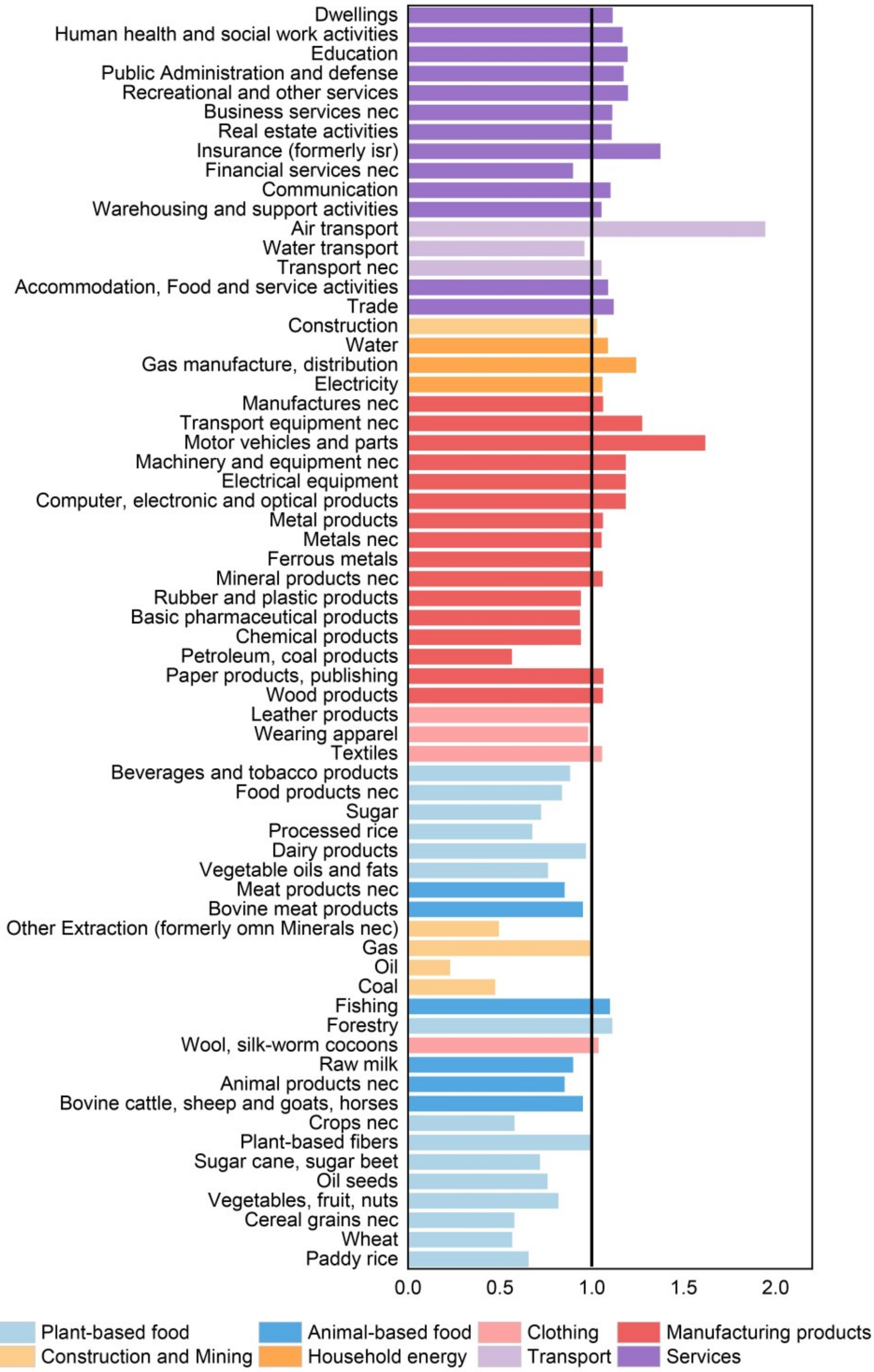
Supplementary Figure 4 Per capita P footprints by national decile in 168 countries. The red vertical line is per capita planetary boundary



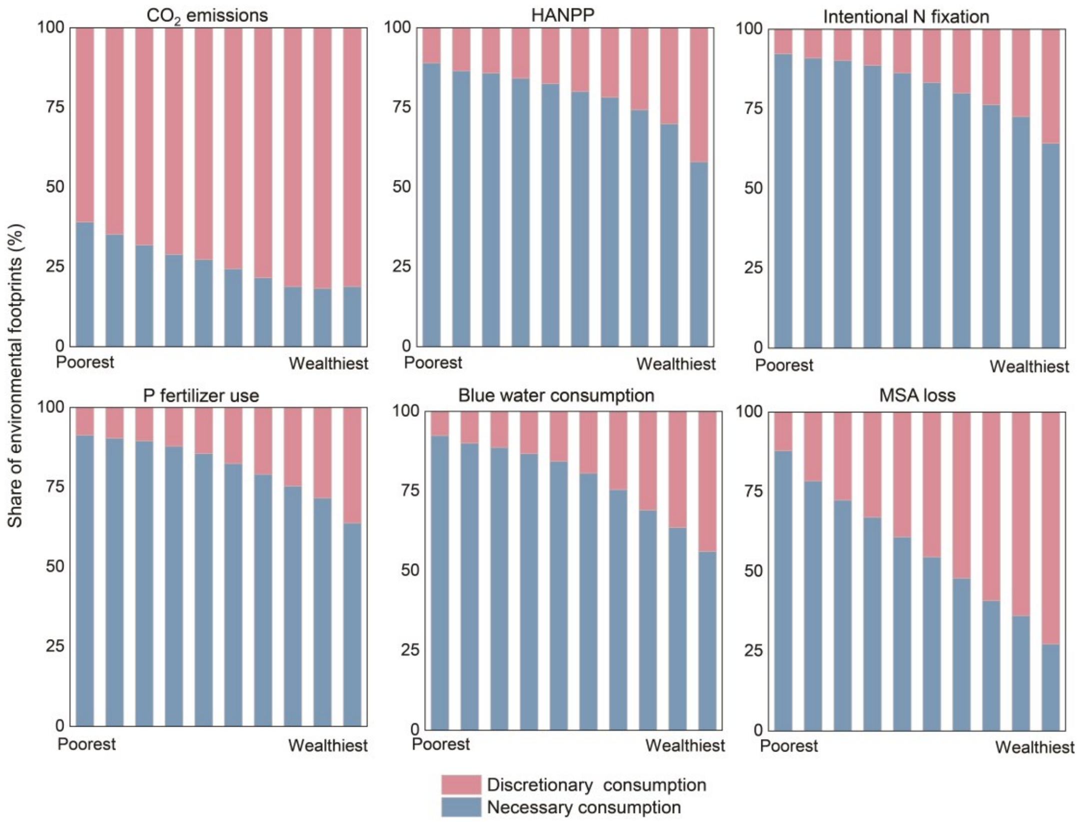
Supplementary Figure 5 Per capita water footprints by national expenditure decile in 168 countries. The red vertical line is per capita planetary boundary



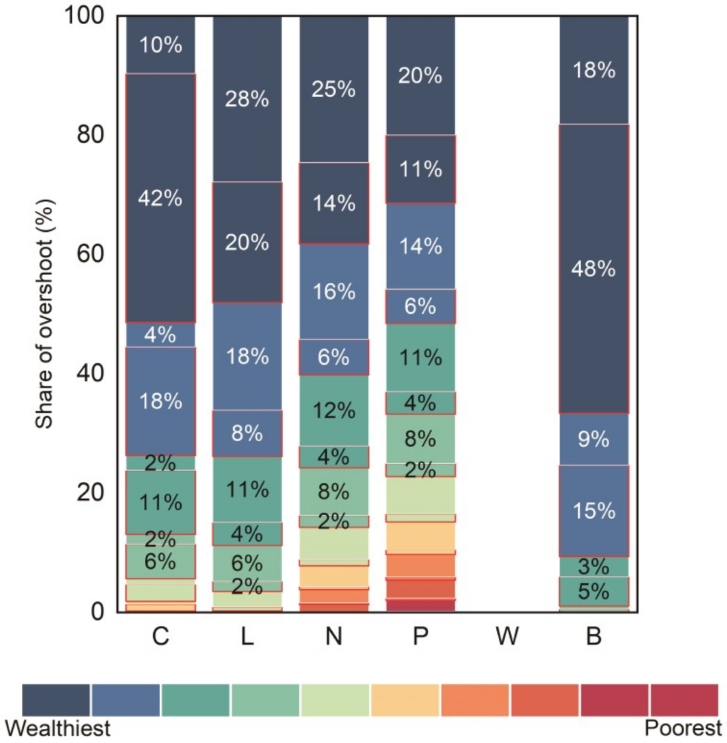
Supplementary Figure 6 Per capita MSA loss by national expenditure decile in 168 countries. The red vertical line is per capita planetary boundary.



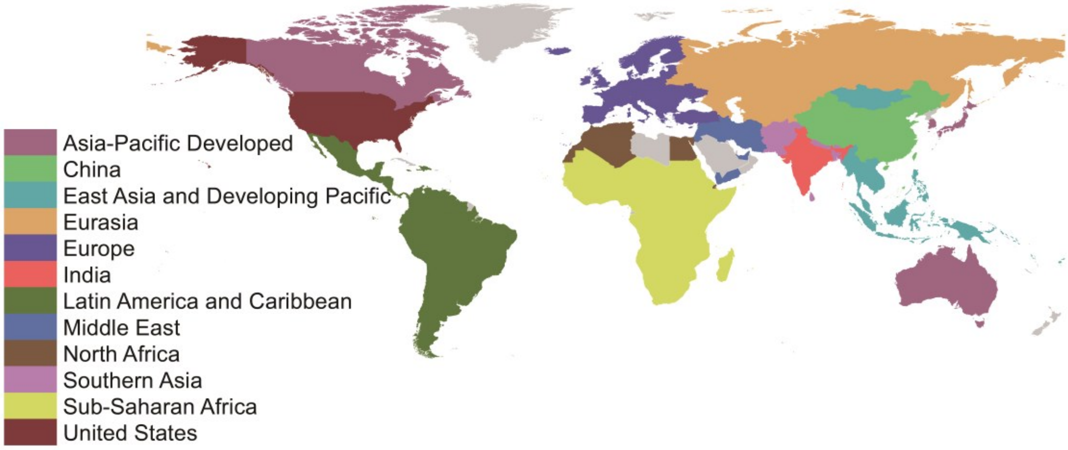
Supplementary Figure 7 Sectoral expenditure elasticity. Sectors classification is consistent with GTAP. The global sectoral expenditure elasticity is the population-weighted average of 168 countries' expenditure elasticities (Supplementary Information Section 2.2).



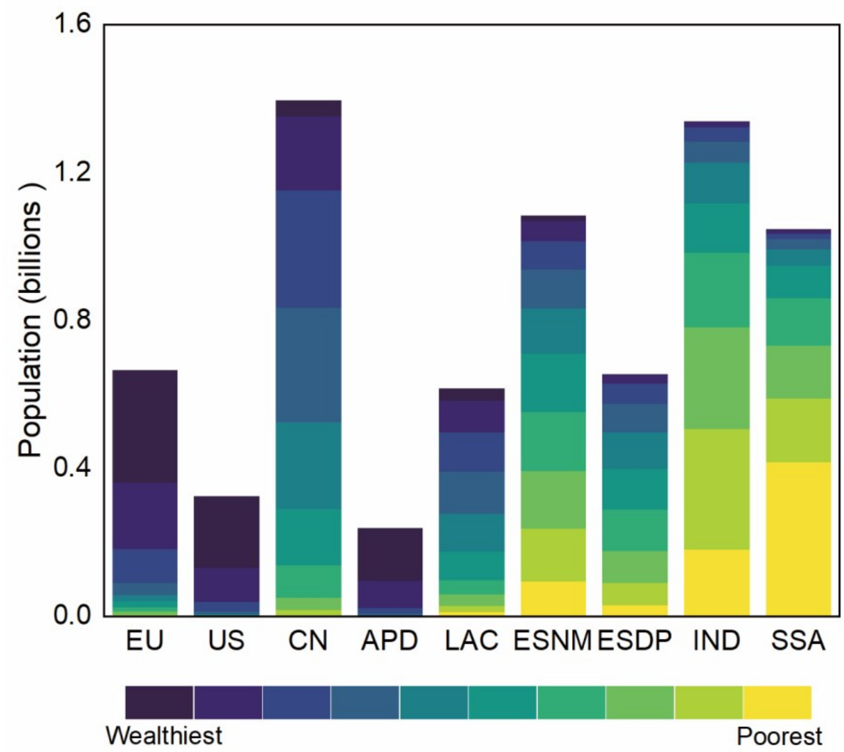
Supplementary Figure 8 Composition of the six environmental footprints across global consumer deciles and by discretionary versus necessary consumption.



Supplementary Figure 9 The shares of overshooting planetary boundaries by global expenditure deciles. The responsibility of each expenditure group is divided into two boxes, with the lower one (bordered in red) refer to the responsibility of discretionary consumption.



Supplementary Figure 10 The world region classification adopted in this study.



Supplementary Figure 11 The distribution of global expenditure deciles of consumers. The global deciles of consumers are classified by expenditure level. 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.

Supplementary Table 1 Global performance of the six key environmental indicators concerning per capita planetary boundaries

Planetary boundary	Indicators	Global budget	Per capita boundary	Per capita pressures (2017)
Climate change	CO_2 emissions	7 Gt CO_2 yr^{-1}	0.95 t CO_2 yr^{-1}	3.8 t CO_2 yr^{-1}
Land system change	HANPP	10.8 Gt C yr^{-1}	1.47 t C yr^{-1}	1.97 t C yr^{-1}
Biogeochemical flows	Intentional N fixation	62 Tg N yr^{-1}	8.5 kg N yr^{-1}	13.7 kg N yr^{-1}
Biogeochemical flows	P fertilizer use	6.2 Tg P yr–1	0.85 kg P yr^{-1}	2.58 kg P yr^{-1}
Freshwater use	Blue water consumption	2800 km^3 yr^{-1}	384 m^3 yr^{-1}	220 m^3 yr^{-1}
Biosphere integrity	MSA loss	3724 Million MSA-loss · ha yr^{-1}	0.51 MSA-loss · ha yr^{-1}	0.67 MSA-loss · ha yr^{-1}

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