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Global and National Safe and Just Operating Space for Humanity

María Fernanda Godoy León

fernanda.godoy@leuphana.de

Leuphana University Lüneburg https://orcid.org/0000-0003-1073-1758

David Abson

Leuphana University https://orcid.org/0000-0003-3755-785X

Article

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Abstract

Achieving a "safe and just operating space for humanity" requires reconciling global equity with national biophysical realities. We compare consumption-based environmental footprints of 158 countries against both national ecological carrying capacities (NECCs) and equitably downscaled global boundaries for six pressures: land use (cropland, pasture, forest), blue water, nitrogen, and phosphorus. Three main findings emerge. First, 40-60% of the global population could theoretically meet consumption needs domestically, yet many high-income nations maintain current consumption only via appropriation of other nations' resources. Second, around 30-50% of the population consumes below global fair shares yet exceeds domestic capacities, revealing that equal per-capita allocation alone cannot ensure sustainability. Third, a "contraction and convergence" scenario demonstrates sufficient global capacity exists when high-income nations reduce consumption substantially while low-income countries increase consumption to meet wellbeing thresholds. This identifies distributional inequity, rather than absolute scarcity, as the primary sustainability barrier.

Sustainability is generally understood as an intra- and inter-generational justice concern, premised on “meeting the needs of the present without compromising the ability of future generations to meet their own needs” (United Nations, 1987). In the attempts to concretize/operationalize this conception of sustainability, the idea of a “safe and just operation space for humanity” (Rockström et al., 2009) has become an increasingly important and influential approach (Oliver et al., 2022). Where ‘safe’ is typically understood as a state in which the environmental pressures caused by economic activity do not transgress global thresholds (ecological ceilings) of key global earth system processes that would compromise the wellbeing of future generations (Leach et al., 2013). In turn, ‘just’ is typically understood as achieving a minimum acceptable state of wellbeing (social floor) for the current human population (Raworth, 2017). As important as the notion of a “safe and just space for humanity” is, we identify three major challenges with these attempts to define sustainability thresholds.

Firstly, assessing ‘ecological safety’ at the global scale, potentially hides significant spatial differences in the functioning of those key Earth system processes. It is possible that global thresholds are respected while multiple local thresholds are exceeded with significant social and ecological consequents (Nykvist, 2013; Steffen et al., 2015). Therefore, both national and global ecological limits need to be considered when considering what constitutes a ‘safe’ ecological space for humanity. Secondly, due to the globalized nature of economic systems, there are spatial disconnects between where those environmental burdens are experienced and where the benefits of that appropriation occurs (Dorninger et al., 2021). Therefore, the ‘safe’ ecological space for humanity is also fundamentally an intra-generational justice concern that must explicitly address spatial patterns of resource appropriation and use. Thirdly, over consumption

in some nations may be offset by underconsumption elsewhere (Rice, 2007). Therefore, the assessment of both global and national ecological boundaries should consider not just current levels of consumption, but what would constitute safe and just levels of consumption in a world where everyone has access to sufficient resources required to achieve a good life. Finally, the social floors are typically defined in terms of social outcomes (e.g., O'Neill et al. (2018)) that are not explicitly linked to the ecological resources required to achieve them. This creates a conceptual disconnect between ecologically defined ceilings and social defined floors, which in turn limits our ability to understand the interdependences or trade-offs, between intra- and inter-generational justice concerns.

In this paper we address the first two challenges (the existence of both national and global ecological limits and the distribution of benefits and burdens) by comparing nation consumption-based environmental footprints against: 1) an equitable per-capita downscaling of global environmental pressures (i.e., do the population of a given country use more than their 'global fair share' of permissible environmental pressures relating to their consumption footprints); 2) the appropriation of national and extra-national ecological carrying capacity (i.e., whether or not nations can theoretically meet their current consumption demands with their own ecological resources or only by the over appropriation of other nations' ecological carrying capacity). We define national ecological carrying capacities (NECCs) as the biophysical limits to resource availability and assimilative capacity within a country's borders. For resources (e.g., water), NCCs represent the maximum sustainable extraction rate that maintains ecosystem functionality. For emissions (e.g., nitrogen), they represent the maximum pollution load that ecosystems can assimilate without degradation.

The third and fourth challenges (the role of underconsumption in defining safe and just spaces for humanity, and the explicit linking of social floor and ecological ceilings) are addressed by establishing benchmark consumption levels (from nations with high social welfare – based on the Social Progress Index (SPI) (Harmacek & Krylova, 2023) – with comparatively low environmental footprints) that are used to identify 'spare' NECCs (the difference between a country's carrying capacity and its consumption) once social floors are meet, and therefore, what constitutes 'safe and just' appropriation of resources outside of national boundaries.

Our approach (Figure 1) is applied via global analysis of 158 countries related to six location-specific environmental pressures — land use (cropland, pastureland, and forest land), blue water consumption, and nitrogen and phosphorus emissions. Using an EEMRIO framework based on the Eora database (2017), we estimate consumption-based environmental footprints for these pressures. We express all footprints and NECCs on a per capita basis to enable cross-country comparison.

This multi-scalar approach reveals not only where national consumption overshoots local ecological limits, but also the extent to which countries could be self-sufficient — meeting their consumption needs from NECCs alone. Spare capacity indicates the potential magnitude of resources that self-sufficient nations could share with deficit countries through trade. Critically, we identify 1) where equality-based global resources hide resource allocation patterns that transgress NECCs add 2) what kinds of changes in resource appropriation via "contraction and convergence" (Meyer, 2000) would be required to create a genuinely safe and just operating space for humanity at both the national and global level.

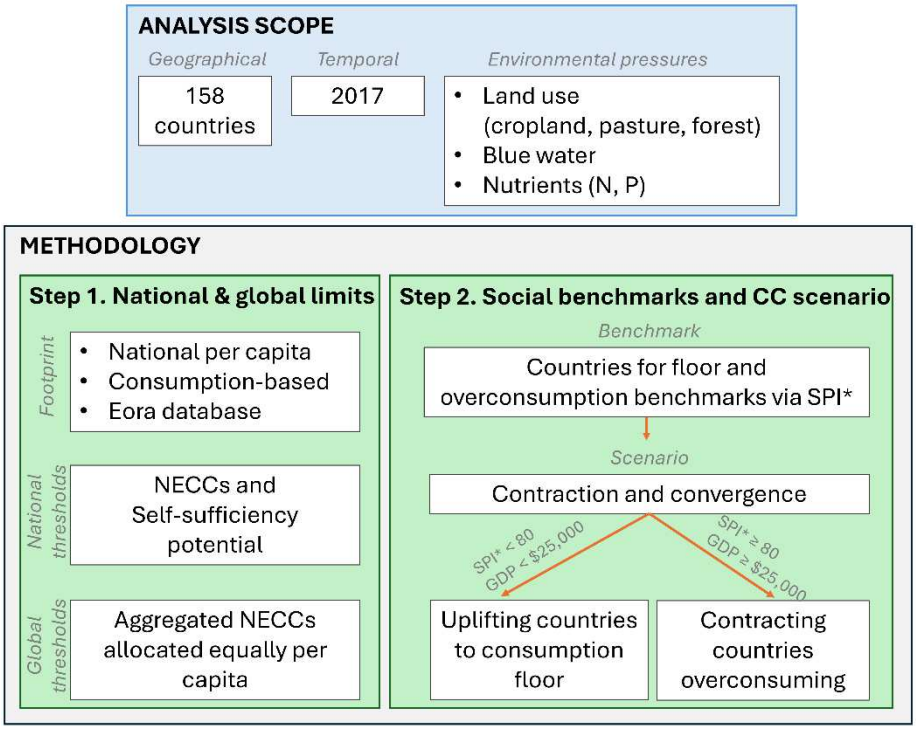


Figure 1. Schematic representation of the research. N: nitrogen, P: phosphorus, NECCs: national ecological carrying capacities, CC: contraction and convergence, SPI: modified Social Progress Index.*

1. Results

1.1 Transgression of national ecological carrying capacities

We first examine the production footprints — the environmental pressures generated within each country's borders — as these reveal the actual utilization of their NECCs. Figure 2 presents the global distribution of production-to-NECC ratios for six environmental pressures (hereafter called simply pressures): cropland, forest land, and pastureland (henceforth forest and pasture) use measured in global hectares (gha), and blue water consumption, nitrogen (N) and phosphorus (P) emissions measured in m^3. Nitrogen and phosphorus emissions are quantified as water pollution levels, comparing grey water footprints to runoff following Mekonnen & Hoekstra (2015, 2018).

The maps reveal highly uneven spatial distribution of pressures across countries, with each pressure showing distinct patterns. In general, North African and Asian countries such as Algeria and India exhibit ratios exceeding one for most pressures, indicating overexploitation of their NECCs. Forest, N, and P show the highest ratios and therefore the most severe national overshoot. Pasture use ratios are constrained to a maximum of one, as this represents the total above-ground net primary production available annually; year-on-year overshoot is therefore not physically possible under this accounting framework (Lin et al., 2019).

Trade patterns differ markedly between absolute and per-capita metrics. In absolute terms, the USA and China are simultaneously top importers and exporters across nearly all resources, reflecting their dual roles as major producers and consumers. Other leading absolute exporters include developed economies (Australia, France) alongside developing nations (Pakistan, Ethiopia — both major N and pasture exporters). Large, wealthy industrialised economies (USA, China, Japan, Germany, Russia) dominate absolute imports. Per capita export intensities are highest in sparsely populated, export-oriented agricultural economies, such as New Zealand and

Australia. Per capita import dependence is most pronounced in small, wealthy city-states with negligible domestic production: Luxembourg, Hong Kong, and Switzerland. For more detail see the Supplementary Information (SI-A1).

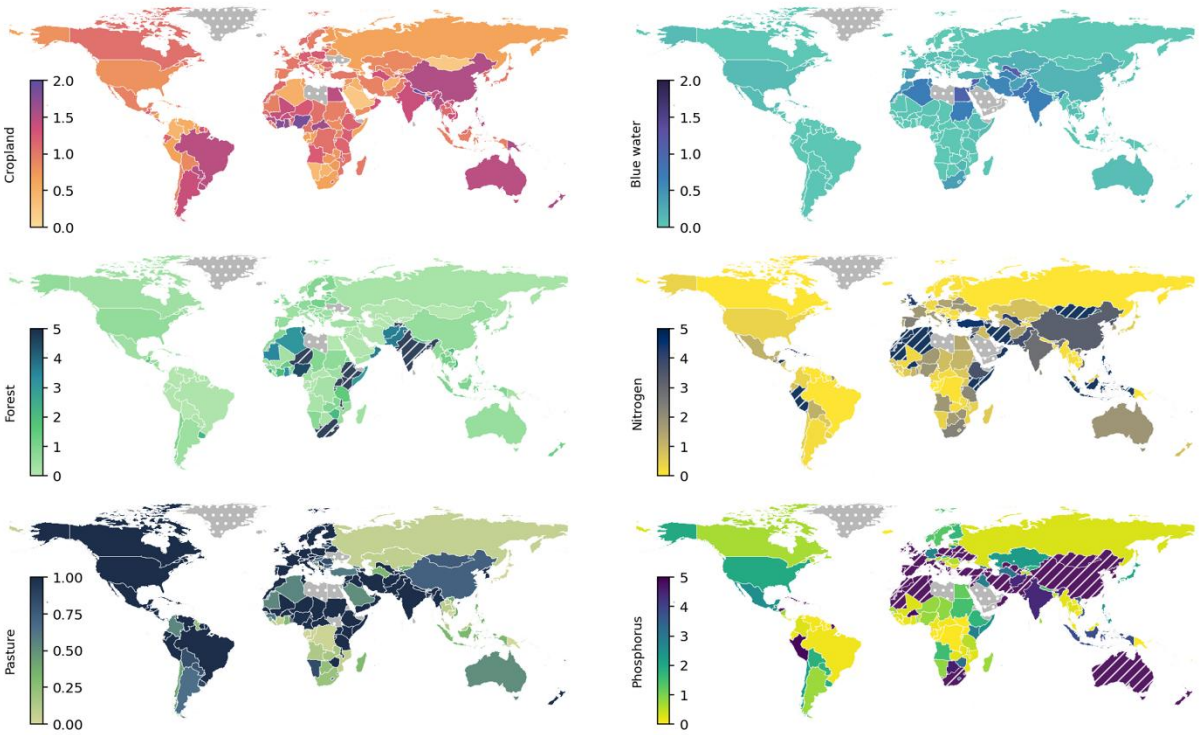


Figure 2. Ratio of the production footprint to the national ecological carrying capacity (NECC) per country. A score of 1 indicates that 100% of the NECC is used in national production. Grey countries with white dots indicate countries for which there is no data. Diagonal lines indicate countries with a ratio higher than the upper limit of the respective legend bar.

1.2 Self-sufficiency potential and thresholds comparison

Given the uneven distribution of pressures and trade patterns, we assessed the national self-sufficiency potential by comparing per capita total consumption footprints (domestic supply plus the embodied footprints from imports) against both NECCs and equally per capita allocated global boundaries. Figure 3 illustrates this approach using cropland, with countries grouped by the World Bank income classification (World Bank, 2026), and divided into terciles based on consumption-to-NECC ratios (from lower to higher values). These terciles generally separate countries with ratios below 1 (T1), around 1 (T2), and above 1 (T3), though for blue water terciles simply range from lowest to highest ratios. Results for the remaining five pressures appear in the SI (SI-B2).

For cropland, the first tercile (T1, upper panel) comprises predominantly low-, lower-middle-, and upper-middle-income countries with few high-income nations. The second tercile (T2, middle panel) shows more even income distribution. The third tercile (T3, bottom panel) is dominated by high-income countries, showing only a few low-income countries. The panel shows a lower self-sufficiency potential for high-income countries driven by both lower NECCs and higher consumption footprints. Approximately two-thirds of countries consume at or above their NECC. Tercile placement varies by pressure—countries in T1 for one resource may appear in T2 or T3 for others, reflecting heterogeneous resource endowments and trade patterns.



Figure 3. Per capita cropland consumption footprints by income group and national ecological carrying capacity (NECC) tercile. Countries are sorted by income group (LI = low income, LMI = lower-middle income, UMI = upper-middle income, HI = high income) and divided into three terciles based on the ratio of total consumption to NECC. The top panel shows countries with the highest spare capacity, the middle panel shows countries consuming near their NECC (no spare capacity), and the bottom panel shows countries in overshoot. Stacked bars represent domestic production (green) and imported resources (yellow). Red circles indicate total per capita NECC for each country. The horizontal dashed line represents the global boundary distributed equally per capita.

Figure 4 extends this analysis across all six pressures. Pasture and P present similar patterns to cropland, with most high-income countries in T2 and T3, indicating that these nations cannot meet consumption needs from domestic capacity alone and are reliant on resource appropriation from other nations. For forest and N, tercile distribution is more even, with many high-income countries in T1 and T2, suggesting self-sufficiency potential and spare capacity. Blue water is distinctive: most countries consume below their NECC even in T3, with only three (Jordan, Pakistan, Israel) showing ratios exceeding one. This suggests widespread spare capacity for blue water, unlike other pressures.

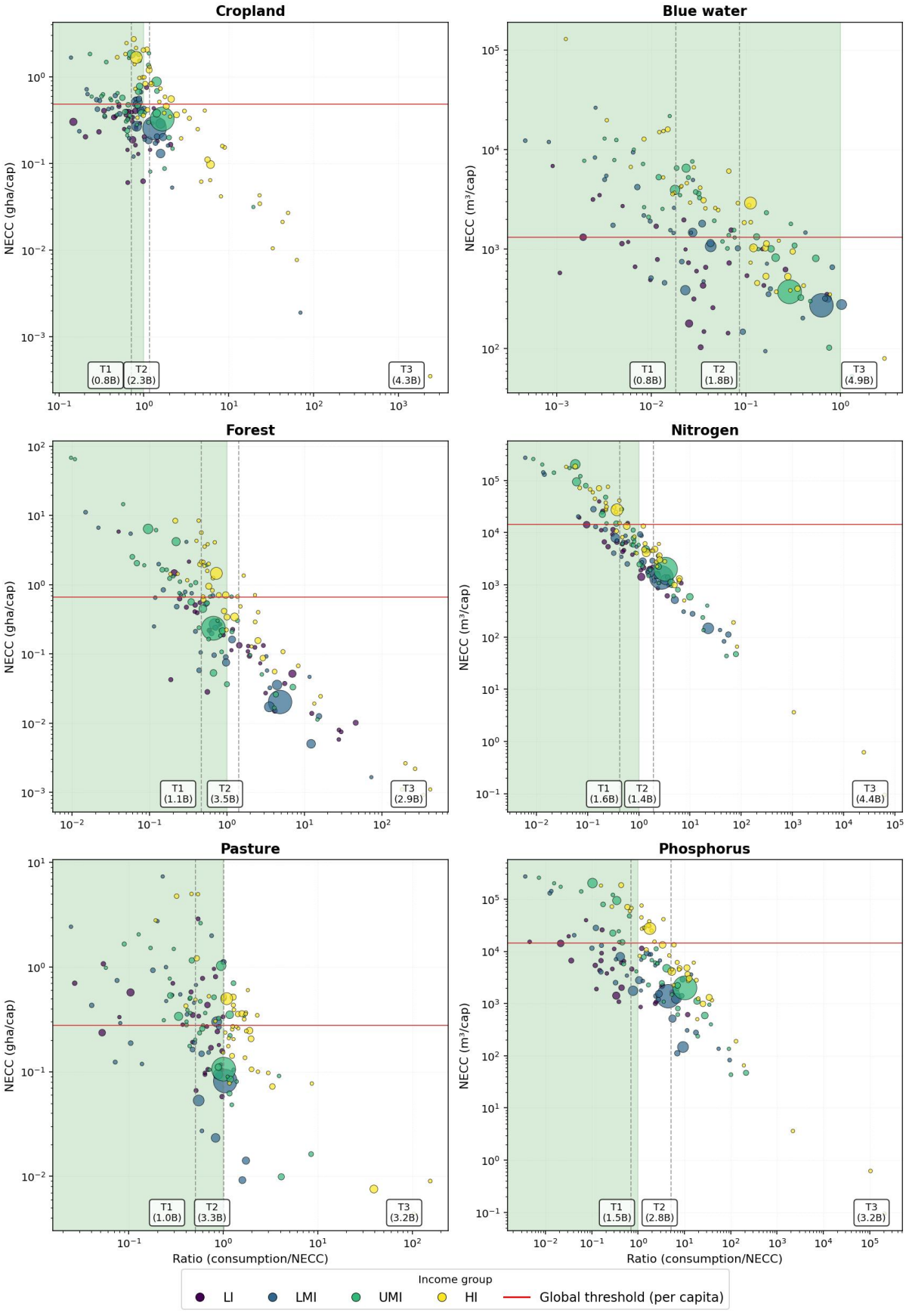


Figure 4. National ecological carrying capacity (NECC) versus total consumption ratio across environmental pressures and income groups. Ratios below one indicates spare capacity (green shaded area). Each panel shows the relationship between per capita NECC and the consumption-to-NECC ratio (both in log scale) for one of six environmental

pressures. Vertical dashed lines divide countries into terciles based on their consumption ratio: T1 (lowest third), T2 (middle third), and T3 (highest third). Numbers in parentheses indicate total population (in billions) within each tercile. Circle size represents country population; colour indicates income group (LI = low income, LMI = lower-middle income, UMI = upper-middle income, HI = high income).

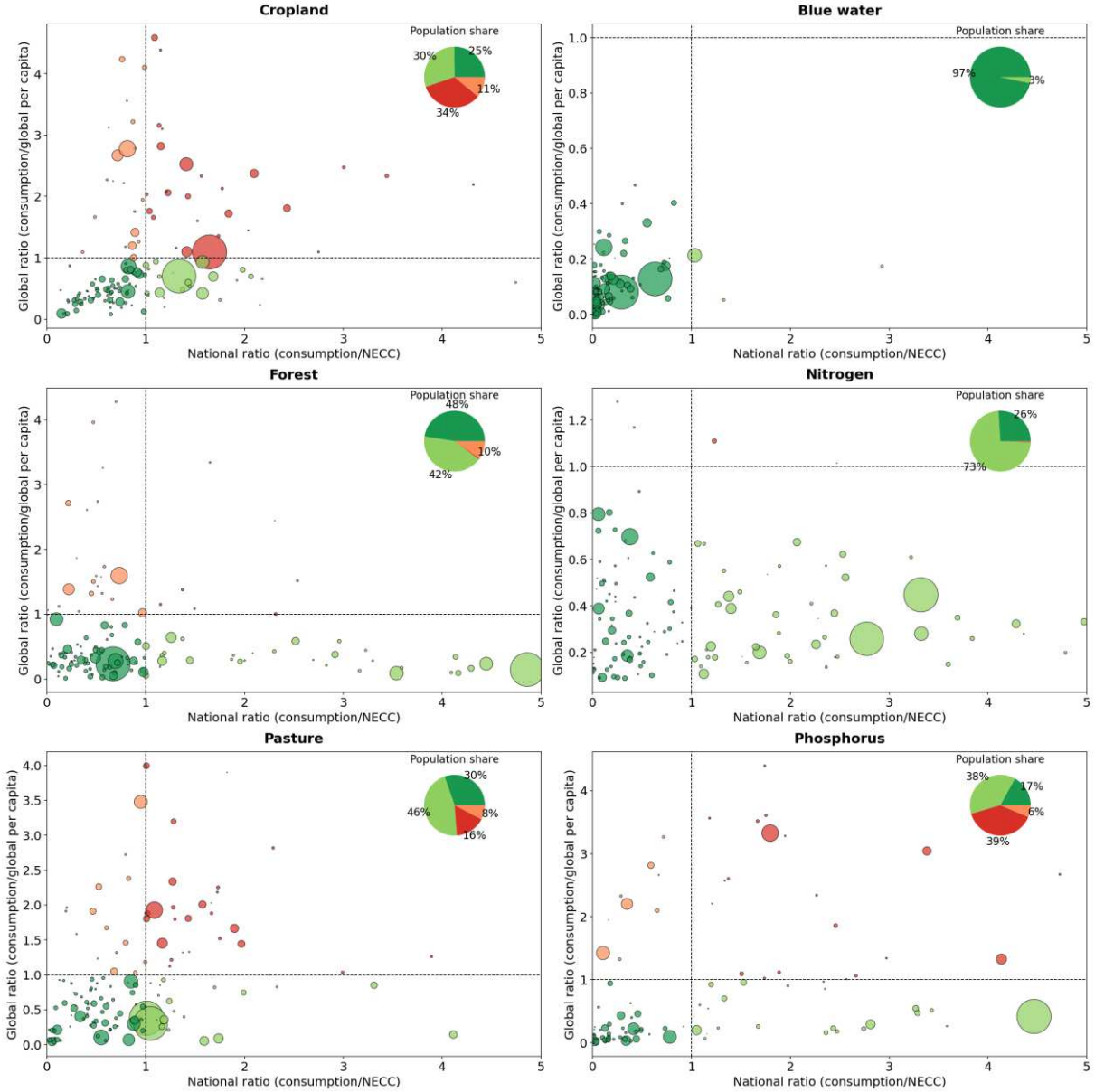


Figure 5. Global versus national consumption ratios across six environmental pressures. Dashed lines at ratio = 1 divide each plot into four quadrants, separating countries consuming within capacity (ratio < 1) from those in overshoot (ratio ≥ 1). The national ratio represents total consumption relative to national ecological carrying capacity (NECC); the global ratio represents total consumption relative to the globally downscaled per capita boundary. Circle size represents country population; colour indicates quadrants. Dark green: bottom-left quadrant (both ratios < 1, spare capacity nationally and globally); light green: bottom-right quadrant (national ratio ≥ 1, global ratio < 1, national overshoot with global spare capacity); red: upper-right quadrant (both ratios ≥ 1, overshoot nationally and globally); and orange: upper-left quadrant (national ratio < 1, global ratio ≥ 1, national spare capacity with global overshoot). Pie charts show the share of global population in each quadrant. Outliers with ratios exceeding 5 were removed and are shown in the SI (SI-B2).

In general, a clear gradient emerges across terciles: T1 countries combine high NECC with low consumption intensity, T3 countries show low NECC with high consumption intensity, and T2 occupies intermediate positions. T1 and T2 countries show self-sufficiency potential across

pressures, except for P where most T2 countries exceed their NECC. For T3 countries, both resource availability and high consumption rates constrain self-sufficiency.

The figure also shows that the divergence between NECCs and equal per capita global boundaries varies substantially by country and pressure. Therefore, the spare capacity differs depending on whether we compare total consumption against NECC or against globally downscaled per capita boundaries. To systematically examine these divergences across all six pressures, Figure 5 compares national ratios (total consumption relative to NECC) against global ratios (total consumption relative to the globally downscaled per capita boundary). The dashed lines at ratio equal to one divide each plot into four quadrants, revealing different patterns of spare capacity and overshoot: dark green (both ratios < 1, spare capacity under both thresholds), light green (national ratio > 1 but global ratio < 1, exceeding NECC but below global allocation), red (both ratios > 1, exceeding both thresholds), and orange (national ratio < 1 but global ratio > 1, within NECC but above global allocation).

These quadrant distributions reveal fundamental tensions between national biophysical reality and equity-based global allocations. For blue water, 97% of population has spare capacity under both thresholds (both ratios < 1). For other pressures, only 17-48% have dual spare capacity, while 1–39% exceed both thresholds — with cropland and P showing the highest shares of dual transgression (34% and 39% respectively).

The light green quadrant — encompassing 30-46% of the global population for cropland, forest, pasture, and P — comprises nations consuming above domestic capacity but below global fair shares, indicating territorial resource deficits that equal per-capita allocations inadvertently permits. India exemplifies this pattern, appearing in this quadrant in all pressures except for blue water consumption.

Conversely, the orange quadrant — 6-11% of the global population (except for water and N) — comprises countries consuming below their NECCs but above global allocations. These are predominantly high-income countries (except for pasture, which shows more even income distribution), whose abundant domestic resources enable consumption levels that appear sustainable nationally but exceed global equity thresholds.

1.3 Contraction and convergence scenario

Under current consumption levels, some countries require resources from others. However, fair redistribution requires first ensuring that all countries meet minimum wellbeing thresholds. We therefore developed a “Contraction and convergence” (CC) scenario as a counterfactual to assess this redistribution potential. Using the SPI basic needs and wellbeing foundations (Harmacek & Krylova, 2023), the scenario contrast current consumption with a fair allocation baseline that prioritises meeting social floor thresholds in low-income countries and reducing overconsumption in wealthy nations, enabling assessment of actual global spare capacity available for redistribution. We identified high-welfare, low-impact target groups (specifically, countries showing a modified SPI higher than 80 on a 0-100 scale, where 100 represents highest welfare, and a Gross Domestic Product based on Purchasing Power Parity (GDP PPP) per capita lower than 25,000 USD) and established two distinct consumption benchmarks: (1) for low-to-middle-income countries, a floor baseline using the average footprint of low-demand and low-footprint countries (Albania, Jamaica, Jordan), uplifting countries currently below this level; (2) for countries with GDP PPP per capita higher than 25,000 USD, a benchmark using high-

efficiency, high-demand nations (Barbados, Chile, Costa Rica), requiring wealthy nations to reduce their total consumption footprints to align with this level.

Figure 6 visualises the global implications of this scenario by showing cumulative population-weighted NECCs and total consumption footprints (current and CC). Each panel is divided into three sections with countries ordered by per capita footprint change – from those requiring the greatest uplifting to those requiring the greatest contraction: "uplifting" (left) shows the population that needs to increase consumption; "no change" (centre) shows the population whose consumption remains at current levels (these countries are ordered from the smallest to the largest footprint per capita); and "contraction" (right) shows the population that must reduce consumption. Under actual consumption, global carrying capacity is insufficient for cropland and P, while blue water, N, and forest show substantial spare capacity.

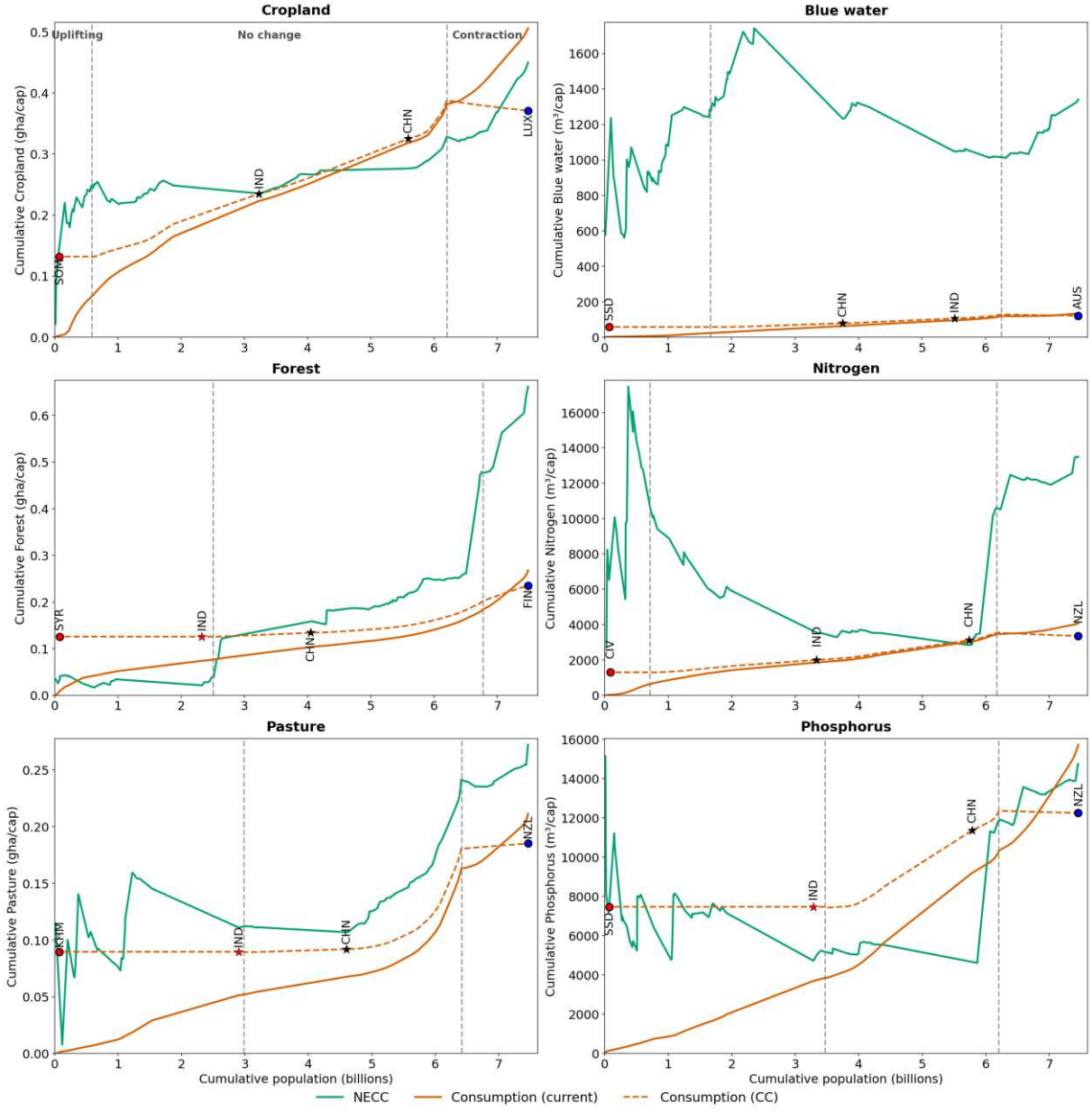


Figure 6. Cumulative national ecological carrying capacity (NECC) and per capita total consumption under current consumption and contraction and convergence (CC) scenario. Countries are ordered from the highest increase in resource demand to the highest decrease in resource demand according to the CC scenario. Dashed vertical lines separate three sections: Uplifting, for countries increasing their resource demand; No change, for countries that do

not change their resource demand; and Contraction, for countries reducing the resource demand. Green line shows cumulative per capita NECC; solid orange line shows cumulative current consumption; and dashed orange line shows cumulative consumption under the CC scenario. Circles mark the countries with the largest absolute change in resource demand: red indicates the highest increase in resource demand, blue indicates the highest reduction in resource demand. Stars denote China (CHN) and India (IND). The x-axis shows the cumulative population (billions).

The CC scenario frees enough global carrying capacity across all six pressures through redistribution. Cropland shifts from 0.06 gha/cap global overshoot to 0.08 gha/cap spare capacity; P shifts from almost 1,000 m^3/cap overshoot to around 2,500 m^3/cap surplus. In both cases, the freed spare capacity could support a 20% increase in global population consuming at the CC global average levels.

The redistribution required under the CC scenario varies substantially by income group and pressure. Low- and low-middle-income countries consumption increases across all pressures, with the largest absolute gains in P emissions (~12,500 km^3), N emissions (~470 km^3), and blue water consumption (~60 km^3), driven by uplifts in countries like Ethiopia and Mozambique. Some countries require dramatic increases compared to their current consumption: South Sudan, DR Congo, Uganda, and Ethiopia must increase P emissions and water consumption by over 1,000% to meet floor thresholds, with South Sudan exceeding 9,000% for both. Countries contributing the largest absolute increases to several pressures include Ethiopia, Bangladesh, India, Indonesia, DR Congo, and Nigeria.

Upper-middle-income countries show mixed patterns. Among those requiring consumption adjustments, blue water consumption is the only pressure where more of the population must decrease consumption than increase it. For all other pressures, however, a larger share requires consumption increases rather than decreases. Examples include Gabon, Iraq, and Fiji, reflecting how some upper-middle-income countries still require uplifts whilst others already exceed benchmarks and must contract.

China (upper-middle-income) and India (low-middle-income), despite their large populations, show divergent patterns: China requires no change across any pressure, while India should increase consumption increasing three pressures (16-36% above current levels) without reducing any.

High-income countries bear the primary consumption reduction burden under the CC scenario. Considering the countries requiring contraction, consumption should decrease by 47–72% on average depending on the pressure, with P emissions showing the highest average reduction, followed closely by cropland use. On a per capita basis, Luxeburg, New Zealand, Finland and Australia require the highest contraction. In absolute terms, the USA shows the largest absolute reductions across all six pressures (32–53% depending on the pressure). More details of the results are in the SI (SI-A1).

2. Discussion

2.1 Uneven resource distribution and the limits of equal per capita allocation

The uneven geographical distribution of resource exploitation (Figure 1) and appropriation (Figure 2) revealed in this study aligns with previous research demonstrating how global trade enables resource-intensive economies to displace environmental pressures to other nations (Hickel et al., 2022; Wiedmann & Lenzen, 2018). However, our dual-threshold framework exposes a critical blind spot in conventional approaches to operationalising global boundaries. Comparing NECCs against equal per capita global allocations reveals that countries consuming below their globally allocated share may nonetheless exceed their domestic biophysical capacities, thereby

requiring resource appropriation from other nations to maintain current consumption patterns. This finding challenges the widespread assumption that equal per capita allocation automatically ensures fair and sustainable resource distribution. Our analysis reveals that 40–60% of the global population lives in countries that could theoretically meet consumption needs from domestic resources, though the specific share varies by pressure. Conversely, for many nations - particularly high-income countries - achieving self-sufficiency is impossible under current consumption patterns due to biophysical constrains. This highlights the need for redistribution mechanisms that account for both global equity and national biophysical realities.

Figure 1 shows severe overexploitation in many regions – particularly Asian and African countries – where production footprints exceed NECCs. Yet Figure 5 reveals spare aggregate global capacity for all pressures except cropland and P (which achieve spare levels under the CC scenario). This contrast shows that sustainability depends not only on redistributing consumption but also on reallocating production away from overexploited regions toward areas with spare capacity. Localised production overshoot persists even when global totals remain manageable, requiring coordinated interventions on both the demand and supply side. Our global thresholds are compared with boundary values from the literature in the SI (SI-B3).

2.2 Decoupling wellbeing from resource consumption

The CC scenario demonstrates that enough global carrying capacity exists across all six pressures when consumption is redistributed to prioritise wellbeing over economic growth. Under this scenario, countries below floor thresholds increase their wellbeing while countries above sustainable consumption ceiling maintain – or potentially improve - wellbeing despite substantial consumption reductions. This finding challenges the conventional focus on decoupling environmental pressures from economic activity (Hickel & Kallis, 2020) and instead supports decoupling environmental pressures from wellbeing itself (O'Neill et al., 2018).

High-income countries bear the primary reduction burden. These reductions are substantial, but not unprecedented: similar "contraction and convergence" frameworks have been proposed for climate change emissions (Meyer, 2000), where high emitters reduce while low emitters gain development space. Applied to resource consumption, this approach transforms the sustainability challenge from a competition over limited resources into a collaborative redistribution problem – one that respect both national biophysical realities and human wellbeing.

Countries with the highest absolute spare capacity are predominantly middle-income nations under both current consumption levels and the CC scenario. Under the CC scenario, spare capacity concentrates further among wealthy nations, particularly for cropland where seven of the top ten countries are high-income. This shift reflects the substantial consumption reductions required from wealthy nations, which simultaneously decrease their footprints and increase their domestic spare capacity available for sharing through trade.

2.3 Policy implications: from competition to collaboration

Our findings show that in a globalised economy, biophysical realities of individual nations must be respected while ensuring everyone has enough. This requires moving from nationalist competition over scarce resources toward international collaboration guided by wellbeing principles. However, the political feasibility of such collaborative frameworks faces different obstacles. Geopolitical tensions increasingly impede climate action and international collaboration (Block & Lenzen, 2025), while growing economic nationalism and protectionist

policies threaten the multilateral cooperation essential for addressing transboundary environmental challenges (Rahiman & Kodikal, 2025).

Our dual-threshold framework contributes to this planetary perspective by revealing how national biophysical realities intersect with global equity concerns, providing empirical grounding for policy discussions that must navigate both local constraints and planetary limits. Yet translating this knowledge into action requires not only scientific understanding but also political will, institutional capacity, and public support for transformative change. Achieving such transformation may require moving beyond incremental reforms toward fundamental restructuring of economic systems, including challenging growth-dependent development paradigms (Hickel & Kallis, 2020; Kallis et al., 2018) and addressing the structural drivers of overconsumption in wealthy nations (Callmer & Boström, 2024; Wiedmann et al., 2020).

2.4 Limitations, future research, and key findings

A key limitation of the methodology is that it assesses current land exploitation but not the ecological transformation required to achieve that state. Future research should include land conversion histories and ecosystems transformation impacts. Moreover, we assess redistribution needs at the national scale, but intra-country redistribution is equally essential: meeting floor thresholds at the national level does not guarantee that all individuals within a country meet basic needs. Future research should integrate subnational analysis to capture within-country inequalities. Finally, our analysis focuses on biophysical feasibility rather than economic or political feasibility. Integrating economic modelling, such as trade dynamics and employment effects, would strengthen the understanding of transition pathways. Despite these limitations, we still identify three critical blind spots in conventional approaches to modelling safe and just operating spaces for humanity.

First, 40-60% of the global population lives in countries that could theoretically meet consumption needs from domestic resources. However, many high-income nations can only maintain their current levels of consumption via the appropriation of other nations' ecological resources, often via unequal trade relations. This highlights the need to consider ecological sustainability as both an inter and intra-generational justice concern.

Second, countries consuming below their globally allocated "fair share" may nonetheless exceed their domestic carrying capacities—a pattern affecting around 30-50% of the global population for most pressures. This reveals that equal per-capita allocation alone cannot ensure sustainability; redistribution mechanisms must account for heterogeneous national biophysical endowments.

Third, sufficient global carrying capacity exists across all six environmental pressures when consumption is redistributed equitably. Uplifting consumption in low-income countries combined with substantial consumption reductions from high-income nations would free spare ecological carry capacity even after meeting wellbeing levels globally. This finding contradicts narratives of absolute scarcity and identifies distributional inequity, rather than aggregate resource limitation, as the primary barrier to achieving both intra- and inter-generational justice.

3. Methods

This study combines Environmentally Extended Multiregional Input-Output (EEMRIO) analysis with location-specific biophysical accounting to assess national consumption footprints against

national ecological carrying capacities (NECCs) for six environmental pressures. We use the Eora26 EEMRIO database (v199.82 basic price) (Lenzen et al., 2012, 2013) for 2017 covering 189 countries, integrated with environmental extensions for land use (cropland, pasture, forest), blue water, and nutrient flows (nitrogen (N) and phosphorus (P)). We then develop a normative consumption scenario to evaluate redistribution potential within global boundaries.

3.1 EEMRIO and environmental extensions

We constructed environmental satellite accounts for cropland, pasture, and forest. For blue water, N and P we used the environmental extensions from Eora.

3.1.1 Land

We applied the Global Footprint Network (GFN) methodology (Borucke et al., 2013; Lin et al., 2019). to build three extensions: cropland, forest, and pasture appropriation, measured in global hectares (gha). For each country and type of land, we estimated:

$$EF_P = \frac{P}{Y_W} \cdot EQF \cdot IYF$$

with EF_P the environmental footprint associated with a product or waste (gha), P the amount of product extracted or waste generated (t/yr), Y_W the world-average yield for product extraction or waste absorption (t/wha·yr), EQF the equivalence factor for given land use type (gha/wha), IYF the intertemporal yield factor of a given land use type (unitless), and wha denotes world hectares.

Production data were sourced from FAOSTAT (FAOSTAT, 2026) for 2017 for cropland (primary crops aggregated categories excluding secondary products), forest (roundwood volumes in m^3), and pasture (livestock stocks in number of heads, and crops feed supply). We allocated national production totals to Eora MRIO sectors using shares derived from Eora's land-use satellite accounts. This approach distributes physical production (in tonnes or m^3) proportionally to the hectares of land used by each sector within each country.

Cropland

The cropland footprint reflects the amount of land necessary to grow all crops consumed by humans and livestock, including agricultural products, market animal feed, and cropped grasses used as livestock feed (Lin et al., 2019).

For the sectoral allocation shares from the Eora satellite account, we used the indicator "Crop and pastureland, from FAO (1000 ha) – Cropland".

FAOSTAT crop production data (in tonnes) were converted to gha using crop-specific world average yields obtained from GFN's National Footprint Accounts (Global Footprint Network, 2018). We applied a EQF of 2.501 and IYF of 0.995 (York University Ecological Footprint Initiative & Global Footprint Network, 2023). A complete list of crop-specific Y_W values is provided in the SI (SI-A2).

Pasture

The pastureland footprint assesses demand for pastureland to feed livestock. Following the GFN methodology, we calculated total feed requirements for all livestock produced and estimated the percentage of livestock energy requirements derived from crop feeds, grass, and crop residues. The difference between total feed requirement and total cropped feed supply (crops plus residues) was taken to equal the demand for pastureland. Notably, because pasture land

carrying capacity represents the total amount of above-ground net primary production available annually, overshoot from year to year is not physically possible (Lin et al., 2019).

For the sectoral allocation shares from the Eora satellite account, we used the indicator "Crop and pastureland, from FAO (1000 ha) - Land under perm. meadows and pastures".

FAOSTAT livestock stock data (number of heads) for several livestock categories were used to estimate the feed demand. Feed requirements were calculated using region-specific feed intake rates (kg dry matter per head per day) (Haberl et al., 2007), accounting for climate-dependent variations in animal metabolism and regional farming systems. Feed supply from crops and crop residues was estimated using FAOSTAT production data, with crop-specific water content and nutrition indices applied to convert to dry matter equivalents.

We applied a Y_W of 6.190 multiplied by the above-ground NPP (%) and the edible % of aboveground NPP (70 and 30% respectively), EQF of 0.458 and IYF of 1.0 (Global Footprint Network, 2018). Detailed parameters for feed demand estimation, including regional feed intake rates, crop residue conversion ratios, and water content values, are provided in the SI (SI-A2).

Forest

The forest products footprint comprises two broad types of primary product: wood used for fuel; and timber and pulp used as a raw material to produce derived wood products. The forest products footprint represents the area of world average forest land needed to supply wood for fuel, construction, and paper (Lin et al., 2019).

For the sectoral allocation shares from the Eora satellite account, we used the indicator "Crop and pastureland, from FAO (1000 ha) - Forest land".

FAOSTAT roundwood production data were used, where roundwood is equal to wood fuel plus industrial roundwood. FAOSTAT reports data in m^3 of roundwood equivalent, a measure of the volume of logs (roundwood) used in the manufacture of wood-based products (including wood pulp, paper, wooden furniture, joinery and plywood) (Global Timber, 2026). Thus, we assumed that the values are in dry weight.

We applied the following values for the different factors: Y_W for wood fuel of 3.347, Y_W for industrial roundwood of 1.819, EQF of 1.270, and IYF of 1 (Global Footprint Network, 2018).

3.1.2 Blue water

We measured blue water consumption using Eora's indicator "WFN: Total water footprint (Mm3/yr) - Blue - Total".

3.1.3 Nutrients

For N, we used Eora's indicator " Nitrogen emissions, itemized (Gg) - N exportable to water bodies (Gg N) - Ag and hhld waste water" converted to kg N/yr. For P, we applied a 5% emission factor to Eora's "P emissions from fertilizer and manure (kg) - Total" based on Mekonnen & Hoekstra (2018), representing the fraction of applied P that reaches water bodies through runoff and leaching. For more details see the SI (SI-A2).

These nutrients load were converted to water volume equivalents, using the grey water footprint (GWF) concept (A. Hoekstra et al., 2011), which quantifies the dilution volume required to assimilate nutrient emissions without exceeding water quality concentration limits:

$$GWF = \frac{Load}{C_{max} - C_{nat}}$$

where Load is the nutrient emission (kg N/yr or kg P/yr), C_{max} is the maximum allowable concentration (2.9 mg N/L for nitrogen; 0.02 mg P/L for phosphorus), and C_{nat} is the natural concentration (0.4 mg N/L for nitrogen; 0.01 mg P/L for phosphorus) (Mekonnen & Hoekstra, 2015, 2018).

3.2 National ecological carrying capacities

We defined location-specific carrying capacities for each environmental pressure, representing the maximum sustainable appropriation given national biophysical constraints. Global values were estimated by adding the NECC of all countries.

3.2.1 Land

Land carrying capacities were derived from the GFN biocapacity data for cropland, pasture, and forest land, measured in gha. We used 2019 data as the closest available to our 2017 consumption analysis (York University Ecological Footprint Initiative & Global Footprint Network, 2023). For countries where only total carrying capacity was available, we estimated land-type shares using 2022 data (York University Ecological Footprint Initiative, FoDaFo & Global Footprint Network, 2025). In addition, we got missing values from Andrew & Forgie (2011) for New Zealand, Ministerio del Ambiente del Ecuador (2016) for Ecuador, and WWF (2010) for Honduras, Cambodia, Moldova, and Lesotho. The details are shown in the SI (SI-A3).

For pasture, we set the carrying capacity equal to the production footprint in case the latter exceeded the reported carrying capacity. This, given that the annual net primary productivity constrains the maximum consumption of pastureland.

3.2.2 Blue water

The blue water carrying capacity for each country was defined as the volume of renewable water resources physically accessible for human use after accounting for ecological flow requirements (EFR). We obtained data on total renewable water resources (TRWR) and EFR from AQUASTAT (FAO, 2026), averaged over the period 1970–2017.

AQUASTAT's EFR estimates are derived from hydrological methods designed to maintain minimum streamflow conditions for aquatic ecosystem functioning. We treated EFR as a prior ecological claim on the total renewable flow (Baggio et al., 2021), subtracting it from TRWR before applying any further constraints.

Not all renewable water is physically accessible in a given year due to seasonal variability and limited storage infrastructure. We applied the potential utilization factor from de Fraiture et al. (2001), which represents the fraction of annual renewable water that is potentially utilisable given hydrological variability and storage constraints. For most countries, this factor is approximately 60%. However, countries with pronounced flood-pulse regimes—where a large proportion of annual discharge occurs as concentrated, high-magnitude flow events—face significantly reduced water accessibility due to limited capacity to capture or regulate peak flows. For these systems, de Fraiture et al. (2001) recommends a reduced utilization factor of 38%.

We applied the 38% factor to countries exhibiting both (i) pronounced flood-pulse or monsoonal hydrology, and (ii) limited water storage and flow regulation infrastructure. This includes the three

countries explicitly mentioned by de Fraiture et al. (2001) —Brazil, India, and Bangladesh—as well as 25 additional countries with comparable hydrological and infrastructural characteristics: China, Indonesia, Pakistan, Vietnam, Laos, Myanmar, Cambodia, South Sudan, Thailand, Suriname, Guyana, Philippines, Nepal, Colombia, Nigeria, Uganda, Mexico, Madagascar, Argentina, Peru, Congo, DRC, Venezuela, Papua New Guinea, and Mozambique.

The blue water NCC was thus:

$$LCC_{BW} = (TRWR - EFR) \cdot f$$

where *f* is the country-specific utilisation factor (0.38 for flood-pulse countries; 0.60 elsewhere). The resulting NCC represents the volume of renewable freshwater that is both ecologically safe to appropriate and physically accessible under prevailing hydrological and infrastructural conditions. It is important to note that this boundary captures blue water only — surface water and groundwater contributing to river discharge — and does not account for green water requirements of terrestrial ecosystems.

3.2.3 Nutrients

For N and P, the carrying capacity is represented by each country's total annual runoff (water flowing from land toward river systems in m^3/yr), obtained from the Global Runoff Data Centre (GRDC, 2026), as average values for the period 1970-2020. This volume represents the dilution capacity available to assimilate nutrient emissions while maintaining concentrations below the thresholds used in the GWF calculations. When a country's GWF (nutrient load converted to dilution volume requirement) exceeds its annual runoff, the country is exceeding its assimilative capacity for that nutrient (Mekonnen & Hoekstra, 2015, 2018).

3.3 Contraction and convergence scenario

Given that many nations cannot achieve self-sufficiency within their NECCs, we developed a “Contraction and convergence” (CC) scenario to establish a normative baseline before assessing redistribution potential. The scenario prioritises meeting floor thresholds in low-income countries and reducing overconsumption in wealthy nations, enabling assessment of actual global spare capacity available for redistribution.

We identified high-welfare, low-impact target countries using the Social Progress Index (SPI) basic needs and wellbeing foundations (Harmacek & Krylova, 2023). The SPI provides a comprehensive assessment of social and environmental outcomes, with the "Basic Human Needs" dimension capturing nutrition, basic medical care, water, sanitation, shelter, and personal safety, and the "Foundations of Wellbeing" dimension capturing access to knowledge, information, health and wellness, and environmental quality.

Target countries met two criteria: (1) modified SPI (average of "Basic Human Needs" and "Foundations of Wellbeing") greater than 80, indicating achievement of high social welfare; and (2) GDP per capita (PPP) below $25,000, representing middle-income nations. This threshold is based on evidence that the relationship between income and social progress follows a saturating curve, with SPI scores increasing more slowly beyond middle-income levels as wellbeing gains from additional income diminish markedly (Jebb et al., 2018; O’Neill et al., 2018). This selection yielded 18 countries. We then establish two distinct consumption benchmarks:

1. Floor benchmark (for countries with modified SPI < 80 and GDP PPP per capita < $25,000): We calculated the mean per-capita footprint across the three countries with the lowest final demand

per capita and lowest environmental pressures per capita across the six environmental pressures —Albania, Jamaica, and Jordan. Countries with environmental pressures below this baseline increase their consumption footprints to reach it, ensuring access to wellbeing-supporting resource levels.

2. Overconsumption benchmark (for countries with modified SPI ≥ 80 and GDP PPP per capita ≥ $25,000): We calculated the mean per-capita footprint across the three countries with the highest final demand per capita but lowest environmental pressures per capita across the six environmental pressures — Barbados, Chile, and Costa Rica. Wealthy countries with environmental pressures above this benchmark reduce their consumption footprints to align with it, eliminating resource-intensive overconsumption whilst maintaining high social welfare.

For all other countries, footprints remained unchanged. In the CC scenario, we directly adjust per-capita footprints to match the benchmark values. We interpret these footprint changes as resulting from proportional changes in consumption volumes, rather than from shifts in production technologies or sourcing patterns, although the specific consumption adjustments needed to achieve these footprints are not explicitly modelled. For more details, see the SI (SI-A4).

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Claude AI in order to improve language and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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