

Decoupling must accelerate threefold to align national environmental footprints with planetary boundaries

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Decoupling must accelerate threefold to align national environmental footprints with planetary boundaries

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Reducing environmental impacts is essential for maintaining Earth-system stability. The planetary boundaries (PB) framework defines a safe operating space for human pressures, yet it remains poorly understood how national environmental footprints are evolving relative to that space, what drives their trajectories, and whether progress is fast enough. We assess consumption-based footprints for seven PB domains against equal per-capita shares of the global safe operating space, and decompose their change into affluence, population, and the environmental intensity of global supply chains, identifying trade sourcing as an explicit driver. No economy remains within all seven boundaries, and two-thirds exceed six or more. Advanced economies have cut footprints on every indicator since 2000 yet still exceed most boundaries by two- to sevenfold, in part because increased globalisation toward higher-intensity suppliers has offset up to a quarter of their efficiency gains. This trade-sourcing effect was comparable in size to rising affluence across several indicators and was 2.8 times larger than affluence for water. Emerging-economy footprints are rising sharply. To reach boundary-consistent levels by 2050, rates of decoupling must more than triple in pace for biosphere integrity, biogeochemical flows and climate. Freshwater and land-system change are the only indicators on track.

The Planetary Boundaries framework defines a safe operating space for human society by identifying critical Earth system processes that regulate the stability of the planet¹. Accumulating evidence shows that human activity has become the dominant driver of global environmental change in the Anthropocene, pushing several of these processes beyond levels considered compatible with long-term societal well-being². This exceedance is thus putting at risk the biophysical foundations of modern economies and societies³.

While the Planetary Boundaries framework has been influential in articulating global environmental thresholds, its inherently global nature creates a persistent disconnect with decision-making at national, regional, and organizational levels^{4,5}. As a result, recent research has focused

on translating global boundaries into actionable targets or limits at sub-global scales, including national and annual metrics^{6–8}. This downscaling inevitably requires normative choices⁶, including how to allocate a shared environmental space across countries and how to allow for future development needs^{4,9}. Despite this growing body of work, a critical gap remains. Although boundary thresholds are increasingly well defined, there is limited empirical evidence on how countries are performing relative to these downscaled boundaries⁵, how their trajectories have evolved over time, and whether recent development pathways are aligned with a transition back toward the safe operating space. In the context of continued population and economic growth, it remains uncertain how large and how rapid policy-driven changes must be to reverse current trends. Two recent studies have begun to address this gap. Tian et al.⁸ use a what-if analysis to assess how demand-side changes among high-consuming groups could reduce environmental pressures, while van Vuuren et al.¹⁰ use a global forward-looking optimisation model to examine the implications of policy pathways, primarily climate policy, for development within planetary boundaries. The second work, however, has not used a consumption-based approach. While both studies provide important insights into possible improvement pathways, especially at the global level, they do not show how national consumption-based footprints have evolved relative to downscaled boundaries, nor how affluence, technology, and trade have shaped countries' divergence from boundary-consistent pathways.

Here we address this gap by presenting a multi-indicator, consumption-based assessment of seven planetary boundary domains, capturing the environmental consequences of recent economic development across major world regions and individual countries. We use consumption-based accounting, which is necessary to capture the environmental responsibility of consumption regardless of production location, thereby avoiding misrepresentation of national performance and reducing the risk of problem shifting through trade. We update the existing EXIOBASE database to bring it up to date for this analysis and provide a new linking of planetary boundary indicators with EXIOBASE environmental extensions. We analyse country-level developments over time and examine the pressure-intensity and trade drivers of boundary pressures, including through a decomposition term designed to isolate changes in domestic and imported sourcing. This framing reduces the risk of misrepresenting national performance when environmental pressures are shifted through trade.

Using this framework, we first analyse trends over the past two decades and assess progress toward, or divergence from, downscaled planetary boundary allocations. We compare countries using per-capita consumption-based footprints, revealing pronounced inequalities in environmental pressure across nations. We then examine the extent to which environmental pressures have decoupled from population and economic growth using a Population-Affluence-Technology decomposition, while distinguishing changes in domestic production, imports and trade sourcing. Finally, we compare observed pressure-intensity improvements with the rates required to return per-capita footprints to boundary-consistent levels by 2050 under baseline population and GDP trajectories. We close by discussing key limitations related to uncertainty, data coverage, downscaling assumptions and temporal lag.

Results

Exceedance of planetary boundaries

Across all major indicators except freshwater, consumption-based pressures exceeded the global safe operating space in 2020, and pressures have continued to rise over the past two decades rather than abate (Fig. 1, Fig. SI 5.1). Consistent with other studies² globally, biosphere integrity is the most severely transgressed, followed by phosphorus and climate, then nitrogen and land-system change, and acidification; freshwater alone remains within the safe operating space at the global aggregate. Global pressures rose substantially across most indicators between 2000 and 2020, acidification by around forty-percent, phosphorus by nearly fifty-percent, climate by thirty-six percent.

The global trend masks divergent regional dynamics. Advanced economies exceed six of the seven boundaries on a consumption basis (downscaled by population), freshwater the sole exception, with biosphere integrity at roughly seven times the safe threshold, phosphorus and climate at around five times, nitrogen at roughly three times, acidification at about two and a half times, and land at nearly twice. However, advanced economies have managed to reduce their footprints across every indicator since 2000, with declines of around a sixth to a quarter across climate, biodiversity, land, and acidification.

Emerging and developing economies as a group currently exceed the biodiversity, phosphorus, nitrogen, and climate boundaries and have just reached the land boundary, remaining within the safe operating space only for acidification and freshwater. Their footprints have grown sharply over the study period, roughly doubling for climate, more than doubling for acidification, rising by around 80% for phosphorus and 70% for nitrogen, and increasing across every indicator. The direction of travel is hence toward greater exceedance, not less.

At the country level (Fig. SI 5.2), no economy remains within all seven boundaries simultaneously, and two-thirds exceed six or more. The most severe and widespread exceedances are for biosphere integrity, phosphorus, climate, and nitrogen, the prominence of the biodiversity and nutrient indicators reflecting the footprint of food supply chains. Land and acidification are exceeded almost as widely but by smaller margins, and freshwater is the only boundary most economies remain within.

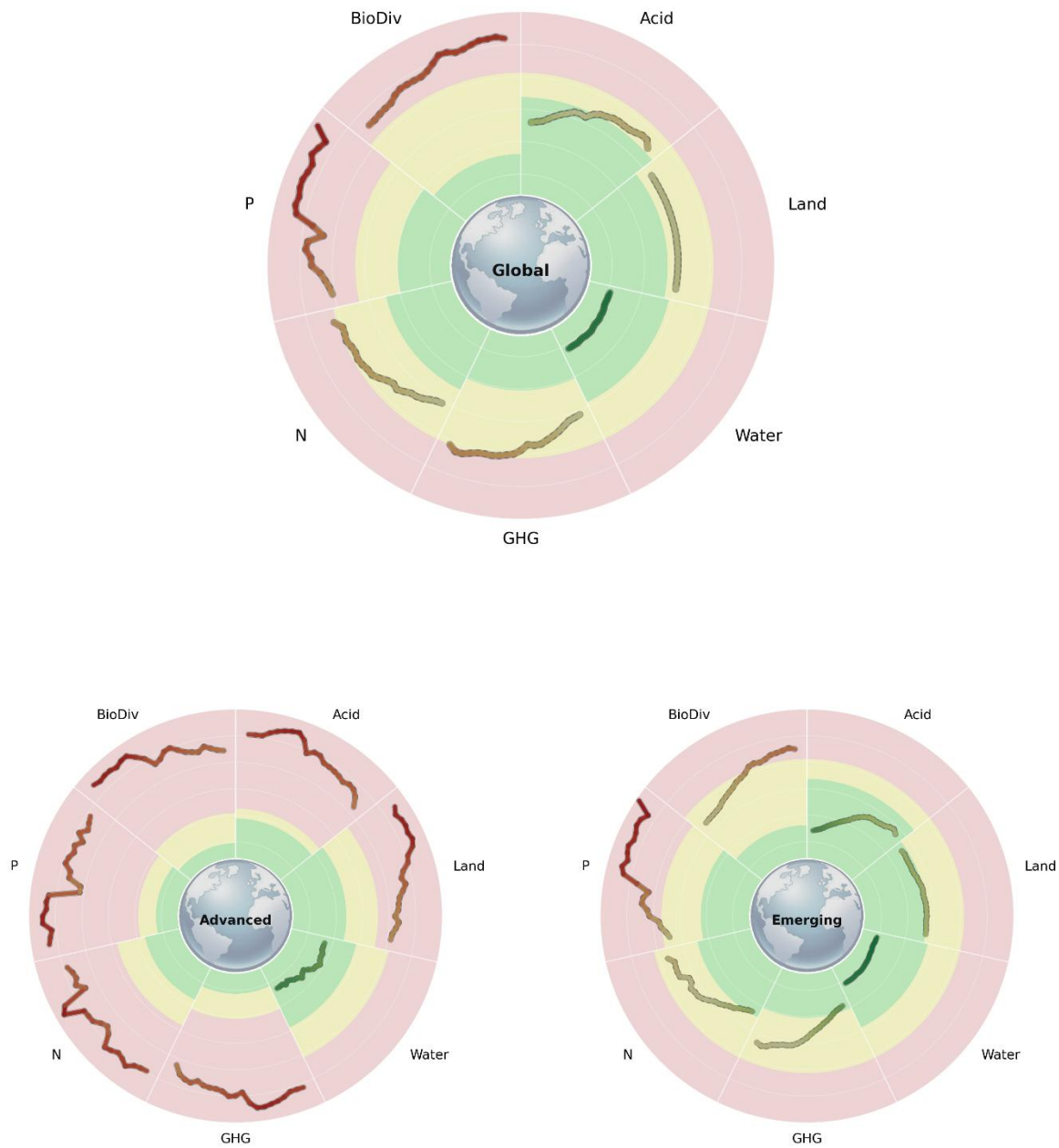


Figure 1. Development of consumption-based planetary boundary footprints, 2000-2020, globally (a), by emerging economies (b), and by advanced economies (c). Radial position shows each pressure relative to its planetary-boundary range on a linear scale: the central Earth marks zero, the green band lies below the safe (lower) boundary, yellow spans the zone of uncertainty between the lower and upper boundaries, and red marks transgression beyond the upper boundary (at the yellow/red join). Each worm traces the 2000-2020 trajectory. Country level results are available in Supporting Information.

Absolute vs. relative decoupling

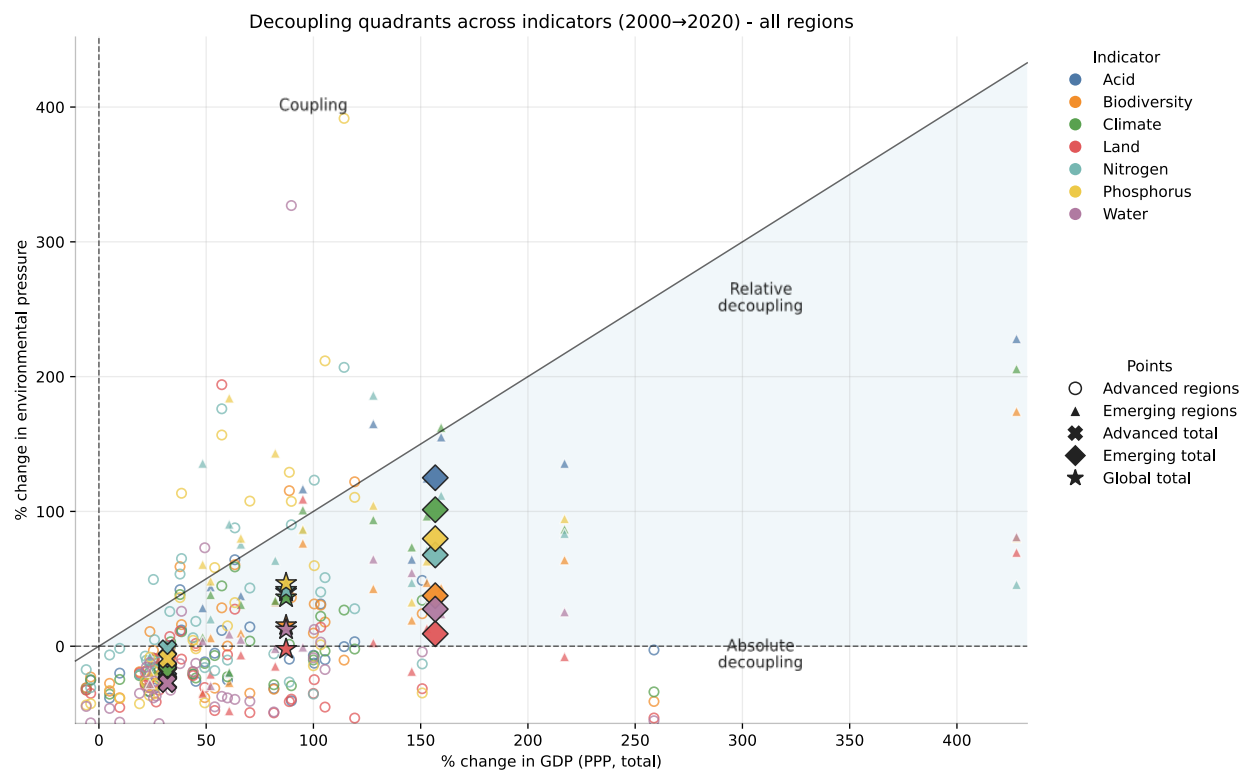


Figure 2 Decoupling outcomes across planetary boundary indicators (2001-2020).

The figure positions countries and regional aggregates according to the relationship between economic growth (x-axis, in 2015 PPP) and changes in environmental pressure (y-axis) for seven planetary boundary indicators. The 45° line separates coupling from decoupling, while the horizontal zero line distinguishes absolute decoupling from rising absolute pressures. Points below the 45° line indicate relative decoupling; points below zero indicate absolute decoupling. Marker shapes distinguish advanced and emerging economies, and larger symbols denote group aggregates.

Looking at how countries are tracking across the time period, we find that economic growth has broadly decoupled from environmental pressure in *relative* terms over the study period (impact intensities per unit of GDP have fallen almost everywhere), but absolute decoupling, where total pressure falls despite GDP growth, is mostly restricted to advanced economies (supporting information for individual country results).

The incidence of absolute decoupling varies sharply across indicators (Fig. 2). Land-system change is the clearest case of widespread absolute decoupling: around 76% of countries reduced their potential forest footprint in absolute terms, consistent with the intensification dynamic identified earlier^{11,12}. Climate, acidification, and water also show a majority of absolute decoupling across countries (around 57-65%), though this is heavily skewed toward advanced economies. Twenty-six of the 28 countries achieving absolute climate decoupling are advanced. Advanced economies as an aggregate achieved absolute decoupling across all seven indicators over the period, while emerging economies in aggregate did not for any indicator. Phosphorus and nitrogen are the most resistant to absolute decoupling: only around 41% of countries achieved it for each, and nearly all

of those are advanced economies. Whilst most advanced regions are clustered around the regional average (Fig. 2), Taiwan (second rightmost cluster of points) shows economic growth of around 260% whilst still achieving absolute decoupling across every indicator. China in comparison has seen the highest affluence growth (furthest right cluster of points, GDP +430%), but its footprints still rose, by roughly 45% to 230% depending on the indicator, well below its GDP growth.

Drivers of change: technology, affluence and trade

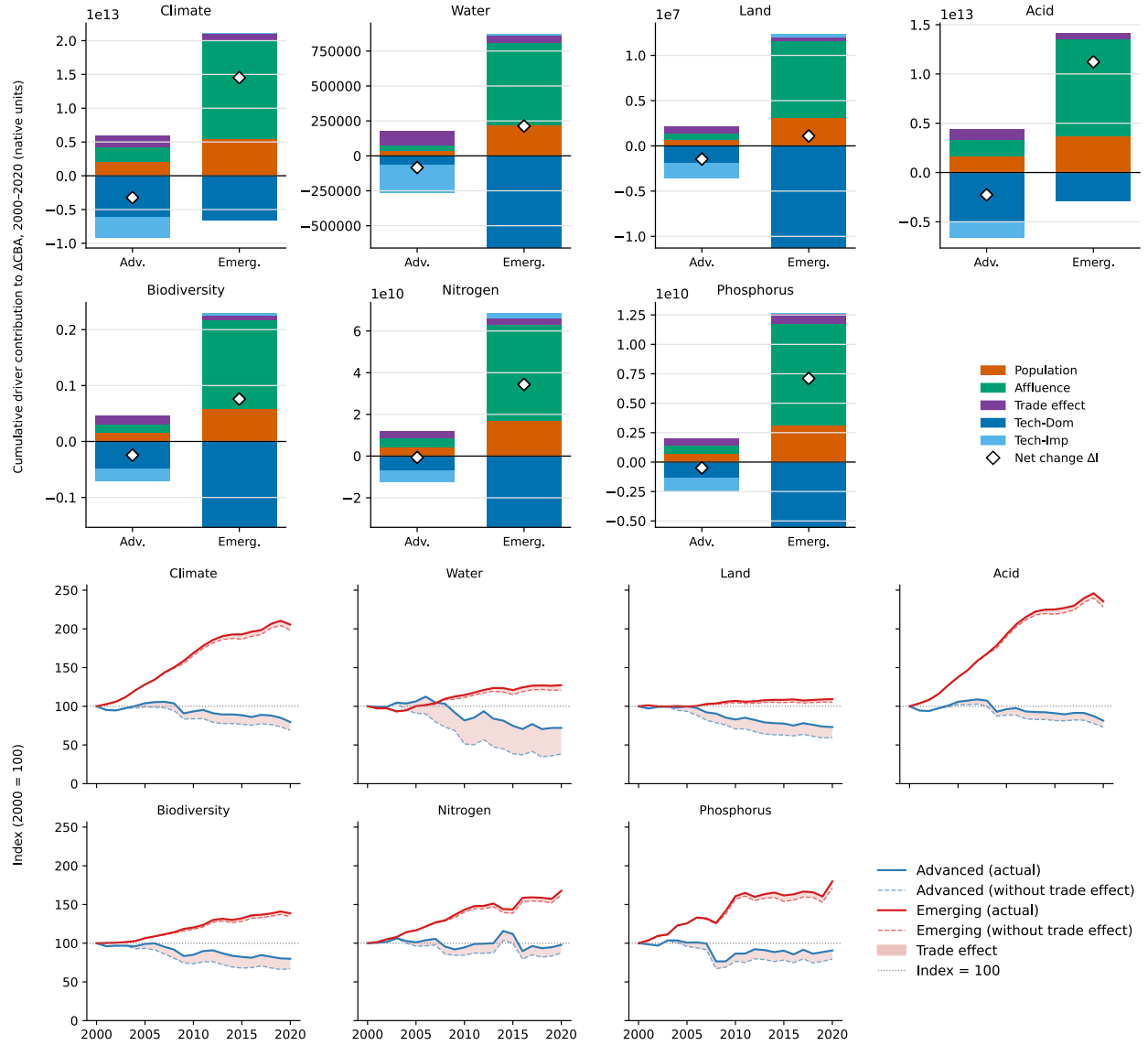


Figure 3. Drivers of change in consumption-based planetary boundary footprints, 2000-2020. Top panel shows the decomposition of total footprint change into population, affluence, trade shares and domestic vs foreign technology. Bottom panel shows the decomposition result isolating the effect solely due to trade.

We further decompose changes in consumption-based footprints into five drivers: population (ΔP), affluence (ΔA), trade composition ($\Delta \alpha$), domestic technology (Δt_d), and foreign technology (Δt_m) (Fig. 3 and methods). Affluence is the dominant upward driver across all indicators and for both regions, and is largest for climate, nitrogen, and water. In emerging economies the affluence effect

substantially exceeds the combined technology terms for most indicators (water and land are exceptions, where the two are comparable), producing the rising aggregates seen above; in advanced economies affluence is more moderate and the technology terms are sufficient to offset the combined affluence, population, and trade effects for every indicator, yielding net declines. Population growth contributes a smaller upward pressure than affluence in emerging economies, and one comparable to affluence in advanced economies.

Decomposing the technology effect into domestic and trade-related components reveals two distinct mechanisms. For emerging economies, the technology effect is almost entirely domestic: efficiency gains in within-region production account for essentially the whole offset against rising affluence, with embodied improvements in imports close to zero. For advanced economies, the technology effect is shared between domestic improvements (Δt_d) and embodied improvements in imported goods (Δt_m), domestic is generally the larger share, but imports contribute roughly a third to a half (and the majority for water), reflecting efficiency gains in major emerging exporting economies. The trade composition effect ($\Delta \alpha$) is small for emerging economies (around +3 to +8% of the 2001 footprint) but substantial for advanced economies, where it adds roughly +9 to +14% across indicators and +34% for water, offsetting a meaningful share of their technology gains (Fig. 3, top). The net regional contrast, rising aggregates in emerging economies versus declines in advanced economies, is driven primarily by the relative magnitudes of affluence and technology, with trade composition a secondary driver that is negligible for emerging economies but materially erodes the advanced-economy reductions.

The trade-composition effect ($\Delta \alpha$) differs sharply between groups (Fig. 3 bottom, Table SI 5.1,5.2). For emerging economies, it is minor (+3 to +8% of the 2001 footprint), an order of magnitude below the affluence effect. For advanced economies, where affluence grew only modestly (+12 to +13%), $\Delta \alpha$ is comparable to or larger than affluence across most indicators, exceeding it for water (+34% vs +12%), land (+14% vs +11%) and biodiversity (+14% vs +12%), and offsets between roughly a sixth and a quarter of the gross technology-driven reductions in advanced economies (Fig. 3 top, and Table SI 5.1, water is the extreme case, where re-sourcing alone added ~34%, about 2.8 times the affluence contribution). Underlying the trade result are two main factors: 1) on average, goods produced in emerging countries have a higher impact per unit than goods produced in advanced countries, and 2) trade has shifted, for both advanced and emerging countries, away from reliance on production in advanced countries toward greater reliance on production in emerging markets. The net direction of change in each group is still set by the balance of affluence and technology, strongly upward in emerging economies, downward in advanced, but for advanced economies trade is a material upward driver rather than a negligible one.

At the country level (supporting information, Fig. SI 5.4 and data workbook), we confirm that technology improvements act to reduce pressure for both regional aggregates across all seven boundary domains and for the large majority of individual countries. Efficiency gains in the resource intensity of consumption are near-universal for climate, acidification, biodiversity, land, and water (reducing pressure in over 90% of countries) and predominate for nitrogen and phosphorus, though for these two around a quarter of countries show technology adding to pressure. Whilst there is more variation in the country-level results, the same overall trend applies.

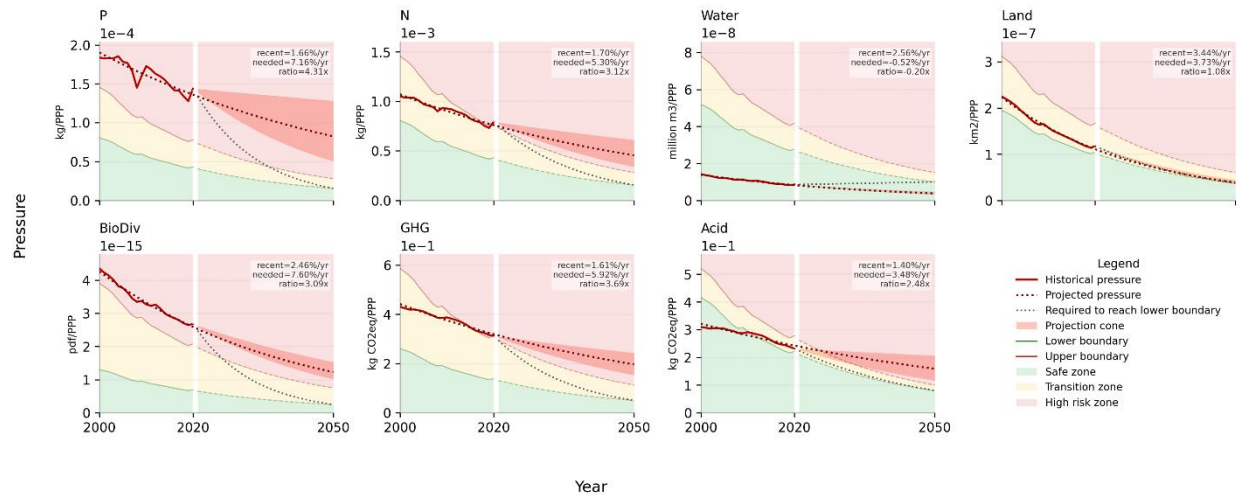
Are we improving fast enough (can technology save us?)

The decomposition above shows that declining pressure intensities have offset much of the upward pressure from affluence. These intensity changes include technology, production efficiency, sectoral composition, and supply-chain structure. We next ask whether the observed pace of technological change is fast enough to bring per-capita footprints within the downscaled boundaries by 2050. Recent trends in pressure intensity (pressure per unit GDP, PPP) are extrapolated under baseline GDP and population scenarios (Fig. 4); shaded background shows the boundary-consistent intensity trajectory, which itself declines over time as continued economic and population growth reduces the amount of pressure compatible with each unit of economic output. Globally, extrapolated pressure intensity falls across all indicators, but the trajectory remains above the boundary-consistent path by 2050 for every indicator except freshwater.

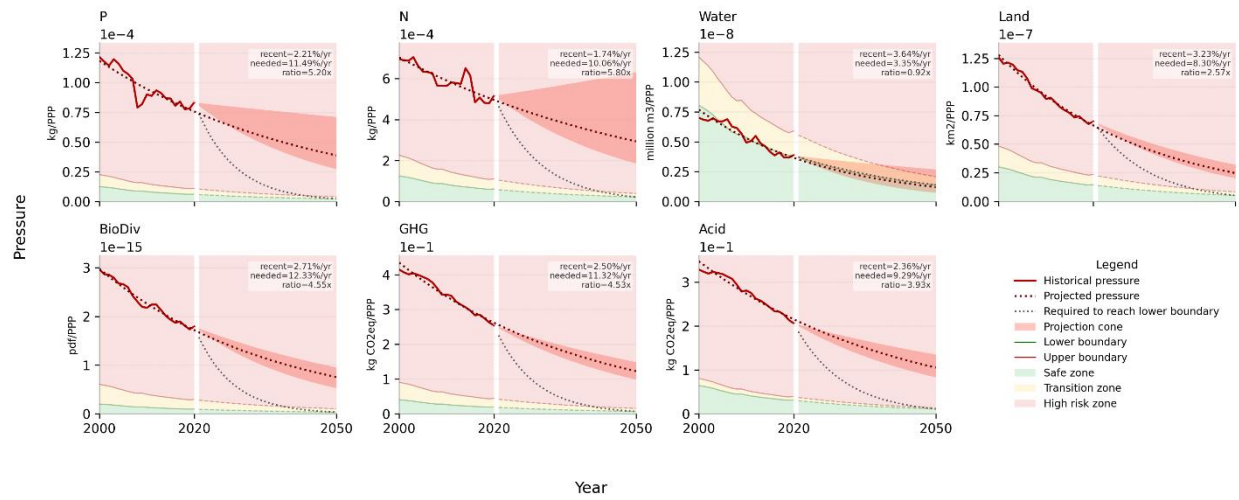
Advanced-economy intensities decline across all indicators but converge above the 2050 boundary-consistent path for every indicator except freshwater. Emerging-economy intensities improve at rates similar to or faster than advanced economies for most indicators (notably land, water, nitrogen, and biodiversity) but more slowly for climate and acidification; substantial residual gaps nonetheless remain in both groups. Freshwater is the clear exception across all regions, with recent rates of decline at or above the required pace. Under baseline growth in GDP and population, no region is on track across the full set of indicators.

Figure 5 quantifies this shortfall by comparing recent decoupling rates (2001-2020) against the annual rate of technological improvement required to bring pressure intensity within the downscaled boundary by 2050. Required rates exceed historical rates for most indicator-region pairs (17 of 21). The largest gaps are for biosphere integrity, phosphorus, and climate, where required improvements of ca. 7-9% per year compare to recent rates of only 2-4% per year, a greater than twofold acceleration. Nitrogen and acidification show smaller but substantial shortfalls in all regions. Land shows a narrower gap, and in emerging economies recent rates already meet the required pace; freshwater is the only indicator on track in all regions.

Planetary boundary pressures, Global



Planetary boundary pressures, Advanced



Planetary boundary pressures, EmergingDeveloping

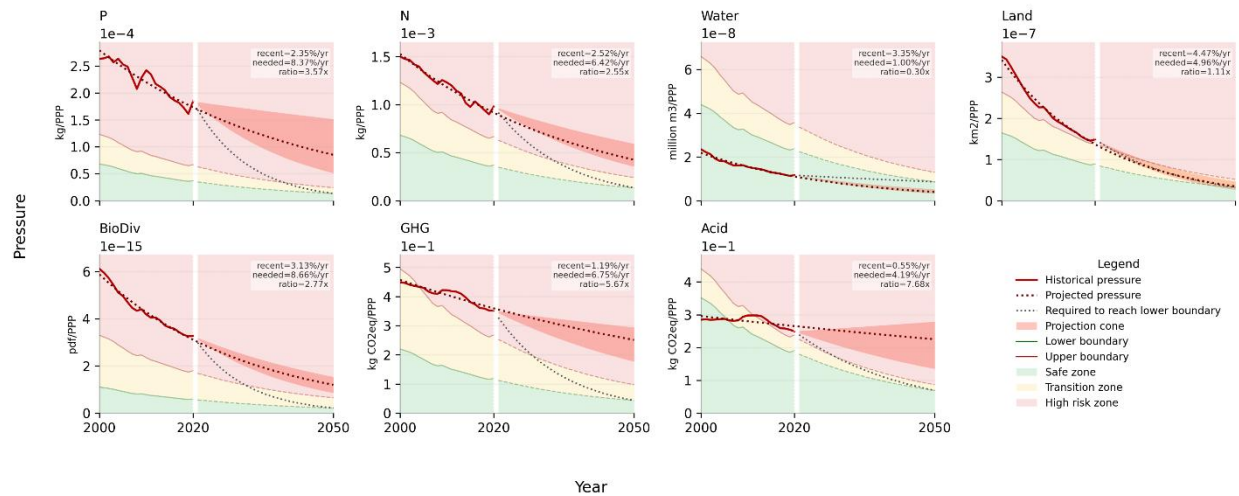


Figure 4 Pressure intensity trajectories versus boundary-consistent paths to 2050. Each panel shows pressure per unit GDP (PPP, 2015) for one indicator. Solid lines show observed trajectories 2000–2020, dashed lines show extrapolation under recent intensity-improvement rates, and shaded bands show the range of pressure intensity consistent with the downscaled boundary under baseline UN population and IMF GDP-growth projections. The lower edge of the band corresponds to the lower-bound boundary; convergence above the band by 2050 indicates that historical decoupling is insufficient. Panels show global, advanced, and emerging-developing aggregates.

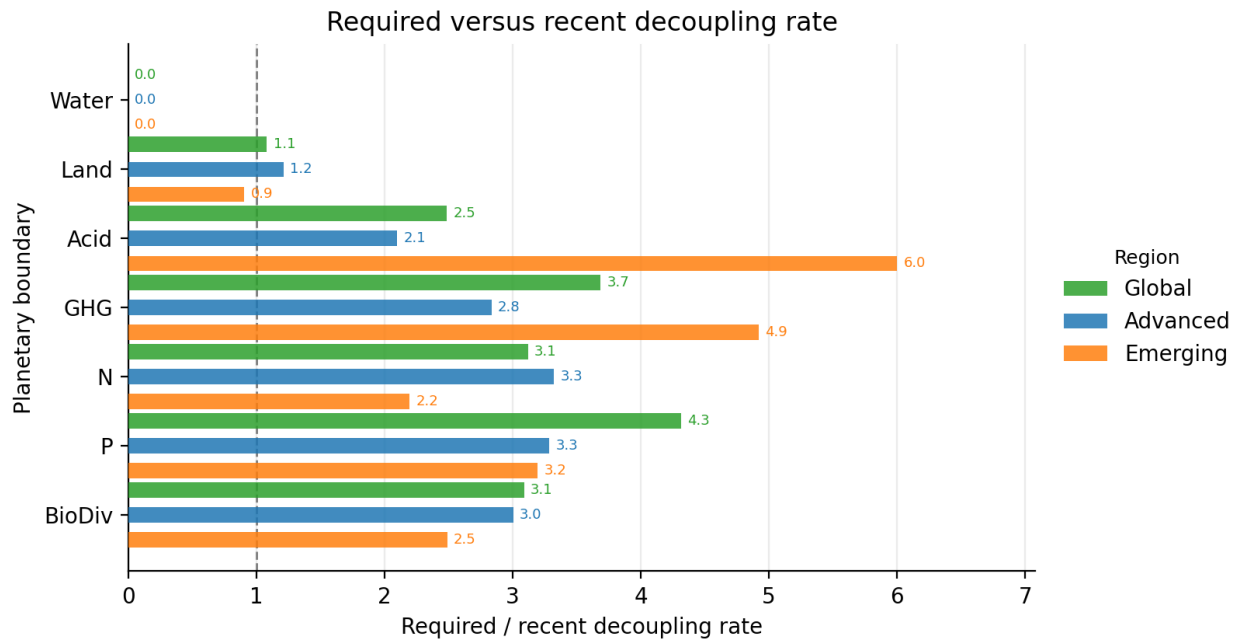


Figure 5 Recent versus required annual rates of decoupling, by indicator and region. Bars show the ratio of required rate of decoupling (to 2050) compared to recent rates of decoupling from observed 2001–2020 trends in pressure per unit GDP.

Discussion

The results confirm that the safe operating space defined by the planetary boundaries framework is being exceeded across all major environmental domains except freshwater, with advanced economies locked into high-impact consumption patterns and emerging economies rapidly converging toward similar levels^{4,13,14}. The results point to challenges of sustainable development: advanced economies must deliver deep absolute reductions far beyond what they have done so far, while emerging economies must bend sharply rising trajectories before they lock in unsustainable infrastructure and consumption systems^{15,16}. The decomposition analysis highlights the primacy of affluence as a driver of environmental pressure, particularly in emerging economies where rising incomes are not yet translating into cleaner consumption profiles. This reflects early-stage Environmental Kuznets Curve (EKC) dynamics, where environmental impacts rise steeply with income before any plateau or decline¹⁷. However, the absence of strong evidence that efficiency

gains, even in the advanced regions, are sufficient to stay within the planetary boundaries suggests that relying on economic growth to deliver heightened environmental improvements is misplaced. Whilst technological progress is occurring, the rates are insufficient to counterbalance the combined pressures of affluence and population (see van Vuuren for some analysis in this direction¹⁰). Extrapolating to 2050 the gap between observed and required rates of improvement, particularly for biodiversity, climate, and phosphorus, indicates that standard efficiency gains need to be radically improved.

Trade patterns complicate the picture further. Consumption-based accounting reveals that apparent domestic improvements in advanced economies are often offset by the outsourcing of resource-intensive production to emerging economies¹⁸. This displacement effect undermines the integrity of national-level performance metrics unless trade related effects are taken into account¹⁹. Whilst improvements in technology are occurring faster in developing regions, the fact they are at higher current intensity levels means that trade still acts to increase footprints in all regions. For emerging economies, the effect trade has had is minor, dwarfed by rising affluence. For advanced economies, where income growth has been modest, re-sourcing toward higher-intensity suppliers is significant, and has added roughly as much pressure as affluence itself (and about 2.8 times as much for water). This trade effect has thus offset between a sixth and a quarter of the reductions achieved through technological improvements. Apparent domestic improvements in advanced economies are therefore materially eroded by the outsourcing of resource-intensive production, reinforcing the case for consumption-based accounting.

A broader implication is the lack of focus on directing technological progress, trade relationships and ultimately consumption toward environmental goals. Innovation (and growth) is primarily driven by cost minimisation (labour, capital, and taxes, considering the full supply chain) rather than by environmental performance²⁰. Without regulation, environmental improvements often arise as a by-product of efficiency gains that primarily serve to reduce production costs and increase affluence²¹. Reduced costs increase affluence, leading to increased consumption²², resulting in higher environmental pressures. Moreover, reductions in labour costs have historically increased energy demand by substituting external energy sources for human effort, often working against environmental objectives²³.

Directing economic development towards lower environmental burdens, for example by explicitly internalising environmental costs in production and consumption decisions, would help steer technological progress towards environmental objectives. More broadly, it suggests that agrowth-oriented policy²⁴ approaches may need to be considered where efficiency improvements and technological substitution are insufficient to deliver absolute reductions in environmental pressure.^{8,15} If we are unlikely to limit impacts through technological progress alone, and given the planetary boundaries are biophysical limits we cannot transgress without substantial Earth-system risks, the other drivers, population and affluence, must be considered more prominently.

However, any potential policy measure, especially those targeting affluence, will need to be nuanced and consider the socio-political dimensions of the time. There are many agrowth policy measures that target shifting demand, rather than explicitly targeting economic growth. Shifts in dietary patterns, material use, and mobility systems will be needed to reduce the scale of the problem that technology is being asked to solve⁸. Globally, ideally environmental externalities aligned to the PB thresholds would be more centrally considered in trade agreements, investment flows, and development finance.

Overall, the results show that declining pressure intensities have not been sufficient to offset the combined effects of affluence and population growth. Advanced economies have achieved absolute reductions across all indicators by widely varying amounts, while their consumption-based footprints remain far above equal per-capita allocations. Emerging economies have lower per-capita exceedance for several indicators, but rising affluence is rapidly increasing total pressure. Under baseline GDP and population trajectories, historical rates of pressure-intensity improvement would need to accelerate substantially, particularly for biosphere integrity, phosphorus, and climate. These results suggest that technology and efficiency improvements remain essential but are unlikely to be sufficient without demand-side changes that reduce the scale of pressure requiring technological mitigation.

Methods

We assess national environmental performance relative to the planetary boundaries (PBs) framework, which defines a global safe operating space for key Earth system processes by identifying scientifically derived thresholds beyond which the risk of destabilising Earth system functions increases^{1,3}. All environmental pressures are quantified on a consumption basis, allocating environmental impacts along global supply chains to the final demand of each country. While PBs are global in nature, we downscale them to the national level, and project required rates of change against a 2050 policy horizon.

Data sources and scope

We update the environmentally extended multi-regional input-output (EE-MRIO) model EXIOBASE v3²⁵ to v3.11.2 for this work (see Wood et al²⁶ for a comprehensive description of data updates). EXIOBASE 3.11.2 spans 1995-2024 across 49 regions, 163 industries, and 200 products. This release represents a comprehensive methodological and empirical update to the database, with several of the environmental extensions used in this study directly updated in this work. The monetary supply-use tables were substantially updated with new data sources and new methods to better integrate energy products in the supply-use table balancing. The energy and emissions extension were rebuilt through the work of Rasul²⁷, to ensure updated residence principle estimates whilst also reconciling greenhouse gas emissions to EDGAR at the sectoral level. Emissions due to deforestation accounts were introduced for the first time in this version, building on Pendrill²⁸ and Singh²⁹. Nutrient accounts were updated as described in Wood et al²⁶. Water accounts were rebuilt from scratch for this work and are described elsewhere³⁰. Novel land accounts were also developed to better capture impacts on native vegetation and are described in the supporting information. Together, these updates substantially reduce the structural uncertainties that affected earlier versions, particularly for the post-2011 period.

All indicators are calculated on a consumption basis, allocating environmental pressures along global supply chains to the final demand of each country. This approach captures both domestic impacts and those embodied in imports, ensuring that footprints in economies that outsource resource-intensive production are fully reflected, and enabling meaningful comparison of environmental responsibility across countries regardless of their position in global supply chains. Countries are grouped into advanced and emerging economies following IMF classification.

Downscaling to national boundaries

The global PB thresholds represent aggregate Earth system limits, not pre-allocated national entitlements. Translating them into country-level targets requires an explicit allocation principle - a normative choice that has been extensively discussed in the literature^{4,7,13}. Proposed approaches include equal per-capita shares, grandfathering proportional to historical emissions, ability to pay, and biophysical allocation based on ecological capacity, each reflecting a different theory of distributive justice. There is no scientific or political consensus on the best approach, and the choice between them reflects fundamentally different views on equity, historical responsibility, and development rights.

We adopt equal per-capita allocation: each country's national boundary is set as its population share of the global PB threshold, updated annually to reflect demographic change. This is the most widely applied approach in the consumption-based PB literature^{4,7,13} and rests on the principle that the resources and ecosystems of the planet are global commons to which all people are entitled to an equal share. We treat the resulting national thresholds as policy-relevant reference points for assessing relative positions and trends, rather than as agreed or binding targets. Because the allocation principle is normative and materially affects the national picture, we test the robustness of our results to it in the Supporting Information, comparing equal per-capita allocation with grandfathering (proportional to base-year footprint) and ability-to-pay (capacity-weighted) allocations. Global exceedance is invariant to the principle by construction; what changes is its distribution across countries.

For indicators where the PB is defined as a cumulative stock constraint rather than an annual flow - most directly, climate change - we translate the global budget into an annual allowance by setting a 2050 policy horizon: the remaining global budget is divided across years and distributed among countries by population share. This approach is consistent with prior work^{14,31,32} and allows the trajectory analysis and technology gap calculations to be defined on a consistent annual basis across all indicators.

Decomposition of drivers

To attribute changes in environmental pressure to their underlying drivers, we apply a Population-Affluence-Technology (PAT) decomposition, following the IPAT identity first formalised by Ehrlich & Holdren³³ and extended by Dietz & Rosa³⁴. Total environmental impact I is expressed as the product of population P , affluence A (GDP per capita in constant 2015 PPP), and technology T (environmental impact per unit of GDP):

$$I = P \times A \times T$$

Changes in each factor are isolated using a multiplicative log-mean Divisia index (LMDI) decomposition, which provides an exact, residual-free attribution³⁵. This allows us to identify, for each indicator and country, the degree to which changes in total environmental pressure are driven by demographic growth, rising affluence, or changes in environmental intensity using a consumption-based approach³⁶. The technology term T captures the combined effect of efficiency improvements, structural economic change, and shifts in the environmental content of traded goods and services. We distinguish relative decoupling (declining T with rising total impact) from absolute decoupling (declining total impact despite GDP growth), which requires T to fall faster than the combined growth in P and A .

To isolate the contribution of trade explicitly, we decompose total consumption-based footprint I by supply channel as $I = I_d + I_m$, where I_d and I_m are obtained as the within-region (d =domestic) and cross-region (m =imports) block sums of the producer to consumer impact matrix $S \cdot L \cdot Y$. Whilst efforts to understand the impact of outsourcing have been developed in the literature for over a decade³⁷, we make this trade-sourcing effect an explicit, decomposable driver of the footprint (see Supporting Information). We write the structural identity $I_d = P \cdot A \cdot \alpha \cdot t_d$ and $I_m = P \cdot A \cdot (1 - \alpha) \cdot t_m$, in which P is population, A is affluence (GDP per capita in constant 2015 PPP), and α is externally specified as the gross-output share sourced within the region group, computed from the column-block partition of $L \cdot Y$: $\alpha = \sum (L \cdot Y)_{c,c} / \sum_p \sum (L \cdot Y)_{p,c}$ (where p =producing region, c =consuming region). Given α , the intensities $t_d = I_d / (\alpha \cdot A \cdot P)$ and $t_m = I_m / ((1 - \alpha) \cdot A \cdot P)$ follow as residual definitions that satisfy the identity by construction. Equivalently, $t_d = (I_d / X_d) \cdot m$ where X_d is the domestically induced gross output and $m = X_{\text{total}} / Y_{\text{total}}$ is the total output multiplier; thus Δt_d (and Δt_m) capture the *combined* effect of changes in true supply-chain intensity and changes in the output multiplier. Empirically, m varies little for Advanced economies over 2000-2020 (1.84 to 1.82) but rises ~8% for Emerging-Developing (1.9 to 2.0), so for the latter group Δt partly reflects supply-chain lengthening rather than pure intensity change. Supporting information gives an alternative six-term decomposition that separates this output-multiplier effect explicitly. Applying additive LMDI³⁵ to $I_d + I_m$ yields five drivers that sum exactly to ΔI : population (ΔP), affluence (ΔA), trade composition ($\Delta \alpha$), domestic technology-and-multiplier (Δt_d), and embodied foreign technology-and-multiplier (Δt_m). The decomposition is computed at the region-group level (Advanced, Emerging-Developing) and at country level over annual year-pairs, accumulated over 2000-2020.

Methodologically, this is an index decomposition (IDA) applied to MRIO-derived aggregates rather than a structural decomposition (SDA). Following the aggregate-embodied-intensity tradition of Su and Ang³⁶ and Wang and Su³⁸, we collapse the MRIO calculation to domestic/import impact totals (I_d , I_m) and apply an LMDI identity to those totals; the Leontief inverse L is not decomposed individually as it would be in a true SDA³⁹. The contribution of this paper is to introduce α as an explicit decomposable driver of trade composition in this hybrid IDA framework, in order to isolate the trade-sourcing effect directly. To our knowledge this construction has not appeared in the published decomposition literature, although the general direction is anticipated by the SDA-based domestic-vs-international input split^{37,39}, who decompose ΔL into regional contributions rather than as a sourcing ratio.

Required technology gap

For each indicator, we derive the annual rate of technological improvement required to return to within the downscaled national boundary by 2050, given projected population and GDP growth. Using UN medium-variant population projections and IMF GDP growth scenarios, the required rate of change in T is back-calculated from the 2050 target established in the downscaling section above. This analysis is dependent on projected P and A : it asks what T must do if demographic and economic growth follow current trajectories. This is not a claim that technology is the only available lever - reducing the scale of consumption or moderating economic growth would lower the required rate of improvement proportionally. Rather, isolating projected P and A provides the most policy-challenging framing: it quantifies the technological ambition implied by continued growth, making visible the full scale of decoupling required and the gap between that and current

performance. Comparing the required rate to the observed rate of change in T over 2000-2020 yields the technology gap - the proportional acceleration in decoupling needed relative to current trajectories.

Indicators and boundaries

Seven planetary boundary domains are assessed in this study (Table 1). For each, we identify either existing or new EXIOBASE environmental extensions as the current-value metric and map them to the corresponding boundary threshold. Where the boundary is defined spatially homogenous the mapping is direct (climate change, ocean acidification, and biogeochemical flows). For indicators with strong spatial heterogeneity, including land-system change, freshwater use, and biosphere integrity, spatially explicit characterisation methods are applied that weight impacts according to local ecological conditions. Aerosol loading is excluded as no agreed global boundary value exists. Stratospheric ozone depletion and novel entities are excluded due to data limitations and the fact that ozone is not a current cause of concern. Full derivations of boundary values are provided in the indicator subsections below.

Table 1. Planetary boundary indicators, control variables, and boundary thresholds used in this study.

EARTH SYSTEM PROCESS	EXIOBASE INDICATOR	UNIT	SAFE BOUNDARY (LOWER)	ZONE OF UNCERTAINTY (UPPER)	SPATIAL WEIGHTING	REFERENCE
CLIMATE CHANGE	GHG emissions	kg CO ₂ eq yr ⁻¹	2.00×10 ¹³	4.50×10 ¹³	No	Steffen et al. 2015 ³ ; Rockström et al. 2017 ³²
OCEAN ACIDIFICATION	CO ₂ emissions	kg CO ₂ yr ⁻¹	3.20×10 ¹³	4.00×10 ¹³	No	Steffen et al. 2015 ³
BIOSPHERE INTEGRITY	Potentially Disappeared Fraction (PDF)	PDF	0.10	0.30	Yes	Steffen et al. 2015 ³ ; Richardson et al. 2023 ²
LAND-SYSTEM CHANGE	Agricultural area on potential forest	km ²	1.50×10 ⁷	2.40×10 ⁷	Yes	Steffen et al. 2015 ³ ; Hengl et al. 2018 ⁴⁰
FRESHWATER USE	Scarcity-weighted blue water consumption	million m ³ eq yr ⁻¹	4.0×10 ⁶	6.0×10 ⁶	Yes	Steffen et al. 2015 ³ ; Richardson et al. 2023 ²

BIOGEOCHEM. FLOWS - N	Synthetic mineral fertilizer N inputs	kg N yr ⁻¹	6.20×10 ¹⁰	1.12×10 ¹¹	No	Steffen et al. 2015 ³ ; Richardson et al. 2023 ²
BIOGEOCHEM. FLOWS - P	Synthetic mineral fertilizer P inputs	kg P yr ⁻¹	6.20×10 ⁹	1.12×10 ¹⁰	No	Steffen et al. 2015 ³ ; Richardson et al. 2023 ²

Notes: Safe boundary = lower limit of zone of uncertainty; Zone of uncertainty upper limit = high-risk threshold.

Category 1 (global scale boundaries)

Climate change

The climate change planetary boundary is expressed as an atmospheric CO₂ concentration limit of 350 ppm (safe operating space) with a zone of uncertainty extending to 450 ppm³. Because the climate boundary is fundamentally a cumulative stock constraint, translation into an annual emission allowance requires specifying a remaining carbon budget and an annualization pathway⁴¹.

We draw on remaining carbon budgets from IPCC AR6 WGI (^{42,43}, Table SPM.2), assessed from January 2020. The lower boundary (safe operating space) is based on the 1.5°C remaining budget at 50% probability (500 GtCO₂); the upper boundary (zone of uncertainty) uses the 2°C budget at 67% probability (1,150 GtCO₂). To convert CO₂-only budgets to CO₂-eq, we apply a scaling factor to account for non-CO₂ greenhouse gas emissions (CH₄, N₂O, and F-gases), following the approach in Nicholls et al⁴⁴. This yields total GHG budgets of approximately 600 GtCO₂eq (lower) and 1,350 GtCO₂eq (upper). Distributing these equally across 2020-2050 gives annual allowances of 20 GtCO₂eq yr⁻¹ (lower) and 45 GtCO₂eq yr⁻¹ (upper). It should be noted however, that equal annual distribution is a simplifying assumption: mitigation pathways consistent with 1.5°C require front-loaded reductions, so flat annualization is more permissive than a realistic near-term trajectory and yields a conservative (lower-bound) estimate of current exceedance. Environmental pressures are quantified as GHG emissions in CO₂-eq using GWP100 AR6 values across all Kyoto gases as reported in EXIOBASE. Global consumption-based GHG emissions in 2020 were approximately 49 GtCO₂eq, an exceedance of roughly 2.5 times the lower boundary.

Ocean acidification

The ocean acidification planetary boundary is defined in terms of the mean surface seawater aragonite saturation state (Ω_a), with a safe operating space at $\Omega_a \geq 2.75$ (approximately 80% of pre-industrial levels) and the high-risk zone entered below $\Omega_a \leq 2.5$ ³. Since oceanic aragonite saturation is driven primarily by the partial pressure of CO₂ absorbed by the ocean, this boundary translates directly into an atmospheric CO₂ concentration limit: the safe threshold of $\Omega_a \geq 2.75$ can be maintained at concentrations up to approximately 450 ppm, while values below $\Omega_a = 2.5$ are approached at concentrations above approximately 500 ppm^{45,3}.

The EXIOBASE indicator for this boundary is CO₂ emissions - which is the same physical quantity driving the majority of climate change but mapped against the higher and distinct ppm thresholds appropriate to the acidification mechanism. Following the same annualization approach as for climate change, we translate the 450 ppm and 500 ppm concentration limits into remaining CO₂ budgets from January 2020, yielding approximately 960 GtCO₂ (lower, safe boundary) and 1,200 GtCO₂ (upper, zone of uncertainty). Distributing these equally across 2020-2050 gives annual allowances of 32 GtCO₂ yr⁻¹ (lower) and 40 GtCO₂ yr⁻¹ (upper).

Note that the ocean acidification boundary is based on CO₂ only, since non-CO₂ greenhouse gases do not directly drive ocean acidification. This makes the acid boundary systematically less stringent than the climate boundary on an annual emission basis, reflecting the physical reality that aragonite saturation remains in a safe zone at CO₂ concentrations that already exceed the climate safe boundary of 350 ppm. Current global CO₂ emissions of approximately 37 GtCO₂ yr⁻¹ in 2020 place the world within the zone of uncertainty for this boundary, approaching but not yet in the high-risk zone.

Category 2 (local scale boundaries)

Biosphere integrity

Biodiversity impacts are quantified using the Potentially Disappeared Fraction of species (PDF), an endpoint-level metric expressing the fraction of species committed to global extinction as a result of land use pressures. LC-IMPACT uses global PDF (the fraction of species committed to global extinction relative to the total) as the metric for biodiversity impacts. The method applies vulnerability factors to distinguish local and regional species loss from irreversible global extinction, on the grounds that global extinction is irreversible while regional species loss is not ⁴⁶.

Characterisation factors (CFs) are taken from Scherer et al⁴⁷, developed within the UN Environment-SETAC Global Guidance for Life Cycle Impact Assessment (GLAM) project. These CFs combine two recent advances in the field - the consideration of land use intensities and landscape fragmentation - covering five species groups (plants, amphibians, birds, mammals, and reptiles) and five broad land use types at three intensity levels, available at the level of terrestrial ecoregions and countries⁴⁷. This represents a substantial methodological advance over earlier characterisation approaches, which used only six broad land use types without intensity differentiation and did not account for fragmentation effects. The CFs are applied to the EXIOBASE land use extensions, linking sector-level land use flows to spatially explicit biodiversity impacts via ecoregion-level characterisation. Land use input data draw on the harmonised land use time series developed as part of the EXIOBASE update⁴⁸.

The planetary boundary for biosphere integrity is defined in terms of the Biodiversity Intactness Index (BII), with a safe operating space above 90% intactness and the zone of uncertainty between 90% and 70% ^{2,3}. Translating these BII thresholds into PDF units: a decline from 100% to 90% BII corresponds to a PDF of 0.10, and a decline to 70% corresponds to PDF of 0.30. This gives boundary values of 0.10 PDF (safe operating space) and 0.30 PDF (zone of uncertainty upper limit). Current global biodiversity loss is estimated to have already transgressed the safe boundary, with BII values in many biomes well below 90%, consistent with².

Land system change

The land-system change planetary boundary is defined as the preservation of at least 75% of potential forest cover globally. That is, the forest that would exist in the absence of human land-use change. Biome-specific thresholds of 85% for tropical and boreal forests and 50% for temperate forests are set³. The zone of uncertainty extends down to 60% of potential global forest cover remaining, corresponding to the high-risk threshold.

Rather than tracking forest cover directly, this study quantifies agricultural land use pressure on potential forests. This approach is appropriate for a footprint analysis because it attributes land-system change impacts to the production processes causing forest loss. Potential forest distributions across boreal, temperate, and tropical biomes are defined using the global potential natural vegetation mapping of Hengl et al⁴⁰, which applies machine learning algorithms to estimate the spatial distribution of forest ecosystems under natural conditions. The encroachment of cropland and grazing pasture on land suitable for forest ecosystems is quantified by overlapping spatially explicit probability of potential forest occurrence with cropland and pasture layers from Winkler et al⁴⁹. These aggregated spatial impacts are subsequently attributed to individual crop and livestock categories to enable supply-chain and consumption-based assessment. Cropland impacts are allocated in proportion to the physical area of individual crops; pasture impacts are distributed across livestock groups using dry matter intake as the allocation key, reflecting both feed demand and land use intensity among livestock systems^{50–54}. Spatially explicit national production impacts are then linked to EXIOBASE sectors through concordance matrices, enabling tracing of potential forest appropriation through global supply chains to final consumption. A full description of the underlying calculations is available in the supporting information.

The global boundary is expressed in area units of potential forest appropriated by agriculture. Applying the Steffen et al³ thresholds to the estimated global potential forest area of approximately 60 million km², the lower boundary (safe operating space) corresponds to 15 million km² of agricultural encroachment on potential forest (25% converted, 75% remaining), and the upper boundary (zone of uncertainty) corresponds to 24 million km² (40% converted, 60% remaining).

Freshwater use

The Steffen et al³ freshwater boundary is defined in terms of global consumptive blue water use, with a safe operating space below 4,000 km³ yr⁻¹ and a zone of uncertainty extending to 6,000 km³ yr⁻¹. This provides a transparent comparator with annual blue-water consumption accounts, but is spatially blunt: freshwater scarcity and ecological impacts depend strongly on basin and seasonal context. Gerten⁵⁵ proposed a more precautionary environmental-flow-based revision of 2,800 km³ yr⁻¹, with an uncertainty range of 1,100–4,500 km³ yr⁻¹, but this was not adopted as the headline boundary³. More recent work reframes the freshwater boundary as freshwater change, incorporating blue-water streamflow and green-water soil-moisture deviations². These newer formulations better capture Earth-system freshwater change, but are not directly commensurate with an annual input-output account of blue-water consumption embodied in production and final demand.

We therefore retain the legacy 4,000-6,000 km³ yr⁻¹ boundary as the transparent physical comparator, but complement it with AWARE 2.0⁵⁶ to address the spatial limitation of the global volume metric. AWARE weights volumetric blue-water consumption by basin-level water scarcity, based on available water remaining after human water demand and environmental flow requirements are accounted for. The basin-level AWARE factors are linked to spatially explicit crop-water consumption and aggregated to country-crop specific factors. Thus, although the input-output model operates at country-sector resolution, the AWARE indicator retains subnational information on where crop water consumption occurs. This provides a pragmatic bridge between planetary-boundary-style assessment and supply-chain footprint accounting: the physical indicator tests consistency with the legacy consumptive blue-water boundary, while the AWARE indicator tests whether this conclusion changes when the location and scarcity context of water consumption are accounted for.

AWARE characterisation factors span 0.1-100, and because global blue-water consumption is dominated by irrigation water use in relatively water-scarce basins, the global consumption-weighted factor is well above 1, remaining stable at approximately 33 m³ world-eq per m³ of blue water consumed across 2000-2023. Dividing AWARE 2.0-weighted results by this global factor preserves relative scarcity weighting while expressing results in global-average-scarcity-equivalent blue-water units, on a scale comparable to the physical blue-water boundary.

As the choice of approach involves methodological judgement, in the supporting information, we provide a sensitivity assessment with results for physical blue water consumption, AWARE weighted results, and results weighted by the Water Stress Index (WSI)⁵⁷. The WSI is useful as an older and simpler water-stress weighting based on withdrawal-to-availability stress and has an average global weighting of 0.51 (range 0-1), but AWARE 2.0 is more closely aligned with the freshwater planetary-boundary critique because it explicitly accounts for remaining water availability after human demand and environmental flow requirements.

The global blue water consumption in 2020 was approximately 1,234 km³ eq yr⁻¹, placing the global total well within the safe operating space at the aggregate level, consistent with the literature². The spatial weighting nonetheless captures local and regional scarcity pressures in water-scarce areas that the volumetric global aggregate conceals.

Biogeochemical flows - nitrogen and phosphorus

Current-value metrics for both nitrogen and phosphorus are based on synthetic mineral fertilizer inputs to cropland. For nitrogen, data are drawn from OECD nutrient balance statistics (Inorganic fertilisers measure), supplemented by FAO cropland nutrient budget data (Synthetic Fertilizers item) using an OECD-first, FAO-fallback approach to maximise country coverage. For phosphorus, the same source hierarchy is applied. Global 2020 totals are 103.8 Mt N and 19.3 Mt P, consistent with independent estimates of approximately 110 Mt N and 17.5-18.2 Mt P from FAO and IFA trade-balance statistics; the ca. 5.5% gap for nitrogen reflects differences between agricultural-use and trade-balance accounting frameworks and is within normal inter-source uncertainty.

Planetary boundary thresholds are taken from Steffen et al.³ and Richardson et al.², defined as the tolerable annual application rate of intentionally fixed nitrogen and mineral phosphorus fertilizer to the global agricultural system: lower bounds of 62 Tg N yr⁻¹ and 6.2 Tg P yr⁻¹, and upper bounds

of 112 Tg N yr⁻¹ and 11.2 Tg P yr⁻¹. Global exceedance in 2020 is 1.7 times for nitrogen and 3.1 times for phosphorus, consistent with the literature consensus of approximately 1.8-2 times and ~3 times respectively².

This inputs-based approach was adopted after systematic investigation of alternatives. An emissions-to-freshwater approach, aligning with the mechanism of concern (eutrophication) more directly, was explored but not adopted for two reasons. First, FAO-reported leaching data for phosphorus are not populated for the large majority of countries, making a credible global P emissions series unachievable from available sources. Second, heuristic scalar approaches to estimate nutrient loss from inputs (applying fixed emission fractions) produce global values well below the literature consensus on boundary exceedance for both nutrients, indicating the scalars are too conservative to reproduce observed conditions. Similarly updating previous work⁵⁸ faced too many data inconsistencies. Total nutrient inputs (including manure, biological nitrogen fixation, and atmospheric deposition) were also considered but rejected because the canonical boundary definitions explicitly exclude these components, and their inclusion inflates exceedance ratios roughly twofold for P relative to the literature consensus. Synthetic mineral fertilizer inputs therefore represent the metric that is simultaneously grounded in the canonical boundary definitions, consistent with available data quality, and produces exceedance ratios in agreement with independent assessments. The total inputs and emissions-to-water series are available from the authors for diagnostic and sensitivity purposes.

Limitations and uncertainties

Several limitations warrant caution in interpreting these results. Downscaling of planetary boundaries to national levels based on national populations is a reasonable, but arbitrary, choice for downscaling planetary boundaries to administrative jurisdictions. Alternative allocation principles redistribute responsibility substantially. In the Supporting Information we show results under three methods. Under an ability to pay allocation, which weights entitlements by income, advanced economies carry a larger share of the overshoot (for climate, their exceedance rises from about 4.9 to about 7.2 times the lower boundary), while emerging economies change little. The EXIOBASE dataset, while comprehensive, carries uncertainties in trade flows, sectoral disaggregation, and environmental extensions, particularly for emerging economies with less robust statistical systems. Finally, the extrapolation toward 2050 (purposefully) does not consider future technological breakthroughs or systemic change.

Data Availability Statement

Results are available in Supporting Information and will be made available on Zenodo upon acceptance. The EXIOBASE data underlying this study is made available through Zenodo at: <https://doi.org/10.5281/zenodo.3583070>.

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AI Statement. The authors used AI language tools to assist with manuscript editing, coding assistance, and quality assurance during preparation of this work. All scientific content, analysis, interpretation, and conclusions are solely the responsibility of the authors. No generative AI was used to produce or modify any figures.

Related work. Due to the extent of database updates for EXIOBASE that go beyond this paper, two related data descriptor papers have been prepared but not yet published that relate to the work produced here.

Wood, R., Stadler, K., Rasul, K., Deck, C., Lutter, S., Kroiss, A., Giljum, S., Jiang, M., Kuenen, J., Hertwich, E., & Tukker, A. (2026). *Tracking global environmental burdens: A consumption-based perspective from an updated EXIOBASE*. Manuscript submitted for publication, *Journal of Industrial Ecology*.

Wood, R., Stadler, K., Rasul, K. (2026). *Physical water accounts for global input-output analysis: A source-specific, output-driven reconstruction for EXIOBASE*. Manuscript in preparation for *Scientific Data*.

They are made available to editors/reviewers here:

<https://xio.box.com/s/cc18xaaseke5wopps1w6eimwvbqasox8>

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