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Globalized consumption undermines efficiency-driven sustainability gains across planetary boundaries[*]

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Abstract Despite decades of ambitious environmental policy, German consumption has continuously exceeded planetary-boundary thresholds in six of seven environmental dimensions since 1995, with little improvement over time. Combining environmentally extended multi-regional input–output tables with life-cycle impact assessment, we develop a consumption-based sustainability indicator across seven impact categories, benchmarked against national planetary-boundary thresholds. Decomposing impacts into scale and impact intensity per euro of production, we find that imports embody more impact per euro than domestic production in every category. A rising import share thus slows aggregate efficiency gains even as intensities fall in both origins, and the growing scale of imports offsets them altogether. We show that had the import share remained at its 1995 level, cumulative impact growth from 1995 to 2022 would have been 12.9 to 96.8 percentage points lower across categories.

JEL classification: C67, F18, Q01, Q54, Q56

Keywords: Planetary boundaries, Environmental footprints, Global value chains, Trade and environment

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1 Introduction

Earth has crossed six of nine planetary boundaries, pushing critical Earth-system processes beyond the safe operating space that has underpinned human civilizations for millennia (Rockström et al., 2009; Steffen et al., 2015; Richardson et al., 2023). Halting this trajectory requires understanding not only whether environmental pressures are declining in absolute terms, but also where they originate. For an open economy, this means asking how much of the pressure behind its consumption—the basis of its standard of living—is generated abroad rather than at home.[1] These questions are especially pressing for high-income economies, which combine high consumption levels with deep integration into global production networks. Yet existing policy mainly (i) relies on territorial production-based indicators, which count exports while excluding the imports that domestic consumption draws in, (ii) focuses on a narrow set of environmental dimensions, or (iii) sets targets against relative rather than absolute limits—each of which can give a misleading picture of progress.

We address these gaps by developing and applying a comprehensive, consumption-based sustainability indicator for Germany.[2] Germany combines two characteristics that are highly relevant for such an assessment. On the one hand, its long-standing policy ambition and relatively stringent environmental regulation provide conditions under which efficiency improvements in production are plausibly substantial.[3] On the other hand, its deep integration into global value chains implies a high exposure of domestic consumption to international production processes and trade-related displacement of environmental pressures. These features make Germany a suitable case for examining whether efficiency gains observed under ambitious policy conditions translate into absolute sustainability once consumption patterns and international supply chains are fully taken into account.

Combining environmentally extended multi-regional input–output (EE-MRIO) tables with life-cycle impact assessment (LCIA) methods, we quantify environmental pressures across seven impact categories—climate change, particulate matter, photochemical ozone formation, land use, water use, fossil resource use, and mineral resource use—and evaluate them against national shares of planetary-boundary-consistent thresholds over the period 1995–2022. To shed light on the drivers behind environmental impact, we disaggregate impacts by geographic origin into a part that is

[1]The consumption-based perspective naturally incorporates the environmental impacts embodied in imports, and it assigns responsibility to those who benefit from consumption rather than to where production happens to occur.

[2]We use the term consumption in a broad sense including consumption by households, the government, and investment. It equals final demand excluding exports.

[3]On the environmental stringency performance, see Kruse et al. (2022). A historical overview of Germany's climate policy and ambitions is provided by Erbach (2024).

embodied in imports and a part embodied in domestic production. We further decompose each of these components into the scale of production and a measure of impact intensity per euro of production for final demand in Germany.

Our central finding is that German consumption has continuously exceeded national planetary-boundary thresholds in six of seven categories, with little improvement over time. Domestic production shows absolute decoupling—aggregate pressure falling even as the economy grows—but this decoupling disappears in every category once imports and upstream supply chains are counted. Two import-linked mechanisms drive this pattern. First, efficiency gains are outweighed by a scale of consumption growth fueled by rising imports. Second, a growing import share, embodying more impact per euro than domestic production, dampens aggregate efficiency improvements. To gauge the role of this shift, we recompute each consumption-based series under an accounting counterfactual holding the import share at its 1995 level, ceteris paribus: the rising share raised cumulative impact growth between 1995 and 2022 by 12.9 (climate change) to 96.8 (water use) percentage points.

Our paper contributes to several interrelated strands of the literature. First, it builds on the planetary-boundaries framework (Rockström et al., 2009; Steffen et al., 2015; Richardson et al., 2023) and the growing body of work that translates planetary boundaries into LCIA-compatible indicators suitable for economic accounting (Bjørn et al., 2017; Ryberg et al., 2018; Sala et al., 2020). A parallel literature has sought to define safe and just operating spaces at the national level, asking what planetary boundaries imply for the consumption and welfare of individual countries (Raworth, 2017; O'Neill et al., 2018; Fanning et al., 2022). Existing applications of this combined framework typically focus on cross-sectional comparisons or short time horizons (Sanyé-Mengual and Sala, 2023). We extend this literature in two directions: by providing a long-run assessment spanning nearly three decades, and by combining absolute planetary-boundary thresholds with a structural decomposition that separates the scale of production from impact intensities per value of production, disaggregated by domestic and foreign production. This allows us to go beyond documenting boundary transgressions to explaining why they persist.[4]

Second, the paper contributes to the literature on consumption-based environmental accounting and the role of international trade in shaping national environmental footprints. Because production and consumption are increasingly geographically separated, territorial accounts systematically misat-

[4]While structural decomposition analysis has been widely applied to carbon and energy footprints, comprehensive multi-category SDA studies remain scarce (Hubacek et al., 2021; Baiocchi and Minx, 2010; Jiang et al., 2021; Dietzenbacher et al., 2020), and none has linked the decomposition to absolute planetary-boundary thresholds over a long time horizon.

tribute environmental pressures in open economies. Consumption-based accounting, implemented through environmentally extended input–output (EEIO) models, reallocates these pressures along global supply chains to the point of final demand (Wiedmann, 2009). Early applications established that international trade substantially alters national environmental profiles (Peters and Hertwich, 2008; Hertwich and Peters, 2009; Wiedmann and Lenzen, 2018), and that high-income countries are typically net importers of emissions, with their consumption driving environmental pressures in the production systems of developing economies (Peters et al., 2011; Davis and Caldeira, 2010). Beyond carbon, trade has been shown to displace biodiversity threats and other ecological pressures from consuming to producing nations (Lenzen et al., 2012), underscoring that the trade-embodied environmental burden extends well beyond the greenhouse gas dimension that has dominated the accounting literature to date. We contribute by decomposing consumption-based environmental pressures into scale and impact intensity components separately for domestic and foreign production. This decomposition allows us to identify a dual role of imports. First, a rising share of imported goods shifts the consumption bundle toward production technologies that are, on average, more impact-intensive than domestic ones, slowing aggregate efficiency gains even as intensities fall within both domestic and foreign production. Second, import growth offsets aggregate technology gains altogether. This dual role of imports has received limited attention in sustainability assessments based on planetary boundaries.

Third, the paper speaks to the broader literature on economic growth, technological change, and environmental pressure. A long tradition decomposes changes in pollution into scale, composition, and technique effects (e.g., Grossman and Krueger, 1993; Copeland et al., 2022). Recent empirical applications find improvements in technology to be the dominant driver of declining pollution from production, with composition and trade playing comparatively minor roles (e.g., Levinson, 2009; Shapiro and Walker, 2018). We add by bringing this scale–composition–technique decomposition to a consumption-based approach.[5] This reveals a composition channel that production-based

[5]While the aforementioned papers decompose environmental impacts into three components, we focus on scale and an output-weighted impact intensity that is determined by both the composition of production for final demand and the sectoral technique effect. In so doing, our results do not depend on the choice of a base year. In fact, a separately measured technique effect would have to be understood as the change in technology that would occur if the composition of consumption remained fixed at some base period. Hence, at its extreme, the measured technique effect may be completely irrelevant, as consumption shifts to other products, making the considered technologies obsolete. The notion of compositional effect present in our paper refers to shifts between foreign and domestic production. Further note that we use the term *impact intensity*—impact per euro of production for final demand—rather than technology because, although we deflate each origin by its own price index so that the change over time reflects technology, we do not equalize price levels between domestic and foreign production; the geographic comparison of intensities therefore also

decompositions cannot detect: the shift of consumption toward more impact-intensive imports. Together with the rising scale of consumption, this channel offsets local efficiency gains and explains why absolute decoupling fails—even though efficiency improves at broadly similar rates in domestic and foreign production.

Fourth, we contribute to the literature on absolute decoupling. Whether efficiency gains translate into absolute reductions at the level of national consumption is contested: evidence for absolute decoupling of environmental pressure from economic growth remains limited (Haberl et al., 2020; Parrique et al., 2019; Vadén et al., 2020; Wiedmann et al., 2020), even as some consumption-based studies report partial decoupling (Hubacek et al., 2021). Our contribution is to show that when focusing on a narrow part of consumption—namely the one produced domestically—absolute decoupling appears feasible. However, this impression vanishes once imports are accounted for.

From a policy perspective, our findings highlight the limits of sustainability strategies that focus narrowly on improving domestic production efficiency. We show that, as consumption increasingly shifts toward imported goods with higher associated environmental impact intensity, efficiency gains achieved within domestic production fail to translate into improved sustainability outcomes. Addressing this disconnect requires complementing territorial accounting with supply-chain measures and policy instruments that explicitly account for the scale and composition of consumption. The German case illustrates that this challenge may extend across a broad range of environmental impact categories.

The remainder of the paper is structured as follows. Section 2 describes the data and methodology. Section 3 presents the results. Section 4 concludes.

2 Data and methodology

This section outlines the data sources and methodological steps used to quantify the environmental pressures associated with German consumption and to assess whether these pressures remain within a safe operating space. We combine three components. First, we use EE-MRIO tables to trace environmental pressures along global value chains. Second, we translate heterogeneous physical stressors into comparable environmental impact indicators using LCIA-based characterization factors (CF). Third, we evaluate these impacts relative to absolute sustainability thresholds derived from the planetary-boundaries framework. Technical details on each step are provided in Appendix B.

reflects differences in price levels, not technique alone.

2.1 Environmentally extended input-output data

We use EXIOBASE 3.9.5 (Stadler et al., 2018), a widely used EE-MRIO database covering 44 countries, five rest-of-world (RoW) regions, and 163 sectors per country for the period 1995–2022. EXIOBASE combines a monetary input–output (IO) system—recording inter-industry flows, final demand, and value added—with environmental satellite accounts that document physical flows associated with production. Our analysis draws on four EXIOBASE environmental extensions relevant for LCIA-based impact assessment: (i) air emissions, (ii) water use, (iii) material use, and (iv) land use. Together, these extensions contain 705 distinct stressors.

To integrate environmental stressors into the IO framework, we express them as intensities, measured as impact per Euro of sectoral output. Combining stressor intensities with the Leontief inverse provides us with the total environmental pressures embodied in production and consumption, including all upstream supply-chain stages.

2.2 Consumption-based accounting and use-phase impacts

There are two complementary sets of environmental impact accounts commonly used in environmental accounting. Production-based impact accounts attribute environmental pressures to the location where production occurs, irrespective of where goods are ultimately consumed. Consumption-based impact accounts, by contrast, attribute environmental pressures to the location of final consumption. Pressures embodied in exports are therefore excluded, while those embodied in imports are included. Importantly, the consumption-based account captures not only the pressures from the final production step, but also all upstream pressures generated along international value chains.

We focus on consumption-based sustainability because it aligns with welfare-based interpretations of environmental responsibility. Furthermore, it avoids misleading improvements that arise when production of environmentally intensive consumption goods is relocated abroad rather than reduced. In open economies with deep global value-chain integration, consumption-based accounts therefore provide a more informative benchmark for assessing sustainability outcomes related to welfare.

We incorporate use-phase impacts, which are generated during the use of goods and services, such as emissions from residential heating, electricity use, or private mobility. These impacts arise directly from final consumption and are reported in a separate extension for the final demand matrix in EXIOBASE.[6]

[6] The consumption-based accounting literature often treats use-phase impacts as part of the consumption-based account itself (Wood et al., 2018; Stadler, 2021). We instead treat use-phase impacts separately from

2.3 Impact categories and characterization factors

Planetary boundaries define biophysical limits for critical Earth-system processes (Rockström et al., 2009; Steffen et al., 2015). However, these limits are expressed in physical control variables that are not directly compatible with IO-based accounting. We therefore rely on LCIA-based planetary boundaries developed by Sala et al. (2020), which translate boundary control variables into LCIA indicators and provide corresponding threshold values for environmental impacts. Due to their compatibility with IO frameworks, LCIA impact categories allow for a systematic attribution and tracking of environmental pressures associated with economic activity across sectors, regions, and impact dimensions.

CFs convert heterogeneous stressors into standardized impact units, allowing environmental pressures to be compared and related to impact categories. For example, greenhouse gases are expressed in CO_2-equivalents, particulate matter precursors in expected disease incidence, and land occupation in LANCA-based soil-quality points.[7] We use CFs from the Environmental Footprint (EF) 3.1 method provided by Bassi et al. (2023).

Characterized impacts are obtained as:

$$\mathbf{P}_t = \mathbf{CF} \times \mathbf{Q}_t,$$

where $\mathbf{Q}_t$ denotes the stressor matrix and $\mathbf{CF}$ the matrix of CFs. For water and land use, CFs vary by country of production because environmental damages depend on local conditions; we therefore construct region-specific CFs for the RoW regions in EXIOBASE.

We retain the seven impact categories for which (i) LCIA-based planetary-boundary thresholds exist and (ii) EXIOBASE stressors can be consistently characterized using EF 3.1. The categories are: climate change, water use, land use, resource use (fossil fuels), resource use (minerals and metals), particulate matter, and photochemical ozone formation. Threshold values and units are reported in Table 4 in Appendix B.4. Not all stressors in our data can be matched to an impact category, since some lack characterization factors and are necessarily left uncharacterized. Appendix D shows that including them would not overturn our main results.

the consumption-based account. In the terminology of that literature, our consumption-based account plus use-phase impacts (the aggregate series in Figure 1) corresponds to the consumption footprint, comprising direct (use-phase) and indirect (consumption-based) impacts.

[7] Where *LANCA* stands for LANd Use Indicator Value CAlculation which is the method used to derive CFs for the land use category in EF 3.1.

2.4 Planetary-boundary thresholds

We assess sustainability by comparing environmental impacts to national thresholds, which are obtained by downscaling global LCIA-based planetary boundaries. We start by collecting global thresholds taken from Sala et al. (2020) and Sanyé-Mengual and Sala (2023).[8] We scale global thresholds to a national level using an equal-per-capita approach:

$$\mathrm{PB}_c = \bar{\omega}_c \cdot \mathrm{PB}_{\mathrm{global}},$$

where $\bar{\omega}_c$ denotes the country's average population share over the period 1995–2022 (United Nations, 2024). Using average shares prevents changes in population from mechanically affecting the sustainability indicator over time. We adopt an equal-per-capita allocation as a transparent and conservative benchmark. Alternative allocation principles based on historical responsibility or mitigation capacity would imply even stricter thresholds for high-income countries such as Germany. Appendix B.4.2 discusses these alternatives.

2.5 Trade decomposition

To separate domestic and international sources of environmental impacts, we decompose impacts into foreign and domestic production. Import-related footprints reflect pressures generated abroad in the production for domestic consumption. They are derived using a block-diagonal representation of final demand in which domestic blocks are set to zero. This decomposition allows us to distinguish whether sustainability gaps are driven primarily by domestic production or imported consumption.

3 Results

We are now equipped to assess the sustainability performance of the German economy. Subsection 3.1 presents our main metric: consumption-based environmental impacts relative to national sustainability thresholds across seven categories. Subsection 3.2 decomposes these impacts into their geographic origin: domestic and foreign production. Subsection 3.3 explains the domestic

[8] For particulate matter, the threshold in Sala et al. (2020) depends on global population. For consistency with our horizon from 1995 to 2022 we use the average global population numbers from 1995–2022 instead of the 2010 value used in Sala et al. (2020). Our adjusted global threshold amounts to 5.13E+5 instead of 5.16E+5 (Appendix B.4.1).

and foreign trajectories by separating the scale of production from changes in the average impact intensity of the value of production for final demand in Germany.

Our central result is that German consumption persistently exceeds absolute sustainability thresholds in most environmental dimensions, despite nearly three decades of technological progress.[9] Evaluating sustainability from a consumption-based perspective reveals that these exceedances have not diminished over time, even as domestic production has grown steadily cleaner. As we show in detail below, the environmental pressures embodied in imports continue to offset these domestic efficiency gains, leaving transgressions across impact categories broadly unchanged.

3.1 Sustainability of the German economy

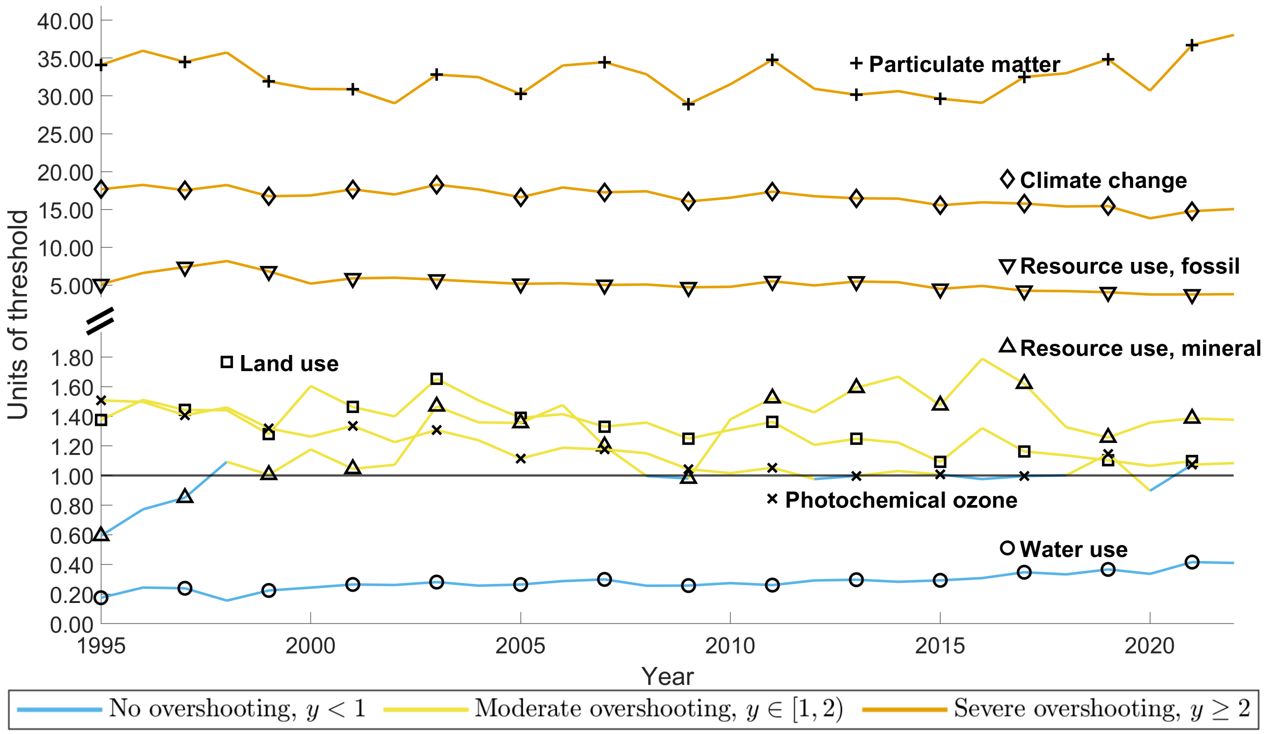
Figure 1 plots the evolution of sustainability indicators for German consumption across seven environmental impact categories. Values are benchmarked against Germany's national share of LCIA-based planetary boundaries. The traffic-light coding indicates whether the threshold is met (blue), moderately exceeded (yellow), or severely exceeded (orange).

Two patterns stand out. First, boundary transgressions are widespread and substantial. Germany exceeds national sustainability thresholds in six of the seven impact categories over 1995–2022; only water use remains within the boundary. The magnitude of transgression differs sharply across the remaining categories: particulate matter, climate change, and fossil resource use exhibit severe overshooting throughout the period, whereas mineral resource use, land use, and photochemical ozone formation are closer to the threshold and mainly moderately overshoot.

Second, transgressions are persistent. Sustainability performance shows little improvement over time, with most series in Figure 1 remaining largely flat. Column (1) in Table 1 confirms that long-run declines from 1995 to 2022—if any—are small, reaching at most 28%. In some categories, we even find sizable increases: mineral resource use and water use increase by more than 130%. Both impact categories, however, start from a low initial level and therefore remain close to or below the boundary threshold. In sum, these figures show that, over nearly three decades, German consumption has not converged toward absolute sustainability in most impact categories.

[9] Compare Footnote 3.

Figure 1: Environmental impact of the German economy



Notes: Each line shows total environmental impact in one category over 1995–2022, defined as the sum of consumption-based (embodied) impact and direct use-phase emissions. Values are normalized to the category's threshold—the German share of the corresponding LCIA-based planetary boundary—so that the horizontal line at 1.00 marks the boundary. Color follows a traffic-light scheme: blue where the threshold is met (below 1.00), yellow where it is moderately exceeded (1.00 up to 2.00), and orange where it is severely exceeded (2.00 and above). The vertical axis is compressed above 2.2 to accommodate the categories that exceed their threshold several-fold.

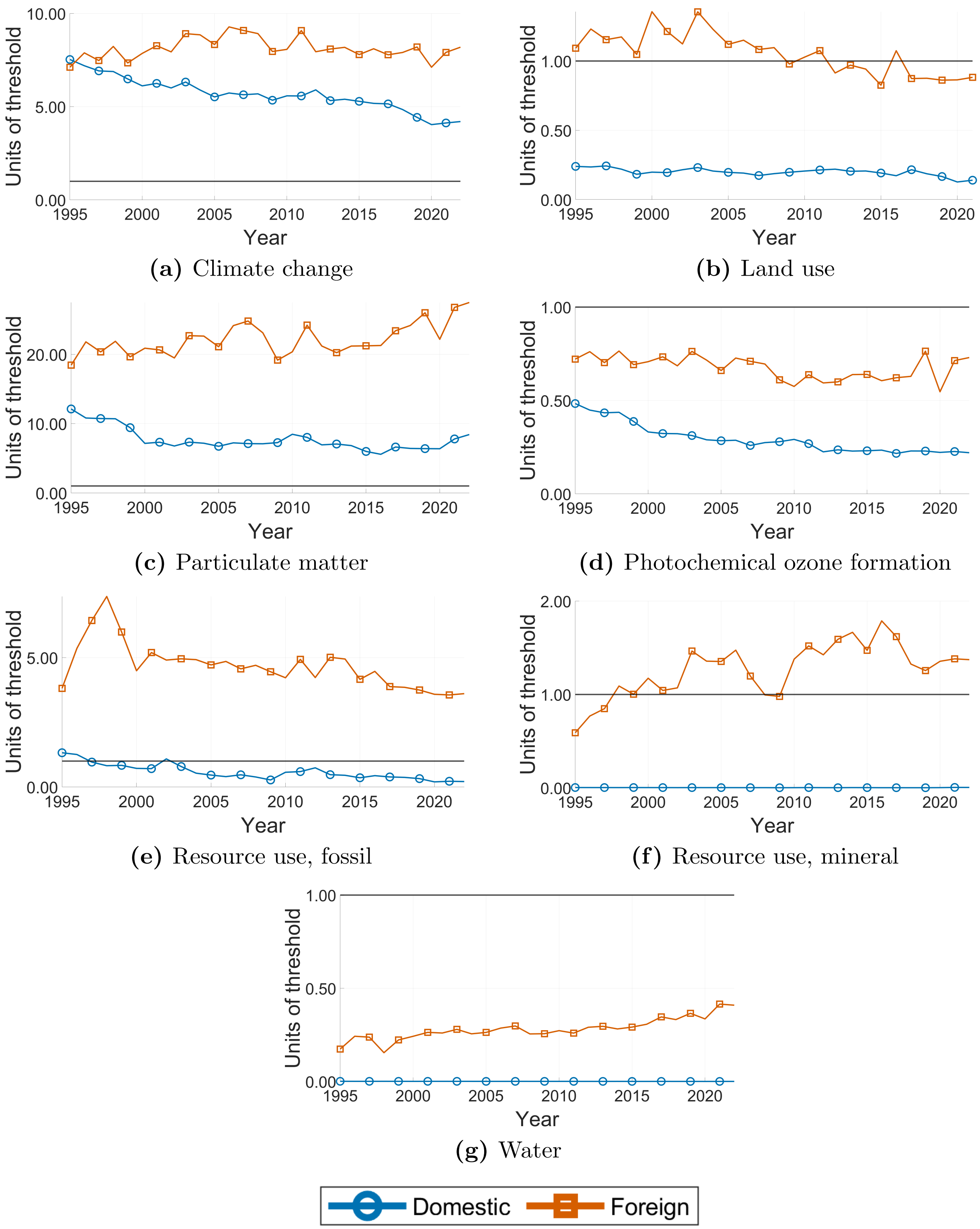
3.2 Geographic decomposition

To better understand why aggregate sustainability performance changed so little, we decompose impacts into their domestic and foreign components. More precisely, we separate impacts embodied in goods produced domestically for German consumption and impacts embodied in imported goods.[10]

Figure 2 shows the results. Circles indicate the domestic component and squares the foreign component. First, across all impact categories, foreign-production impacts exceed domestic-production impacts throughout the sample period. Second, environmental pressures attributable to German consumption are increasingly generated outside Germany. Domestic-production impacts decline over

[10] To keep the discussion focused, we do not further discuss use-phase externalities, which are small relative to production-related impacts and decline over time in most categories. This indicates that Germany's sustainability gap is driven primarily by upstream production and global supply chains rather than direct impacts during use. The maximum contribution to overall impact is 20.84% for photochemical ozone formation in 2001. The average contribution across all years and impact categories is 6.70%.

Figure 2: Geographic decomposition



(a) Climate change

(b) Land use

(c) Particulate matter

(d) Photochemical ozone formation

(e) Resource use, fossil

(f) Resource use, mineral

(g) Water

Notes: Germany's consumption-based impact in each category, split by where production occurs: domestic production for German consumption (domestic) and foreign production for German consumption (foreign). Use-phase emissions are omitted for clarity; they are small relative to both components (Footnote 10). The two production components plus use-phase emissions sum to the aggregate series in Figure 1.

Table 1: Long-run growth rates by impact category

	CBA impacts & use phase (%) (1)	Domestic production(%) (2)	Foreign production (%) (3)
Water use	134.15	-54.99	135.54
Land use	-20.25	-41.68	-19.23
Climate change	-14.81	-44.20	15.08
Resource use, minerals	132.20	30.99	132.75
Resource use, fossil	-25.69	-84.22	-5.39
Photochemical ozone formation	-28.10	-54.45	1.15
Particulate matter	11.63	-30.48	49.02

Notes: Cumulative growth rates (%), 1995–2022. Column (1) shows the consumption-based account plus use-phase emissions (the aggregate series in Figure 1). Columns (2) and (3) represent the domestic and foreign production components.

time in almost all categories, as the long-run growth rates in Column (2) of Table 1 confirm. The key exception is mineral resource use, which rose by 31%. By contrast, foreign-production impacts increase in almost all categories; compare Column (3) of Table 1. Only land use and fossil resource use display a limited long-run decline, and photochemical ozone formation is roughly flat.

The geographic decomposition clarifies why aggregate sustainability indicators remain largely flat: improvements in domestic production are counterbalanced by the larger and increasingly dominant impacts embodied in imports. Accounting for imports is becoming more and more central to environmental policymaking. In the next subsection, we assess the contributions of the scale of production and the impact intensity per euro produced across origin.

3.3 Decomposition into scale and impact intensity

This section aims to distinguish whether environmental pressures arise primarily from the growing scale of production for German final demand or from the impact intensity of that production—the impact embodied per euro of production. To this end, we separate impacts by origin $O \in \{F, D\}$, where F and D indicate foreign and domestic production. For each origin, total impacts can be written as[11]

$$Impact_O = \sum_i e_{iO} = \sum_i f_{iO} v_{iO} \tag{1}$$

[11] See Appendix C for details on the derivation and the deflation procedure.

$$= \underbrace{V_O}_{\text{scale}} \underbrace{\sum_i f_{iO} \frac{v_{iO}}{V_O}}_{\text{impact intensity}} ,$$

where f_{iO} denotes the impact per euro of production in sector i of origin O that is destined for German final demand—the sector-country-specific impact intensity.[12] The variable v_{iO} denotes the corresponding total value of production in sector i in O for German final demand, and V_O is the total value of production from origin O for German final demand.[13] Equation (1) shows that total impact can be separated into a scale and an impact intensity component where impact intensity is an output-weighted average across sectors.

In contrast to the literature (Levinson, 2009; Shapiro and Walker, 2018), we do not further decompose the impact intensity component. The reason is that decomposing it into a composition and a technique effect would isolate the change in efficiency that would arise if the consumption basket stayed fixed at its base-period composition—a counterfactual that is sensitive to the choice of base period and can be economically uninformative when consumption shifts away from a sector, since technology improvements in goods no longer consumed do not bear on realized impact.

We deflate the scale and impact intensity component using origin-specific inflation rates. Since these individual components of environmental impacts depend on prices, missing to correct price changes would bias our results. For example, price increases would falsely be considered improvements in efficiency, since the same degree of impact intensity is divided by a higher nominal value of consumption. We capture heterogeneous price movements across origins by deflating domestic production with the German GDP deflator and imports with the import price index, and the full consumption basket with the output-weighted average of the two. As we show in Appendix C.2, sector-country price movements cancel from the impact-intensity term under the assumption that the sector-country price embedded in the value of production-for-German-demand equals the price embedded in total sectoral output.

Hence, our measures of impact intensity reflect technology improvements over time net of price changes, in line with the literature that isolates a technique effect (Levinson, 2009; Shapiro and Walker, 2018). The comparison of foreign and domestic production, however, is not adjusted for

[12]Our data reflect average intensities at the country-by-sector level. We cannot distinguish technologies used for export versus domestic sales within a country-sector and therefore implicitly assume that average impact intensities apply to traded and non-traded output.

[13]To be precise, V_O is the output value of goods and services absorbed by German consumption, government, and investment. This is a production-side magnitude and does not coincide with purchaser-price final expenditure, which additionally includes trade and transport margins and net taxes on products.

price-level differences between origins, which is why we refer to impact per euro of production for final demand as impact intensity rather than technology. To the extent that imports originate in lower-price economies, price level differences inflate foreign relative to domestic intensity. The cross-origin gap we report should therefore be read as partly reflecting prices rather than physical technique alone.

Figure 3 compares the levels of each component across domestic and foreign production: Panels 3b–3h depict impact intensity and Panel 3a represents the scale of production. In all impact categories, the impact intensity is substantially higher for foreign than for domestic production. At the same time, the scale of domestic production for domestic consumption is larger than that of imports. The dominance of foreign-production impacts therefore reflects systematically higher impact intensities rather than larger import volumes—an observation that will be important for understanding weak efficiency gains on aggregate.

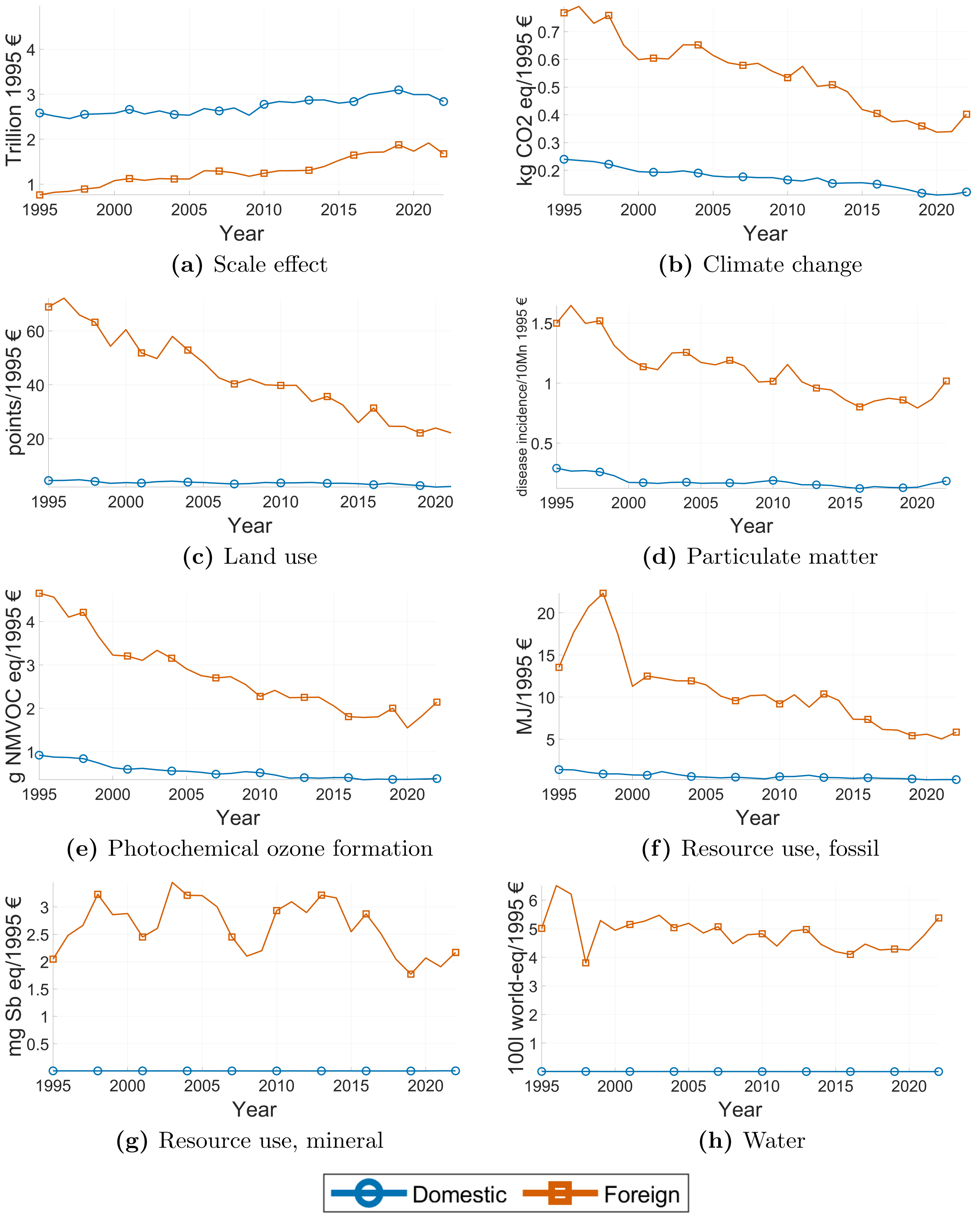
To more clearly analyze the lack of improvement over time, Figure 4 shows growth rates of scale and impact intensity by origin relative to the base year 1995.[14] The first thing to note is that the real scale of production for final demand increases, and that imports rise substantially faster than domestic production (Panel 4a). At the same time, there is improvement in impact intensity, both abroad and at home. Hence, efficiency gains in imports are offset by consumption growth, leading to a rising trend in environmental impact (compare Figure 2). As regards home production, the local efficiency gains are not fully offset by a rising scale of consumption—evidence for absolute decoupling when focusing solely on home production.

Across all impact categories, efficiency improvements occur at broadly similar rates in domestic and foreign production. However—with only one temporary exception in land use in the 2010-2020 period—aggregate efficiency gains fall behind local efficiency gains in all categories. This result is explained by the level differences in impact intensities and the rising share of imported goods in the German final demand basket. As a result, even parallel improvements in domestic and foreign impact intensity will not translate into aggregate sustainability gains as long as consumption shifts toward production systems that remain more impact-intensive on average.

Taken together, the decomposition clarifies the precise mechanism through which Germany's consumption has remained persistently outside planetary boundaries despite nearly three decades of technological progress. The constraint is not primarily a lack of efficiency improvement—impact intensities fall consistently in both domestic and foreign production across all seven impact categories.

[14] See Appendix C.

Figure 3: Impact intensity and scale component



(a) Scale effect
(b) Climate change
(c) Land use
(d) Particulate matter
(e) Photochemical ozone formation
(f) Resource use, fossil
(g) Resource use, mineral
(h) Water

Notes: The figure shows in Panel (a) the scale component, split into domestic and foreign. Panels (b)–(h) depict the impact intensity of domestic and foreign production for each of the seven categories. The scale component is common to all categories. Impact intensity is measured in impact units per constant-1995 euro of production for German final demand; the scale component, in trillion euros at constant 1995 prices. Constant prices use the German GDP deflator (domestic) and the import price index (foreign), as detailed in Appendix C.2.

The constraint is that these improvements are too slow and too small relative to the combined effect of rising consumption volumes and a structural shift toward more impact-intensive imported goods. Hence, while technological progress moves the economy in the right direction, the scale and composition of consumption pull it back. These forces prevent absolute decoupling on the aggregate consumption basket and keep environmental impacts persistently above safe operating limits.

3.4 Contribution of the rising import share

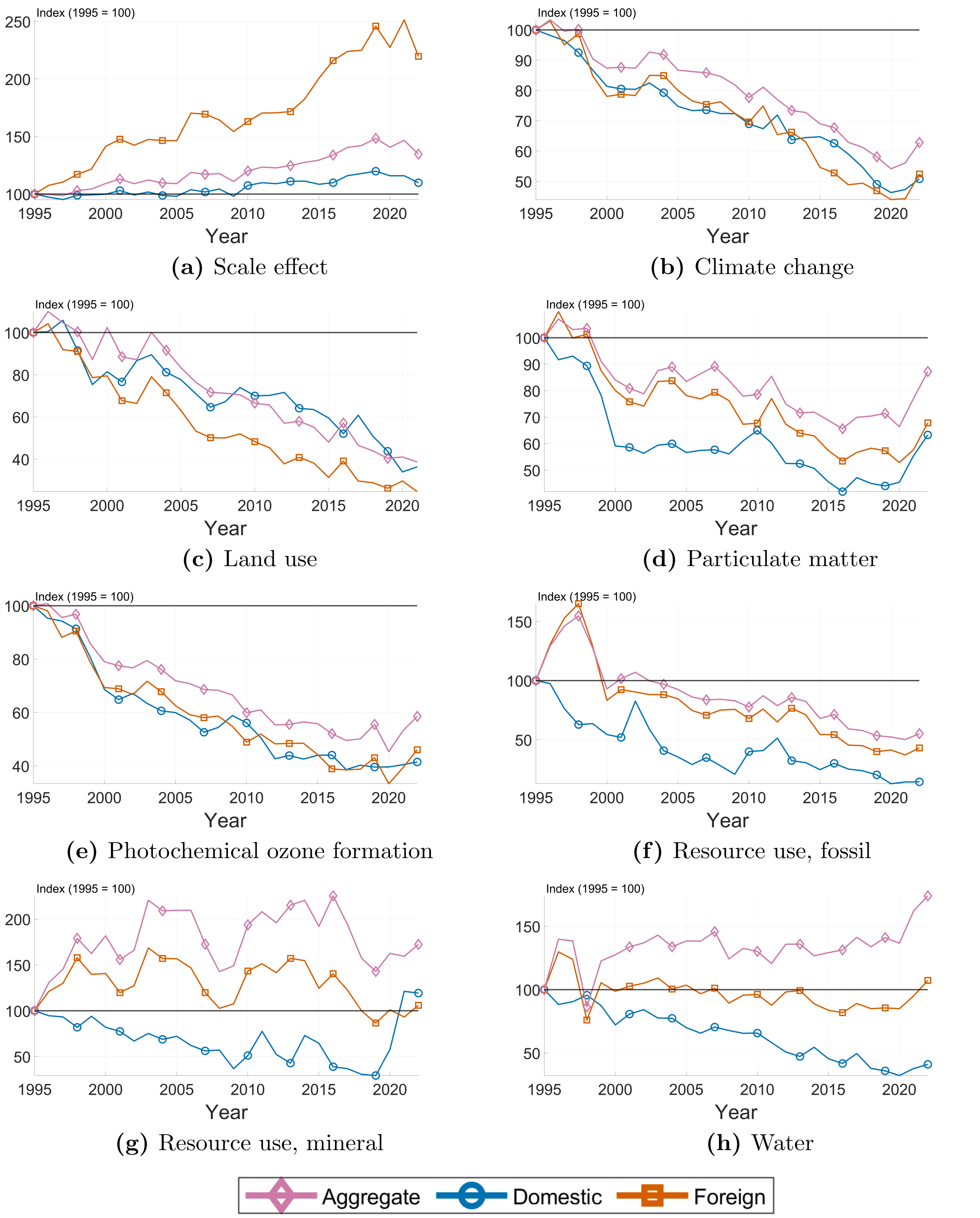
The decomposition so far attributes the persistence of boundary transgressions to two forces: a rising scale of consumption, and a shift of that consumption toward foreign production that embodies more impact per euro. To quantify the second force on its own, we ask how the impact trajectories would have differed had the import share of German consumption not risen. We construct a constant-import-share counterfactual—an accounting exercise that holds the 1995 production share of imports fixed while letting total value of production and origin-specific intensities evolve as observed.[15] The experiment can be read as asking how environmental impact would have evolved if, of each euro of production for German final demand, the amount needed to hold the import share at its 1995 level had been spent on the domestic bundle rather than on imports, all else equal.

We find that the rising import share raised cumulative 1995–2022 impact growth by 12.9 (climate change), 16.2 (photochemical ozone formation), 22.9 (land use), 26.9 (particulate matter), 28.0 (fossil resource use), 95.8 (mineral resource use), and 96.8 (water use) percentage points relative to the constant-import-share counterfactual. The smallest increase is observed for the climate change category. The largest effects arise for water and mineral resource use, where domestic production is nearly impact-free, so the rising import share contributes most to cumulative impact growth. The effect operates through the foreign–domestic gap in impact intensity: because each euro reallocated from domestic to foreign production carries more impact, a rising import share raises aggregate impact even as intensities fall within both origins.[16] Figure 5 in Appendix C.4 illustrates the comparison of the counterfactual to the observed impact from consumption for all impact categories.

[15]Appendix C.4 details the construction of the experiment as a partial-equilibrium reallocation rather than a structural simulation: displaced imports are met by domestic production at observed intensities, with no adjustment of prices or technologies. Use-phase impacts are respected as observed in the counterfactual measure.

[16]We show this formally in Appendix C.4.

Figure 4: Trends in impact intensity and scale component



(a) Scale effect

(b) Climate change

(c) Land use

(d) Particulate matter

(e) Photochemical ozone formation

(f) Resource use, fossil

(g) Resource use, mineral

(h) Water

Notes: All series are indexed to 100 in 1995. Panel (a) shows the real scale effect – how impacts would have evolved if impact intensities had stayed at their 1995 levels while deflated expenditure on domestic and imported goods followed its observed path. The scale effect is common to all categories. Panels (b)–(h) display the impact-intensity effect for each category – how impacts would have evolved if the scale component had stayed at its 1995 level, separately for domestic, foreign, and aggregate production. Deflation uses the German GDP deflator (domestic), the import price index (foreign), and the weighted average (aggregate) as detailed in Appendix C.2.

4 Conclusion

Continued global environmental degradation increasingly threatens the safe operating space for human societies (Richardson et al., 2023). Assessing whether national economies are moving toward or away from that space requires indicators that are multi-dimensional, account for global supply chains, and are benchmarked against absolute limits rather than relative trends. Applying such an indicator to Germany—a leading-edge case for environmental policy ambition—we find that consumption has exceeded six of seven planetary-boundary thresholds continuously, with little progress toward absolute sustainability since the mid-1990s.

The persistence of these transgressions reflects a structural mechanism operating across all seven categories. Impact intensities have improved at broadly similar rates in domestic and foreign production, confirming that technological progress has been widespread; but these efficiency gains are systematically offset by growth in the scale of consumption, particularly through rising imports that embody more impact per euro than domestic production. Holding the import share at its 1995 level, impact growth between 1995 and 2022 would have been lower by 12.9 to 96.8 percentage points across categories, confirming that the shift toward imports is a quantitatively central driver of the missing progress.

These mechanisms are structural features of open, high-income economies where consumption relies heavily on international production networks and where policy has focused on improving domestic production efficiency rather than constraining absolute pressures. That focus increasingly misses its target on two counts: efficiency gains are too slow to offset rising consumption, and a growing share of pressures lies abroad, beyond the reach of domestic policy. Our results therefore underscore the need for strategies that move beyond efficiency alone and address the scale and composition of consumption—including supply-chain instruments such as carbon border adjustments and mandatory due diligence—to align economic activity with absolute environmental limits.

Several limitations should be borne in mind. First, our analysis focuses on Germany as a case study, and while the mechanisms we identify are likely to apply to other open, high-income economies, the quantitative magnitude of boundary transgressions will depend on country-specific consumption patterns and trade structures. Second, our decomposition relies on input–output data capturing average production technologies at the country–sector level, and does not allow us to distinguish technologies used for domestic consumption versus exports within a sector. Third, we measure impact intensity per euro of production. Our deflation removes price changes over time within each origin, so the time-series evolution reflects technology; but any comparison of intensity levels—in particular between foreign and domestic production—also reflects price-level differences. Future work extending this framework to multiple countries or to higher-resolution production and price data would help assess the generality and policy relevance of these findings more fully.

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A Abbreviations

Table 2: Abbreviations

Abbreviation	Definition
CF	characterization factor
EE-MRIO	environmentally extended multi-regional input-output
EEIO	environmentally extended input-output
EF 3.1	Environmental Footprint 3.1
GRAS	generalized RAS
IO	input-output
LANCA	LANd Use Indicator Value CAlculation
LCIA	life-cycle impact assessment
LCA	life-cycle assessment
RAS	a biproportional matrix balancing technique
RoW	rest-of-world

B Method

This appendix provides details on the empirical framework underlying the main analysis. Appendix B.1 describes the EE-MRIO system and the construction of stressor intensities. Appendix B.2 describes the data cleaning and outlier treatment procedures. Appendix B.3 explains how we characterize environmental stressors using the EF 3.1 method. Appendix B.4 documents the derivation of global and national thresholds based on LCIA-aligned planetary boundaries.

B.1 Environmentally-extended input–output tables

We work with a multi-regional, multi-sectoral EEIO framework based on EXIOBASE, which covers 44 individual countries and five RoW regions (Asia and Pacific, America, Europe, Africa, and Middle East), with 163 sectors per country or region.

B.1.1 Input–output tables

IO tables describe the flows of intermediate and final goods across sectors and regions. Let there be m countries (or regions) and k sectors per country, implying $n = mk$ country–sector combinations. The core monetary data consist of:

- a transaction matrix $\mathbf{Z} \in \mathbb{R}^{n \times n}$, where z_{ij} denotes intermediate sales from sector i to sector j;
- a final demand matrix $\mathbf{Y} \in \mathbb{R}^{n \times m}$, where y_{ij} denotes final demand in country j for the output of sector i (private and public consumption and investment);
- a value-added vector $\mathbf{VA} \in \mathbb{R}^{1 \times n}$, where va_j denotes value added in sector j;

- a total output vector $\mathbf{x} \in \mathbb{R}^{n\times 1}$, where x_i denotes total output of sector i.

Formally,

$$\mathbf{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}, \quad \mathbf{Z} = \begin{bmatrix} z_{11} & \dots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{n1} & \dots & z_{nn} \end{bmatrix}, \quad \mathbf{Y} = \begin{bmatrix} y_{11} & \dots & y_{1m} \\ \vdots & \ddots & \vdots \\ y_{n1} & \dots & y_{nm} \end{bmatrix}.$$

For sector i, total output equals the sum of intermediate and final sales:

$$x_i = \sum_{j=1}^{n} z_{ij} + \sum_{j=1}^{m} y_{ij}.$$

In matrix notation,

$$\mathbf{x} = \mathbf{Z}\mathbf{i}_n + \mathbf{Y}\mathbf{i}_m,$$

where $\mathbf{i}_n$ and $\mathbf{i}_m$ are summation vectors of ones of appropriate dimension. The total input to sector j equals the sum of all intermediate inputs plus value added:

$$x_j^{\text{input}} = \sum_{i=1}^{n} z_{ij} + va_j.$$

By construction, IO tables satisfy $x_j^{\text{input}} = x_j$ for all sectors j.

The technical coefficient matrix $\mathbf{A} \in \mathbb{R}^{n\times n}$ has elements

$$a_{ij} = \frac{z_{ij}}{x_j},$$

and captures the direct input requirements per unit of output of sector j. In matrix notation,

$$\mathbf{A} = \mathbf{Z}\widehat{\mathbf{x}}^{-1},$$

where $\widehat{\mathbf{x}}$ denotes the diagonal matrix with $\mathbf{x}$ on its diagonal. Total requirements, including all direct and indirect inputs, are captured by the Leontief inverse

$$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}.$$

Given a vector of final demand $\mathbf{y}$ (e.g. $\mathbf{y} = \mathbf{Y}\mathbf{i}_m$), total output is

$$\mathbf{x} = \mathbf{L}\,\mathbf{y}.$$

Block-diagonalization of final demand For the consumption-based accounting formulas below, it is convenient to construct a block-diagonal representation of final demand. We define an operator $\operatorname{diag}^*(\mathbf{Y})$ that builds a block-structured matrix $\mathbf{B}$ from the columns of $\mathbf{Y}$. Formally,

$$\mathbf{B} = \operatorname{diag}^*(\mathbf{Y}) = \begin{bmatrix} \widehat{\mathbf{Y}}_{11} & \dots & \widehat{\mathbf{Y}}_{1m} \\ \vdots & \ddots & \vdots \\ \widehat{\mathbf{Y}}_{m1} & \dots & \widehat{\mathbf{Y}}_{mm} \end{bmatrix},$$

where each block $\widehat{\mathbf{Y}}_{ij}$ is a $k \times k$ diagonal matrix with entries corresponding to the final demand vector of country j for the k sectors of country i. This block structure underlies the compact expression for consumption-based accounts in Appendix B.1.4.

B.1.2 Environmental extensions

EEIO tables augment the monetary IO system with environmental satellite accounts. EXIOBASE provides such satellite accounts in the form of a stressor matrix $\mathbf{Q}$:

$$\mathbf{Q} = \begin{bmatrix} q_{11} & \dots & q_{1n} \\ \vdots & \ddots & \vdots \\ q_{s1} & \dots & q_{sn} \end{bmatrix},$$

where q_{sj} denotes the amount of stressor s (e.g. CO_2, land use, water use) associated with the output of sector j. In EXIOBASE, these stressors are initially uncharacterized, i.e., not yet translated into units of the LCIA impact categories.

We convert stressors into intensities per euro of output:

$$\mathbf{F} = \mathbf{Q}\,\widehat{\mathbf{x}}^{-1} = \begin{bmatrix} \frac{q_{11}}{x_1} & \dots & \frac{q_{1n}}{x_n} \\ \vdots & \ddots & \vdots \\ \frac{q_{s1}}{x_1} & \dots & \frac{q_{sn}}{x_n} \end{bmatrix},$$

where $f_{sj} = \frac{q_{sj}}{x_j}$ denotes the amount of stressor s per euro of output of sector j. Inserting $\mathbf{x} = \mathbf{L}\,\mathbf{y}$ and rearranging yields the stressor matrix $\mathbf{Q}$ expressed in terms of $\mathbf{F}$, $\mathbf{L}$ and $\mathbf{y}$:

$$\mathbf{Q} = \mathbf{F}\,\widehat{\mathbf{L}\mathbf{y}}.$$

For a specific stressor s, the vector of total impacts embodied in final demand is given by the s-th row of $\mathbf{F}\widehat{\mathbf{L}\mathbf{y}}$. This defines stressor multipliers: impacts embodied in one unit of final demand for each sector.

B.1.3 Aggregation

Aggregation follows Stadler (2021). Let $\mathbf{N} \in \mathbb{R}^{s \times k}$ be any sectoral matrix (e.g. stressor intensities or impacts) with k sectors. To aggregate sectors into $q < k$ groups, we define a sectoral aggregation matrix $\mathbf{G}_k \in \mathbb{R}^{q\times k}$:

$$\mathbf{G}_k = \begin{bmatrix} g_{11} & \cdots & g_{1k} \\ \vdots & \ddots & \vdots \\ g_{q1} & \cdots & g_{qk} \end{bmatrix},$$

where each column has exactly one entry equal to 1 indicating the group to which the original sector belongs while all others are set to 0. Aggregated values are obtained as

$$\mathbf{N}_{\text{agg}} = \mathbf{N}\,\mathbf{G}_k^\top.$$

Aggregating all $k = 163$ sectors to a single national aggregate corresponds to $\mathbf{G}_k$ being a $1 \times k$ row vector of ones.

B.1.4 Consumption-based accounts and use-phase externalities

We denote the consumption-based stressor account by $\mathbf{D}_t^{cba}$ for a given year t. Using the notation above and the block-diagonalization operator $\text{diag}^*(\cdot)$, they can be written as:

$$\mathbf{D}_t^{cba} = \mathbf{F}_t\mathbf{L}_t\ \text{diag}^*(\mathbf{Y}_t).$$

The consumption-based stressor account attributes stressors to sectors based on the location of final consumption (including imported goods and services). The explicit block-diagonal structure is given in Appendix B.1.1.

The consumption-based account can be decomposed into domestic and foreign components. Let $\mathbf{D}^{dom}$ denote the impacts associated with domestic production for domestic use and $\mathbf{IM}$ the impacts embodied in imports, then

$$\mathbf{D}^{cba} = \mathbf{D}^{dom} + \mathbf{IM}.$$

Use-phase externalities EE-MRIO analysis captures externalities associated with production and upstream supply chains but omits externalities generated during the use of final goods and services (e.g. emissions from private vehicle use, home heating, or appliance operation). To obtain a more comprehensive measure of environmental pressure, we add these direct use-phase stressors to the consumption-based account:

$$\tilde{\mathbf{D}}_t^{cba} = \mathbf{D}_t^{cba}\mathbf{G}_{\mathbf{n}}^\top + \mathbf{F}_{y,t},$$

where $\mathbf{G}_{\mathbf{n}} \in \mathbb{R}^{m\times n}$ is an aggregation matrix that aggregates the $s \times n$ $\mathbf{D}_t^{cba}$ matrix to the country level and where $\mathbf{F}_{y,t} \in \mathbb{R}^{s\times m}$ denotes a matrix of use-phase stressors directly attributed to final consumption activities in year t.

B.1.5 Imports

Import footprints are derived using a block-diagonal representation of final demand in which domestic blocks are set to zero. The footprint embodied in imports is derived analogously, using the block-diagonal representation $\mathbf{B} = \text{diag}^*(\mathbf{Y})$ from Appendix B.1.1. To remove domestic final demand, we set the blocks along the main diagonal of $\mathbf{B}$ (all $\widehat{\mathbf{Y}}_{ij}$ where $i = j$) to zero, yielding

$$\widetilde{\mathbf{B}} = \begin{bmatrix} 0 & \widehat{\mathbf{Y}}_{12} & \dots & \widehat{\mathbf{Y}}_{1m} \\ \widehat{\mathbf{Y}}_{21} & 0 & \dots & \widehat{\mathbf{Y}}_{2m} \\ \vdots & \ddots & \ddots & \vdots \\ \widehat{\mathbf{Y}}_{m1} & \widehat{\mathbf{Y}}_{m2} & \dots & 0 \end{bmatrix}.$$

The consumption-based footprint associated with imports is then

$$\mathbf{D}^{IM} = \mathbf{F}\,\mathbf{L}\,\widetilde{\mathbf{B}}.$$

B.1.6 Comparison to process-based life-cycle assessment

Compared to process-based LCA, EE-MRIO approaches capture upstream and downstream value chains more fully. Product-level LCA must draw a finite system boundary, truncating impacts beyond it (Agez et al., 2022). Using EXIOBASE-based EE-MRIOs thus reduces truncation error while retaining the ability to attribute impacts to sectors and consumption categories.

B.2 Data cleaning

This section documents the data treatment and balancing procedures applied to the input-output system prior to the analysis. By doing so we aim to reduce the influence of extreme observations and improve temporal consistency, while preserving accounting consistency. The data cleaning pipeline has three steps: (i) winsorizing, (ii) temporal smoothing, and (iii) rebalancing of the IO system.

B.2.1 Winsorizing the data

To mitigate the influence of extreme observations, both the technical coefficient matrix A as well as the final demand matrix Y are winsorized. For the technical coefficient matrix, this step is done on a column-by-column basis. For each column j we compute the 99.5th percentile of the off-diagonal elements $\{A_{ij} : i \neq j\}$ only. The diagonal elements are excluded, as they are by construction larger, which would otherwise dominate the percentile calculation. Off-diagonal elements of column j that exceed the threshold are capped at the 99.5th percentile, while elements that are below the threshold remain unchanged. We confirm that the elements are strictly below one, as the technical coefficient matrix cannot exceed unity.

The final-demand data are cleaned using a share-based approach on a country basis. We create the final demand shares by as $S_{i,k} = \frac{Y_{ik}}{\sum_k Y_{ik}}$. In contrast to levels, shares are scale-invariant and therefore better suited for the winsorizing process. Within each country block, we winsorize the final-demand shares column by column at the 99.5th percentile, capping unusually large shares as $S_{ik}^{win} = \min(S_{ik}, p_{99.5})$. We then reconstruct the final-demand levels in two steps: we renormalize the winsorized shares to sum to one, $\tilde{S}_{ik} = \frac{S_{ik}^{win}}{\sum_k S_{ik}^{win}}$, and multiply them by the original row totals, $Y_{ik}^{new} = \tilde{S}_{ik} \sum_k Y_{ik}$.

B.2.2 Temporal smoothing

Next, we feed the winsorized data into a targeted smoothing procedure to improve dynamic consistency. Without smoothing, the EXIOBASE data displays implausibly large jumps in the technical coefficients matrix across time periods. More precisely, we address two common data issues. First, we interpret isolated zero observations of the technical coefficient A_{ijt} at time t that occur between two positive values at $t-1$ and $t+1$ as interpolation artifacts. These observations are replaced via linear interpolation of their non-negative neighbors. Second, we treat sharp one-period spikes, defined as observations that exceed five times the maximum of adjacent years, as transitory outliers and set them to the average of the neighboring values. No smoothing is applied to extended runs of zeros as well as trailing zeros.

B.2.3 Rebalancing with generalized RAS

After winsorizing and smoothing the intermediate transactions and the final demand matrix, the data most likely no longer satisfies the fundamental input-output accounting identities exactly. In particular, row and column totals might slightly deviate from the original reference system. To restore the full accounting consistency, we apply the RAS rebalancing procedure (Miller and Blair (2009), ch. 9).

The RAS algorithm iteratively alternates between two steps. First, columns are scaled such that their sums match the target column total. In the second step, rows are scaled such that their sectors match the target row totals. These two steps are repeated until the maximum deviation between achieved and target row/column totals falls below the tolerance level. The goal is to re-adjust the cleaned data such that the target totals are matched exactly, while altering individual cells as little as possible in relative terms. Rebalancing is performed on an extended matrix that stacks the transaction matrix and final demand matrix into a single block matrix $\mathbf{M} = \begin{bmatrix} \mathbf{Z} & \mathbf{Y} \end{bmatrix}$. The row and column sums, i.e., total output and total input, of the pre-cleaning system are treated as fixed targets.

Since standard RAS rebalancing requires all matrix elements to be non-negative—which is not the case for the final-demand matrix $\mathbf{Y}$—we use generalized RAS (GRAS), developed by Junius and Oosterhaven (2003) and refined by Lenzen et al. (2007) and Temurshoev et al. (2013). GRAS partitions $\mathbf{M}$ into a matrix $\mathbf{P}$ of its positive elements and a matrix $\mathbf{N}$ holding the absolute values of its negative elements, so that $\mathbf{M} = \mathbf{P} - \mathbf{N}$. Rebalancing weights are applied separately to $\mathbf{P}$ and $\mathbf{N}$, which are then recombined into the rebalanced $\mathbf{M}$. When all elements of $\mathbf{M}$ are non-negative, GRAS reduces to standard RAS.

B.3 Characterization of environmental stressors

The EXIOBASE environmental accounts contain uncharacterized stressors, i.e., physical flows that are not directly expressed in terms of impact on the Earth system. To assess planetary-boundary-relevant pressures, we (i) match these stressors to appropriate CFs (Appendix B.3.1) and (ii) transform them into characterized stressors expressed in units consistent with our impact categories (Appendix B.3.2).

Table 3: Characterization of environmental stressors

Impact category	**EXIOBASE extension** (1)	**CF Scope** (2)	**Unit (unchar.)** (3)	**Unit (char.)** (4)
Water Use (WU)	Water	Country / region specific	Mm^3	m^3 world-eq
Land Use (LU)	Land	Country / region specific	km^2	Pt (LANCA index)
Climate Change (GWP)	Air emissions	Global	kg	kg CO_2-eq
Photochemical Ozone Formation (POF)	Air emissions	Global	kg	kg NMVOC-eq
Particulate Matter (PM)	Air emissions	Global	kg	Disease incidence
Resource Use: Minerals and Metals (MRD)	Material extraction	Global	kt	kg Sb-eq
Resource Use: Fossils (FRD)	Material extraction	Global	kt	MJ

Notes: Column (1) details the category-specific EXIOBASE extension which we use. Column (2) indicates whether CFs from EF 3.1 vary globally or by country/region. Columns (3) and (4) report the units of stressors before and after characterization, respectively. Appendix B.3.1 documents the full CF–stressor matching procedure.

B.3.1 Matching characterization factors to EXIOBASE stressors

We rely on the EF 3.1 LCIA method to characterize stressors. EF 3.1 is the European Commission's recommended method for the Product and Organisation Environmental Footprint framework (European Commission, 2021; Bassi et al., 2023). It provides CFs for 16 impact categories. Table 3 summarizes, for each impact category, the relevant EXIOBASE extension, the scope of CFs, and the units before and after characterization.

EF 3.1 provides CFs for several stressors that are not contained in EXIOBASE and, conversely, EXIOBASE includes stressors that are not characterized in EF 3.1. Following Sala et al. (2020) and their supplementary material, we match CFs and stressors where possible, resulting in coverage comparable to their work. Where no corresponding stressor exists in EXIOBASE, the CF cannot be applied; where a stressor is included in EXIOBASE but has no EF 3.1 CF relevant for our impact categories, we assign a CF of zero. Consequently, our impact estimates should be interpreted as lower bounds of the German economy's true contribution to each impact category. While incomplete coverage may affect absolute levels in some categories, it is unlikely to alter our qualitative conclusions, as boundary exceedances are large, persistent, and driven by stressors with well-characterized CFs. Appendix D assesses the importance of missing characterization factors for our main results.

Characterization can be viewed as an implicit weighting scheme: CFs convert heterogeneous stressors (e.g. kg CO_2, CH_4, N_2O) into a common impact unit (e.g. kg CO_2-eq), and aggregate impacts (e.g. climate change) are the unweighted sums of characterized stressors. Columns (3) and (4) in Table 3 report units before and after characterization for each impact category.

For five of the seven impact categories (climate change, photochemical ozone formation, particulate matter, resource use–fossil, resource use–minerals), EF 3.1 CFs do not vary by region. For some of these impact categories (climate change, resource use) this reflects that the damage mechanisms are largely independent of the geographical location of emissions or extraction. For others (particulate matter, photochemical ozone formation), the choice of a single global CF is a modeling simplification.

For land use and water use, impacts depend on local environmental conditions. EF 3.1 provides region- and in some cases country-specific CFs for these categories. Since EXIOBASE distinguishes 44 individual countries and 5 composite RoW regions (RoW Asia and Pacific, RoW America, RoW Africa, RoW Europe, RoW Middle East), the country-by-country CFs in EF 3.1 must be aggregated to match EXIOBASE's RoW regions. We construct RoW-specific CFs as GDP (PPP)-weighted averages of country-specific CFs within each RoW region. Let CF^j denote the CF for country j in a given impact category, and let PPP_t^j denote its GDP in PPP terms in year t. We first compute the average PPP over the sample period $t = 1995, \ldots, 2022$:

$$PPP^j_{\text{avg}} = \frac{1}{T} \sum_{t=1995}^{2022} PPP^j_t,$$

with $T = 2022 - 1995 + 1 = 28$. We then define PPP-based weights within each RoW region:

$$PPP^j_{\text{weight}} = \frac{PPP^j_{\text{avg}}}{\sum_{l=1}^{L} PPP^l_{\text{avg}}},$$

where $l = 1, \ldots, L$ index the countries in the region. The RoW-specific CF is given by

$$CF_{\text{RoW}} = \sum_{j=1}^{L} PPP^j_{\text{weight}} \cdot CF^j.$$

We apply this procedure for each of the five RoW regions and for both land use and water use, obtaining a complete set of 49 country-/region-specific CFs matching the EXIOBASE geography.

B.3.2 Calculation of impacts

Let $\mathbf{Q}_t$ denote the stressor matrix in year t (cf. Appendix B.1), and let $\mathbf{CF_w}$ denote the matrix of CFs for impact category w. The impact vector for impact category w is obtained from

$$\mathbf{P_{t,w}} = \mathbf{i_s}(\mathbf{CF_w} \odot \mathbf{Q_t}),$$

where $\mathbf{i_s}$ is a summation vector of appropriate length. For most impact categories, $\mathbf{CF_w}$ is equal to the $s \times 1$ column vector $\mathbf{cf_{single}}$ containing the global CFs for each stressor s. But as mentioned in Appendix B.3.1, land use and water use have country specific CFs for each stressor, which are contained in the $s \times m$ matrix $\mathbf{CF_{country}}$ with s the number of stressors and m the number of countries. Since these country-specific CFs do not vary by sector as well, $\mathbf{CF_{country}}$ has to be expanded such that each column (representing one country) is repeated k times, with k the number of sectors per country. Therefore $\mathbf{CF_w}$ is formally written as

$$\mathbf{CF_w} = \begin{cases} \mathbf{cf_{single}} & \text{for } w \notin \{\text{Land use; Water use}\} \\ \mathbf{CF_{country}} \otimes \mathbf{i_s} & \text{for } w \in \{\text{Land use; Water use}\} \end{cases}.$$

Finally, all impact vectors are stacked to obtain the impact matrix $\mathbf{P_t}$

$$\mathbf{P_t} = \begin{bmatrix} \mathbf{P_{t,1}} \\ \vdots \\ \mathbf{P_{t,W}} \end{bmatrix}.$$

The previous steps convert uncharacterized stressors (with heterogeneous units) into characterized stressors expressed in consistent impact units (e.g. kg CO_2-eq, disease incidence, m^3 world-eq).

Analogous to the stressor intensity matrix $\mathbf{F}_t$, we define the impact intensity matrix $\mathbf{p}_t$ as

$$\mathbf{p}_t = \mathbf{P}_t \, \widehat{\mathbf{x}}_t^{-1},$$

where $\widehat{\mathbf{x}}_t$ is the diagonal matrix of total sectoral output in year t. The consumption-based impact account follows from replacing $\mathbf{F}_t$ with $\mathbf{p}_t$ in the formula of Appendix B.1.4:

$$\mathbf{D}_t^{cba} = \mathbf{p}_t \mathbf{L}_t \, \text{diag}^*(\mathbf{Y}_t).$$

B.4 Thresholds

Our sustainability assessment compares Germany's environmental impact to thresholds derived from the planetary boundary framework. The matching proceeds in two steps: (i) we adopt global

LCIA-based planetary boundary thresholds from the literature (Appendix B.4.1); (ii) we downscale these thresholds to the national level using an equal-per-capita allocation (Appendix B.4.2).

B.4.1 Global thresholds

Global thresholds are taken from Sanyé-Mengual and Sala (2023), who compile LCIA-based planetary boundaries grounded in Sala et al. (2020). Table 4 reports the impact categories, indicator units, thresholds, and the underlying LCIA models for each category.

All thresholds are taken directly from Sala et al. (2020) and Sanyé-Mengual and Sala (2023), except for particulate matter, where the threshold depends on global population. To ensure consistency with the population data used in our national downscaling and our horizon, we recompute the particulate matter threshold using the average global population between 1995 and 2022 from United Nations (2024) following the methodology in Sala et al. (2020). This yields a global threshold of 5.13×10^5 disease incidence, slightly below the 5.16×10^5 disease incidence reported by Sala et al. (2020) and Sanyé-Mengual and Sala (2023).

Table 4: LCIA impact categories

Impact category	**Unit** (1)	**Underlying model** (2)	**Global threshold** (3)	**German threshold** (4)
Climate Change (GWP)	kg CO_2-eq	Bern carbon-cycle model (100-year GWP)	6.81×10^{12}	8.23×10^{10}
Particulate Matter (PM)	disease incidence	USEtox/PM human-health damage model	5.13×10^5	6.20×10^3
Photochemical Ozone Formation (POF)	kg NMVOC-eq	LOTOS–EUROS atmospheric chemistry model	4.07×10^{11}	4.92×10^9
Land Use (LU)	Pt	LANCA soil-quality model	3.98×10^{15}	4.81×10^{13}
Water Use (WU)	m^3 world-eq	AWARE water-scarcity model	1.82×10^{14}	2.20×10^{12}
Resource Use: Fossils (FRD)	MJ	ADP fossil depletion model	2.24×10^{14}	2.71×10^{12}
Resource Use: Minerals and Metals (MRD)	kg Sb-eq	ADP ultimate-reserve model	2.19×10^8	2.65×10^6

Notes: Global thresholds follow Sanyé-Mengual and Sala (2023) based on LCIA-aligned planetary boundaries. German thresholds are derived using an equal-per-capita allocation (Appendix B.4.2). The threshold for particulate matter is aligned with the UN population series used for scaling global thresholds to a national level.

B.4.2 National thresholds

The original planetary boundary framework is global in scope. To assess the environmental performance of the German economy, global thresholds are translated into national limits. We use an equal-per-capita approach, which assigns each individual an equal share of the global safe operating space. Let $\mathrm{PB}_{\mathrm{global}}$ denote the global threshold for a given impact category and $\mathrm{Pop}_{c,t}$, $\mathrm{Pop}_{\mathrm{world},t}$ the populations of country c and the world in year t. To allocate the global threshold on an equal-per-capita basis while preventing demographic shifts from affecting the indicator over time, we use the average population share over 1995–2022,

$$\bar{\omega}_c = \frac{1}{T} \sum_{t=1995}^{2022} \frac{\mathrm{Pop}_{c,t}}{\mathrm{Pop}_{\mathrm{world},t}}, \quad T = 28,$$

and define the time-invariant national threshold as $\mathrm{PB}_c = \bar{\omega}_c \, \mathrm{PB}_{\mathrm{global}}$.

We opt for an equal-per-capita approach as it is straightforward, transparent, and constitutes a conservative choice for a high-income country like Germany. Alternative allocation principles that are considered ethically plausible in the literature—such as equal-cumulative-per-capita (accounting for historical responsibility) or capability-based approaches (accounting for differences in ability to mitigate)—would tend to yield stricter per-capita thresholds for industrialized economies.[17]

C Decomposition into scale and impact intensity

This section derives the decomposition of impacts into a scale component and impact intensity (Appendix C.1), discusses our approach to inflation (Appendix C.2), and formalizes the trend decomposition (Appendix C.3). Appendix C.4 elaborates on the counterfactual analysis that we use to study the role of a rising import share.

C.1 Decomposition of impacts

We start from the definition of environmental impact and multiply by unity:

$$Impact_O = \sum_i e_{iO} = \sum_i \frac{e_{iO}}{v_{iO}} v_{iO},$$

where e_{iO} denotes the environmental impact generated by sector i in origin O, v_{iO} denotes nominal value of production in sector i in O that is attributable to final demand in Germany. We proxy impact intensities per Euro of expenditure, $\frac{e_{iO}}{v_{iO}}$, with the impact intensities per Euro of sectoral production that is given in the EEIO tables:

$$\frac{e_{iO}}{v_{iO}} = f_{iO} \equiv \frac{q_{iO}}{x_{iO}},$$

with x_{iO} denoting the total value of output of sector i and q_{iO} total impact both associated with production in sector i in O.

[17] See Robiou Du Pont et al. (2017), Häyhä et al. (2016), Hjalsted et al. (2021), and Lucas et al. (2020) for extensive discussions of allocation principles and their implications.

This approximation assumes that the impact intensity of the total production in sector i is the same as the impact intensity of sector i's production for final demand in Germany. In other words, the approximation is valid if production technology is homogeneous within each sector regardless of the destination of the final product. This assumption aligns with the fundamental IO assumption that each sector produces a homogeneous good.

Substituting impact intensity and multiplying by unity yields the decomposition shown in the main text equation (1):

$$Impact_O = \underbrace{V_O}_{\text{scale}} \underbrace{\sum_i \frac{q_{iO}}{x_{iO}} \frac{v_{iO}}{V_O}}_{\text{impact intensity}} \tag{2}$$

where $V_O \equiv \sum_i v_{iO}$ is total value of final demand in Germany that has been produced in origin O. Note that the impact intensity equals the impact intensity of total sectoral impacts in origin O over the total value produced in O for final demand in Germany. Table 5 summarizes the notation used in the decomposition.

Table 5: Notation used in the decomposition

Variable	Meaning and measurement
v_{iO}	value of production in sector i attributable to final demand in Germany
V_O	value of total production in origin O attributable to final demand in Germany
f_{iO}	impact per Euro of production in sector i in origin O
f_{iF}	weighted average impact intensity of production abroad in sector i: $f_{iF} = \sum_{o \in \tilde{F}} f_{io} \frac{v_{io}}{\sum_{o \in \tilde{F}} v_{io}}$, where $\tilde{F}$ is the set of foreign countries

C.2 Inflation and heterogeneous price levels

We deflate aggregate output separately for domestic and foreign production, rather than at the sector-country level of the raw IO tables. Sector-country deflation would require sector-country-specific price indices, which are unavailable for an important share of country-sector combinations in our data. Deflating at the aggregate level circumvents this limitation while still allowing a meaningful comparison of the decomposition results over time and across origins. We show below under which assumptions aggregate-level deflation is sufficient.

First note from equation (2) that price changes on the sector-country level embodied in v_{iO} and x_{iO} cancel from the impact intensity term under the assumption that inflation rates are similar between production and the part of production serving final demand in Germany. More formally, $\frac{v_{iO}}{x_{iO}} = \frac{\tilde{v}_{iO}}{\tilde{x}_{iO}}$ where the tilde indicates real variables.

Let P_{Ot} denote the aggregate price level in origin O at time t expressed in 1995 prices. We can then write the decomposition only in terms of real variables by multiplying by $\frac{P_{Ot}}{P_{Ot}}$:

$$Impact_{Ot} = \underbrace{\frac{V_{Ot}}{P_{Ot}}}_{\text{scale in 1995 prices}} \underbrace{\sum_i \frac{q_{iOt}}{\tilde{x}_{iOt}} \frac{\tilde{v}_{iOt}}{\frac{V_{Ot}}{P_{Ot}}}}_{\text{impact intensity in 1995 prices}}.$$

Decomposition results in the paper are based on real scale and impact intensity measures expressed in 1995 prices. Not accounting for inflation would result in an upward bias of the scale effect, and price increases result in an apparent improvement of the impact intensity.

C.3 Trends

Similarly to the literature (Levinson, 2009; Shapiro and Walker, 2018), we define growth rates relative to a base year, b, as

$$\begin{aligned}\frac{Impact_t}{Impact_b} &= \frac{V_t \sum_i f_{it} s_{it}}{V_b \sum_i f_{ib} s_{ib}} \\ &= \underbrace{\frac{V_t \sum_i f_{ib} s_{ib}}{V_b \sum_i f_{ib} s_{ib}}}_{\text{Scale effect}} + \underbrace{\frac{V_b \sum_i f_{it} s_{it}}{V_b \sum_i f_{ib} s_{ib}}}_{\text{Technique effect}} + \underbrace{\frac{(V_t - V_b)(\sum_i f_{it} s_{it} - \sum_i f_{ib} s_{ib})}{V_b \sum_i f_{ib} s_{ib}} - 1}_{\text{Interaction effect}}\end{aligned}$$

where the subscript for origin and the tilde to indicate real variables are suppressed for readability. The second equation follows from adding and subtracting $V_b \sum f_{it} s_{it}$, $V_t \sum f_{ib} s_{ib}$, and $V_b \sum f_{ib} s_{ib}$, and rearranging terms. The equation can be expressed in growth rates as $1 + g_{Impact} = (1 + g_{scale}) + (1 + g_{tech}) + g_{int} - 1 = 1 + g_{scale} + g_{tech} + g_{int}$.

C.4 Contribution of the rising import share

Summing the origin-specific decomposition in equation (2) over domestic and foreign production yields the economy-wide consumption-based impact in a given category:

$$CBA_t = \text{Impact}_{Dt} + \text{Impact}_{Ft} = V_t \left(S_{Dt} \bar{f}_{Dt} + S_{Ft} \bar{f}_{Ft} \right),$$

where $V_t = V_{Dt} + V_{Ft}$ is total value of production for German final demand, $S_{Ot} = V_{Ot}/V_t$ is the aggregate production share in origin $O \in \{D, F\}$ (so $S_{Dt} + S_{Ft} = 1$), and $\bar{f}_{Ot} = \sum_{i \in O} \frac{v_{it}}{V_{Ot}} f_{it}$ is the within-origin, expenditure-weighted average impact intensity. To isolate the contribution of the shift from domestic to foreign production, we hold the aggregate origin shares, S_{Ot}, at their 1995 values while letting the total value of production for German final demand and the within-origin impact intensities evolve as observed:

$$CBA_t^{\text{cf}} = V_t \left(S_{D,1995} \bar{f}_{Dt} + S_{F,1995} \bar{f}_{Ft} \right),$$

which gives the counterfactual consumption-based impact had import shares remained constant.

Differencing the original and the counterfactual series and using $S_{Dt} + S_{Ft} = 1$ isolates the role of the higher foreign impact intensity for the effect of a growing import share.

$$\begin{aligned} CBA_t - CBA_t^{\mathrm{cf}} &= V_t \Big[\big(S_{Dt} - S_{D,1995}\big) \bar{f}_{Dt} + \big(S_{Ft} - S_{F,1995}\big) \bar{f}_{Ft} \Big] \\ &= V_t \left(S_{Ft} - S_{F,1995}\right) \big(\bar{f}_{Ft} - \bar{f}_{Dt}\big), \end{aligned}$$

The difference is thus total production value times the rise in the import share times the foreign–domestic gap in impact intensity. Because imports embody more impact per euro than domestic production ($\bar{f}_{Ft} > \bar{f}_{Dt}\, \forall t$) and the import share rises ($S_{Ft} > S_{F,1995}\, \forall t$), the observed account exceeds its counterfactual in every category. Use-phase impacts are unaffected and included as observed in the counterfactual impacts depicted in Figure 5.

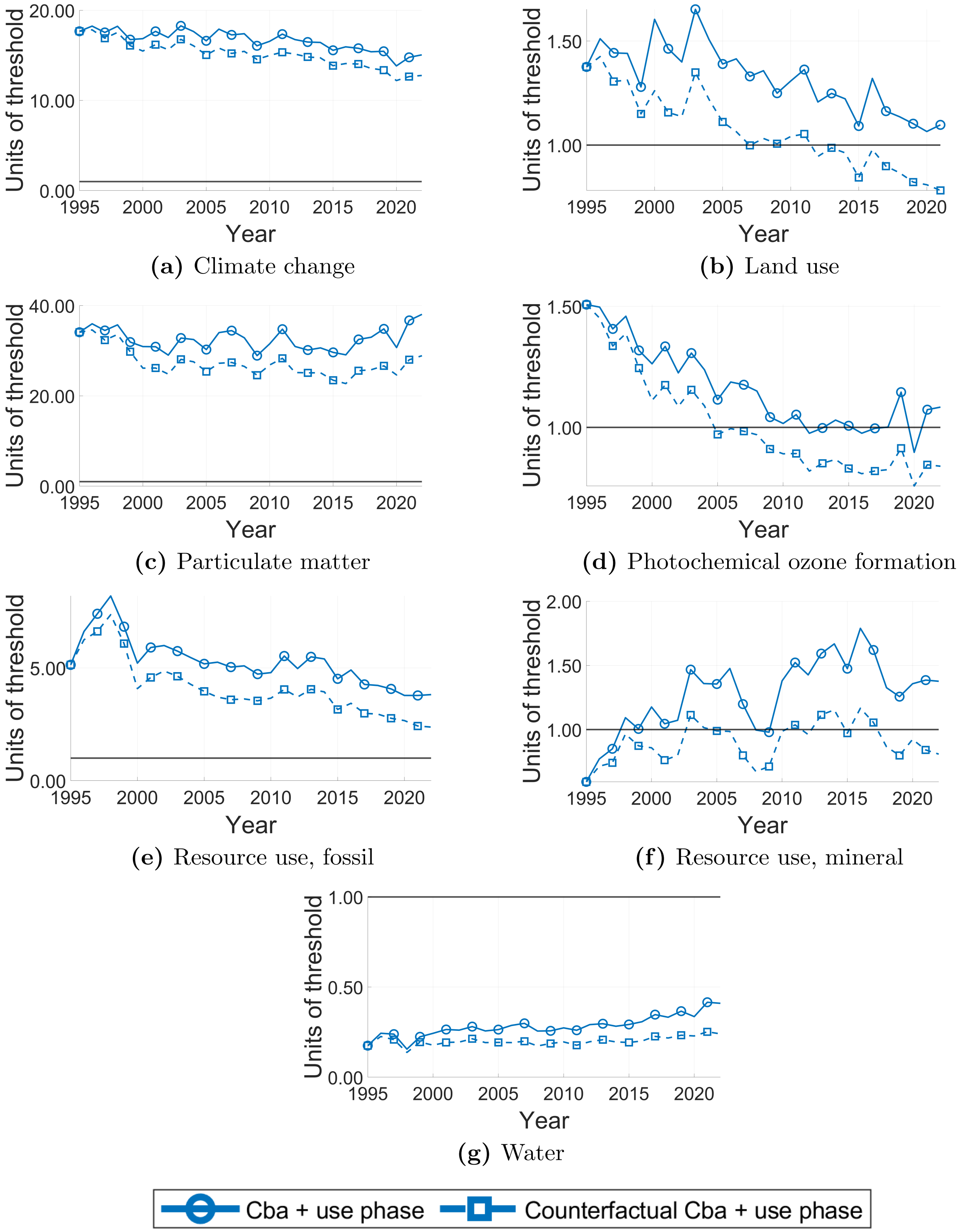
Three qualifications apply. First, the counterfactual fixes only the aggregate import share, not the sectoral composition of demand within either origin; both the observed and counterfactual series still embody within-origin shifts in sector composition. Second, the construction is partial-equilibrium: displaced imports are met by domestic production at the observed domestic impact intensity with no adjustment of prices, technologies, or sectoral structure. Third, the value of production withdrawn from imports is absorbed by domestic production in proportion to its observed sectoral mix—a reduction in steel imports, for instance, raises domestic production across the whole domestic basket rather than domestic steel one-for-one. The experiment thus holds the structure of domestic production fixed while varying the aggregate import share. Because it operates on values of production rather than physical output, the implied quantities need not match observed final-demand quantities. It can therefore be read as asking how environmental impact would have evolved if, of each euro consumed, the amount needed to hold the import share at its 1995 level had been spent on the domestic bundle rather than on imports, all else equal.

D Robustness to incomplete stressor characterization

Our impact estimates use only those EXIOBASE stressors for which EF 3.1 provides CFs; the remaining stressors are assigned a factor of zero. Since their EF 3.1 factor is zero—most plausibly because they are not relevant to the category—they are unlikely to matter much. Nevertheless, omitting relevant stressors could in principle distort the geographic decomposition (Figure 2), on which two findings rest: that foreign production accounts for a larger share of impacts than domestic production (a level result), and that the foreign–domestic gap widens over time (a trend result). We assess each in turn.

We assign potential uncharacterized stressors to a category by extension: any stressor from the EXIOBASE extension underlying the category's characterized impacts is treated as a candidate, even if its EF 3.1 factor is zero. This is intentionally generous—many such stressors are unlikely to

Figure 5: Consumption-based impact compared to counterfactual with constant 1995-import share



(a) Climate change

(b) Land use

(c) Particulate matter

(d) Photochemical ozone formation

(e) Resource use, fossil

(f) Resource use, mineral

(g) Water

Notes: Solid lines show the observed impact of consumption-based impacts and use-phase emissions. Dotted lines show the impact of the counterfactual consumption-based impacts and the observed use-phase emissions. The counterfactual holds the import share of German consumption fixed at its 1995 level, while letting within-origin impact intensities and the scale of consumption evolve as observed. The gap between the two lines isolates the contribution of the rising import share, all else equal. Appendix C.4 describes the construction.

be relevant to the category—so it biases the robustness check toward finding threats rather than dismissing them. Column (1) of Table 6 lists the number of uncharacterized stressors by impact category. The concern is confined to the five categories that contain uncharacterized stressors; land and water use contain none and are therefore unaffected. All five affected categories use global, origin-invariant characterization factors (Table 3); we therefore assume that omitted stressors would carry the same CF in domestic and foreign production.

Level: environmental impacts embodied in imports exceed impacts from domestic production We first ask whether omitted stressors could overturn the finding that imports dominate the footprint. Define the import share of a stressor as

$$Share_{IMP} = \frac{IMP}{CBA}.$$

Including an omitted stressor would raise the domestic impact relative to the foreign one whenever $Share_{IMP} < 0.5$. Note that this is only a necessary condition for an uncharacterized stressor to reverse the gap. In the end, a gap reversal depends on the unknown CF and the joint contribution of the set of uncharacterized stressors. A joint assessment is infeasible due to a lack of a joint unit.

Table 6, Column (2), reports the time average share of uncharacterized stressors meeting this condition. It ranges from about 4% to 17% and lies below 10% in three of the five categories, so the large majority of omitted stressors would, if anything, reinforce rather than threaten the result.

Trend: the foreign–domestic gap over time We next ask whether omitted stressors could reverse the finding that domestic impacts improve while impacts embodied in imports offset these improvements in the aggregate; i.e., a widening of the gap between foreign and domestic impacts.

Define

$$Gap_t = FOR_t - DOM_t,$$

where FOR_t and DOM_t are the foreign (imported) and domestic parts of the consumption-based account.

Let $Gap^c = FOR^c - DOM^c$ be the gap from characterized impacts and $Gap^u = FOR^u - DOM^u$ the gap in an omitted stressor's inventory. Including that stressor with factor CF^u gives the augmented gap

$$Gap^{included} = (FOR^c + FOR^u CF^u) - (DOM^c + DOM^u CF^u) = Gap^c + Gap^u CF^u,$$

The characterized gap widens in most categories; i.e., $0 < \left(Gap^c_{t+1} - Gap^c_t\right)$. A necessary condition for the reversal of this finding when adding an uncharacterized stressor is that

$$0 > \left(Gap^c_{t+1} - Gap^c_t\right) + CF^u \left(Gap^u_{t+1} - Gap^u_t\right). \tag{3}$$

Since the first term in brackets and CF^u are positive, a necessary condition is that

$$\left(Gap^u_{t+1} - Gap^u_t\right) < 0. \tag{4}$$

The share of uncharacterized stressors meeting this condition amounts to 35–40% across categories (Table 6, Column (3)).

Within the set of uncharacterized stressors for which condition (4) holds we derive the minimum contribution of an uncharacterized stressor using equation (3), that is, a lower bound on CF^u so that leaving out the stressor biases our results in a relevant way:

$$CF^u > -\frac{\left(Gap^c_{t+1} - Gap^c_t\right)}{\left(Gap^u_{t+1} - Gap^u_t\right)} > 0$$

We compare for each stressor the minimum CF^u to the maximum CF in the set of characterized stressors within an impact category. We report the share of uncharacterized stressors for which the necessary CF lies below the maximum CF observed in the data. These are uncharacterized stressors that may reverse our result of a widening gap under a plausibly high CF.

Column (4) of Table 6 shows the results. This share is below 3% for climate change, photochemical ozone formation, and particulate matter, but reaches 13% for minerals and 37% for fossil resource use. The trend is therefore robust for the majority of categories; the fossil-resource and, to a lesser extent, mineral-resource trends are sensitive only under the extreme assumption – assigning the category's maximum factor to stressors whose EF 3.1 factor is in fact zero.

Overall, incomplete characterization is unlikely to overturn either the level or the trend of the foreign–domestic gap, with the strongest reservation attaching to the fossil-resource trend under the most conservative possible factor assumption. Again, we cannot assess the joint importance of left-out stressors due to a lack of a joint unit.

Table 6: Robustness to missing characterization factors

Impact category	number unchar. stressors (1)	Level threats (%) (2)	Trend threats (%) (3)	Trend, max-CF (%) (4)
Land use	0	—	—	—
Water use	0	—	—	—
Climate change	395	7.96	38.48	2.78
Resource use, minerals	46	17.24	34.78	13.04
Resource use, fossil	51	12.40	37.25	37.25
Photochemical ozone formation	294	4.37	39.80	0.68
Particulate matter	272	9.23	37.50	1.47

Notes: Column (1) reports the number of EXIOBASE stressors in the category left uncharacterized. Because a stressor can be a candidate in several categories, the counts in Column (1) do not sum to the 705 stressors in the environmental extensions. Column (2) reports the share of those stressors, averaged over time, that could threaten the level result, defined as having an import share below 0.5. Column (3) gives the share with a negative trend in the foreign–domestic gap, which could in principle reverse the widening of that gap. Column (4) gives the share that would actually reverse the trend result if assigned the category's maximum observed characterization factor, a worst-case bound on Column (3). Land and water use have no uncharacterized stressors, so Columns (2)–(4) are undefined.