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Beyond greenhouse gases – Comprehensive planetary boundary footprints to measure environmental impact

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ABSTRACT

The planetary boundary framework identifies nine areas of key environmental risk globally. The causes of climate change are well understood as a serious and existential threat; however the other eight areas of concern have a much more limited understanding of what is driving their continued increase.

This research utilises Global Resource Input Output Assessment (GLORIA) multiregional input-output (MRIO) tables to map 15 footprint indicators across 51 sectors and seven global regions, identifying key sectors driving planetary boundary impacts and suggesting targeted interventions for sustainability.

The relative role of emission intensity and total expenditure is shown, and potential trade-offs and synergies between sectors and indicators are identified. High-impact footprint clusters are identified as food and textiles, and the built environment, with moderate impacts from the services and energy sectors. These relationships are compared to several transformation agendas, identifying overlooked relationships and drivers, including the predominant role of commercial buildings and infrastructure in built environment impacts and the correlation between greenhouse gas emissions and air pollution. The primary driver of plastic use footprints is seen to be the built environment, however as a whole chemical pollution levels remain a significant unknown, and the challenge to globally stop the flow of further dangerous substances and clean up existing contaminated sites is large.

By providing a detailed breakdown of planetary boundary drivers this work enables decision-makers to understand the risks and issues associated with economic purchases across all critical environmental pathways simultaneously to better prioritise action for a stable planet.

1. Introduction

1.1. Planetary boundaries – beyond greenhouse gas emissions

The definition of planetary boundaries (PB) in 2009 has focused the sustainability discussion globally (Rockström et al., 2009), with a significant effort from the research community to determine the status of boundaries, enunciate the degree to which they are exceeded or retain a safety buffer, and determine how these can be operationalised into goals (Li et al., 2021; Randers et al., 2019; Rockström et al., 2023), such as "science-based targets" (Andersen et al., 2021).

Planetary boundary limits have been calculated as the level of global variation that can be tolerated by earth systems before exiting a stable and resilient state, based on pre-industrial Holocene conditions (Richardson et al., 2023), see Table 1. Boundary overshoot has been identified for 6 planetary boundaries, including greenhouse gases, functional integrity of the biosphere, natural ecosystem area, surface water use and groundwater extraction, biogeochemical flows (nitrogen and phosphorus), and novel entities with the ocean acidification boundary close to breaching amid worsening emissions (Persson et al., 2022; Richardson et al., 2023; Rockström et al., 2023). Air pollution is breached regionally, but not globally, while stratospheric ozone depletion is within boundary and improving (Richardson et al., 2023).

To some extent, planetary boundary-related efforts have been dominated by an intense focus on climate change, due to the urgency of reducing impacts and profound global repercussions (Ripple et al., 2022). While the focus on climate change is necessary, the interconnected nature of planetary boundaries and the level of overshoot currently occurring for other boundaries also requires urgent attention, with a truly comprehensive overview of impacts missing from much

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environmental policy debate (Goodwin et al., 2021).

Historically, biodiversity loss and novel entities are particularly significant and understudied (Goodwin et al., 2021; Persson et al., 2022; Steffen et al., 2015), although an increasing focus on the triple planetary crisis (climate change, biodiversity loss and pollution), including annual UN Biodiversity conferences and movement towards a global plastics treaty, is now gaining traction (Dasgupta, 2021; UNEP, 2024; UNFP, 2024).

1.2. Linking economic demand with planetary boundary impacts

A major challenge in the sustainability debate is connecting the physical science information available with the day-to-day choices that drive impacts, which are often both remote from the location of impact generation, and in-obviously linked to the underlying economic system that drives resource usage decisions globally.

Climate impacts have been shown to be disproportionately driven by wealthy consumers (predominantly located in high and middle-income countries) who source highly processed goods from long supply chains often based in distant and less-wealthy regions (Nielsen et al., 2021; Otto et al., 2019; Wiedmann and Lenzen, 2018). These source regions suffer from both the natural destruction associated with resource extraction and additionally often lack the income to ameliorate impacts such as through insurance, temperature control systems, water processing and waste management facilities (Rockström et al., 2023; Romanello et al., 2022; Thomas et al., 2019).

High consumption levels have become normalised in wealthier nations, amidst a general shift in values towards individualistic and materialistic aims (Oliver et al., 2022; Wiedmann et al., 2020), with increasing physical and social stratification underpinning a disconnection in both time and space from the impacts and shortages that might otherwise form a negative feedback loop in economic systems (Green and Healy, 2022; Stoddard et al., 2021).

Environmentally extended, multi-region input-output (EE-MRIO) analyses can address this spatial disconnection by using economic data to re-allocate environmental impacts from the industry of production to the final goods and services that are purchased, thus identifying products and services that are contributing significantly to environmental impacts and enabling identification of changes in consumption that need to occur to reduce impact (Minx et al., 2009).

1.3. Previous studies and research gap

Numerous previous studies have investigated environmental and social footprints (Wu et al., 2021), with global studies that focus on national total footprints (O'Neill et al., 2018; Schlesier et al., 2024), or consider multiple footprints for a limited range of countries (Nykvist et al., 2013; Sala et al., 2020); or a limited range of planetary boundaries (Hickel et al., 2022; Lucas and Wilting, 2018). Further, numerous detailed studies looking at all global regions and a breakdown of economic sectors have been completed for individual indicators and their drivers such as nitrogen (Malik et al., 2022b; Oita et al., 2016); deforestation and land use change (Chaves et al., 2020); biodiversity (Lenzen et al., 2012; Malik et al., 2022a); materials (Lenzen et al., 2022; Wiedmann et al., 2015); water (Lenzen et al., 2013; Soligno et al., 2019); pesticides (Tang et al., 2021); and employment (Alsamawi et al., 2014). An alternate stream of research has focused on global footprints for particular economic sectors of concern such as food (Gerten et al., 2020); healthcare (Lenzen et al., 2020; Malik et al., 2018), fashion (Peters et al., 2021) and the plastics industry (Jin et al., 2023).

No study, however, has specifically investigated the drivers of all economic sector and at-risk planetary boundary impacts from a

Table 1
Environmental Satellites, data sources and related planetary boundaries.

Satellite	Units	Global data	Planetary boundary (Richardson et al., 2023)
Greenhouse Gases (GHG) - excluding Land use, land-use change and forestry (LULUCF)	kt CO2-eq	GloriaMRIO database Release 057 (https://ielab.info/resources/gloria) (Lenzen et al., 2022, 2017)	350 ppm CO2 Atmospheric CO2 concentration
GHG - LULUCF	kt CO2-eq		350 ppm CO2 Atmospheric CO2 concentration
Water	ML H2O-eq blue water consumption		10.2 % Bluewater - Global land area with deviations greater than during preindustrial
Landuse	ha		75 % - Area of forested land as the percentage of original forest cover
Biodiversity loss	Potentially Disappeared Fraction (PDF)		<10 extinctions per million species-years
Materials	t		N/A
Ocean Acidification (OA)	kt CO2-eq. OA		>80 % of mean preindustrial aragonite saturation state of surface ocean
Air Pollution	Disability Adjusted Life Years (DALY)		0.1 mean annual interhemispheric difference in aerosol optical depth
Energy	TJ		N/A
Employment	1000 people		N/A
Nitrogen	Gg	Global Industrial Ecology Virtual Laboratory (IELab) Nitrogen datafeed (Oita et al., 2016)	62 Tg Industrial and intentional fixation of Nitrogen (N) per year
Pesticide load	grams-bodyweight (g-bw)	Global Industrial Ecology Virtual Laboratory (IELab) Pesticide datafeed (Tang et al., 2022)	No synthetic chemicals released to the environment without adequate safety testing
Plastics	t plastic	(Ryberg et al., 2019) Global environmental losses of plastics across their value chains Table S1	No synthetic chemicals released to the environment without adequate safety testing
Excess phosphate (applied to agriculture)	t excess phosphorus	Our world in Data, Excess phosphorus from croplands, https://ourworldindata.org/grapher/excess-phosphorous?country=CHN~IND~USA~GBR~MEX~ZAF~FRA Data Source (West et al., 2014)	6.2 Tg Phosphorus per year mined and applied to agricultural soils
Phosphate mined	t phosphate rock	USGS Mineral Commodities Survey 2022 – Phosphate Rock (U.S. Geological Survey, 2022)	6.2 Tg Phosphorus per year mined and applied to agricultural soils

consumption perspective across all global regions. This partial perspective limits the ability of decision-makers to understand the risks and issues across all planetary boundaries, and thus prioritise resources to best address the many risks associated with current lifestyle choices and behaviours. This is the research gap that this paper aims to fill.

1.4. Aims of this study

By being the first study to look at 15 indicators simultaneously and calculating detailed footprints across all economic sectors, world regions and at-risk planetary boundary impacts this paper aims to enable the identification and prioritisation of key areas of environmental risk at multiple levels.

This information also enables the analysis of similarities in impacts between impact drivers and sectors, and thus facilitates the quantitative verification of previously estimated relationships used in transformation studies and boundary interaction studies.

Specific questions asked in support of these goals include: Which economic sectors are driving planetary boundary impacts globally from a production and consumption perspective (Sections 3.1 and 3.2)? How do the consumption patterns of major world regions compare in their impact on planetary boundaries (Sections 3.4 and 3.5)? What is the relationship between the level of expenditure and the intensity of impacts, from both a regional and sectoral perspective (Sections 3.3 and 3.6)? Which sectors and indicators have a similar pattern of impacts (Sections 3.7 and 3.8)? How do the relationships identified relate to the transformation agendas (Section 3.9)?

2. Methods

2.1. Approach

This study applies an environmentally extended, multi-region input-output (EE-MRIO) database to map territorial and consumption-based environmental impacts that are applying significant pressure to environmental resources (Wiedmann and Lenzen, 2018). Input-output analysis is a useful approach due to its ability to simultaneously allocate impacts globally across the entire supply chain while conserving total impact levels, thus providing a timely and comprehensive estimate of impacts at a global level while avoiding truncation errors and duplication of data that can occur using bottom-up methods such as Life cycle assessment (LCA) (Crawford et al., 2018).

Input-output analysis does, however, rely on aggregation and disaggregation of data and the calculation method utilises an averaging process. While this is a reasonable assumption in the absence of better information, aligning model design with underlying economic relationships can produce more accurate results; additionally, relatively small sectors and regions can have a disproportionally high level of uncertainty (Lenzen et al., 2010; Wiedmann et al., 2008). Uncertainty for total impacts per region has typically been calculated as around 10 % in similar studies, however smaller sectors such as phosphate mining in this study are likely to be less reliable (Lenzen et al., 2010; Wiedmann et al., 2008).

The Global Resource Input Output Assessment (GLORIA) database was chosen here due to its accessibility and data validation, and the wide range of social and environmental indicators available (Lenzen et al., 2022, 2017; Lutter et al., 2024). Where planetary boundary driver indicators were not available in GLORIA these were sourced where possible from high-quality global sources (see Table 1). Some datasets (e.g. for ozone layer-depleting substances) were not able to map adequately to the sectors chosen, and accordingly this dataset has not been included in this study. GLORIA data has been validated against the United Nations SNA Main Aggregates and ILO labour data (IELab, 2022, 2021).

A 51-sector model of the global economy was used, with sectors chosen to represent well-understood industry groupings, or areas of environmental interest. 13 global regions were considered, with 7 focused on East Asia (aggregated here in results), and the remaining 6 based on World Bank groupings.

GLORIA economic data maps 164 regions and 120 sectors. To enable calculation using the computing resources available an algorithm was written to aggregate GLORIA data into the modelled regions and sectors. These sectors and regions were chosen to preserve as much information as possible by retaining underlying economic relationships (e.g. only aggregating mining sectors with other mining sectors), separating out categories of interest at both primary and secondary levels of the economy (such as metal/non-metal mining and products and animal/plant-based agriculture and food products) and to enable allocation of impacts sourced other than from GLORIA to relevant sectors (e.g. plastics and phosphate mining).

This study investigates drivers of planetary impacts from both a production and consumption perspective, considering: the relative contribution of different economic sectors and world regions; the impact of total expenditure and impact intensity on different sectors; the impact of regional wealth on per capita footprints and impact intensity; and similarity of the patterns of impact between sectors and indicators, and how this relates to the transformations agendas.

2.2. Calculation of environmental impacts

Consumption-based accounts of 12 PB-related indicators, plus materials, energy and employment, were calculated using EE-MRIOA (see Table 1). Greenhouse gas emissions (GHG) excluding Land use, land use change and forestry emissions (LULUCF) were then further disaggregated into carbon dioxide (short-term and other), methane, nitrous oxide, and other gases.

Indicators were chosen to represent anthropogenic drivers of planetary boundary impacts. This enables an allocation to economic transactions, thus providing a logical basis for reallocation between producers and consumers. It is acknowledged that this incompletely covers planetary boundary impacts that may not be related to the economic system, such as the impact of invasive species on biodiversity, and the impact of dust storms and volcanic eruptions on atmospheric aerosols.

The standard Leontief-inverse demand-pull input-output model was used to reallocate impacts from each industry sector of production to the product category of final demand from final consumers, including households, government, and businesses capital accumulation (Leontief, 1966, 1936; Miller and Blair, 2009).

Direct environmental impacts were allocated to sectors based on the information provided, as detailed in S1.2.2.

2.3. Data sources

For international economic data we used 2019 data from Release 057 of the GLORIA MRIO database (https://ielab.info/resources/gloria) (Lenzen et al., 2022) constructed in the Global MRIO Lab (Lenzen et al., 2017). Environmental data was sourced from a combination of GLORIA (as above) and other reputable data sources as detailed in Table 1. GLORIA data was aggregated into the 51 sectors and 13 global regions of this analysis prior to input-output calculations being run.

Note that all per capita values are calculated as 1/1000 of the main data units.

Ocean acidification is caused by carbon dioxide (CO_2) in the atmosphere, which is largely impacted by human-released CO_2, however methane (CH_4) also combines with oxygen (O_2) and converts to CO_2 and hydrogen (H_2) in the atmosphere at an average of 8 years after release, based on the chemical reaction $CH_4 + 0_2 > CO_2 + 2H_2$. Ocean acidification potential was calculated as CO_2 plus CH_4 converted to CO_2 using molecular weight ratio. This approach does not consider the delay in conversion timing as it matches human releases to economic activity.

Two indicators are considered for phosphorus: ‘phosphate mined’ shows the total phosphate mined by country which is then reallocated using financial data to end categories, while 'excess phosphorus' considers only excess phosphorus applied to agricultural land. This latter category mirrors more closely the proposed planetary boundary for phosphorus (currently defined as surplus agricultural application (Rockström et al., 2023)).

This study considers only plastic use and pesticide for the novel entities boundary, given a paucity of data, which is a small yet critical sector of chemical usage amongst the hundreds of thousands of often poorly understood human-created chemicals currently in use today (Villarrubia-Gómez et al., 2018).

Plastics are widespread and long-lasting, with impacts on biodiversity at all stages of decomposition (Naidu et al., 2021). Macro-plastic pollution (driven by waste management escape, litter, and fishing industry discarding equipment at sea) leads to widespread harm to marine life, while microplastics pollution (notably originating from car brake pads, tyres and washing of synthetic textiles) is biologically incorporated in many species, including plants and humans, with impacts on growth and health (Crossman et al., 2020; Guo et al., 2020; Ryberg et al., 2019; Yan et al., 2022).

Further details of the methodology and data used can be found in the S1 of the Supplementary Material.

2.4. Downscaled boundaries

Because anthropogenic drivers represent only a partial view of the complex environmental systems that impact planetary boundaries, importantly not considering natural regeneration, and because the determination of "safe" levels of emission is dependent on not just the annual flows of impacts but also the state of the boundary itself, we conclude that the "allowable" level of additional impact should be zero in all cases of boundary state exceedance (including climate change, biodiversity loss, pesticides and plastics) (Richardson et al., 2023).

Nitrogen and phosphorus boundaries represent a unique case in that limits are defined in terms of annual human use of these elements, rather than a stock to be exceeded. The "excess phosphorus applied to croplands" indicator used implicitly includes a boundary measure (and again the allowable level of impact should be zero), while the nitrogen measure does not consider excess application, however as defined (see Table 1) could support a downscaled boundary of 8.05 kg/person/year Total nitrogen. Assuming a 14 % yield of phosphorus from phosphate rock mined (Cordell et al., 2009) gives a per capita share of 5.7 kg of phosphate rock mined per person per year. In both cases the regional distribution of use is critical for actual impacts and using less than the amount of nitrogen and phosphorus calculated here in total is inferior to ensuring no excess application is made to soils.

Land use is defined here as a state variable (total hectares in use), and accordingly can be compared to the boundary specified, however the footprint calculation made does not distinguish based on the original land cover type, while the boundary is defined in terms of a limited number of forestry types, especially tropical and boreal forests (Richardson et al., 2023). A rough boundary of 25 % of global land area in human use could be applied here (applying the forest boundary to all land use types), giving a land use boundary of 0.42 ha/capita.

Given the substantial contribution of non-anthropogenic drivers to air pollution, it is unlikely that downscaling human emissions would meaningfully address this issue, and no downscaled boundary is calculated. It may be possible to apply a DALY limit (e.g. 1/10ˆ6 risk per capita per year) to address human health issues, however this is outside the scope of planetary boundaries per se.

Updated boundaries for freshwater in 2023 do not support a simple downscaling approach, and it is noted in Richardson et al. that previous boundaries significantly overestimated allowable usage. As with nitrogen and phosphorus, local excess water usage is more relevant to planetary boundary impacts, however this also requires consideration of seasonal and annual variability in many catchments and is further complicated by water quality requirements that can be impacted by contamination and salination. No attempt has been made to downscale the ocean acidification boundary, however it is noted that ocean impacts from deoxygenation, acidification and warming are both highly interconnected and cumulative in nature (Heinze et al., 2021).

Note that the exceedance of any single planetary boundary can impact the allowable level of other planetary boundaries, and given that six of nine planetary boundaries are already exceeded, caution should be taken in interpreting the levels calculated as a licence to consume. Further, the per capita boundaries calculated above are based on a population of 7.7 billion people and would need to be proportionately decreased for higher population levels. Given that it is not feasible to compare impacts between all environmental drivers as a proportion of downscaled boundaries, results have been normalised relative to global averages.

2.5. Similarity of indicators and sectors

A simplified Euclidean distance analysis has been performed to determine the similarity of indicator and sector impacts by normalising sector impacts as a percentage of total impact for each indicator, and then comparing which other indicators have a similar pattern of high and low impact sectors. Sectors were compared by normalising the % indicator impacts calculated previously against the total of all % indicator impacts allocated to that sector (i.e. for all 15 indicators), expressed as the proportion of the total impacts for each indicator. This approach results in removing the impact of both varying final demand between sectors and varying units between indicators to enable comparison of the pattern of high and low impacts between sectors.

The similarity of indicators and sectors was calculated using a modified Euclidean distance based on Eq. (1)

$$d_{a,b} = \sum_{r=1}^{n} |r_a - r_b| \tag{1}$$

$d_{a,b} = \textit{distance between a and b}$

$a, b = \textit{the sectors or indicators being compared}$

$n = \textit{number of different results}\ (51\ \textit{for sectors}, 12\ \textit{for indicators})$

$r_{a,b} = \textit{the result for each value of a or b, as a \% of the total}$

2.6. Clusters of sectors

Clusters of sectors and indicators were then identified using *k*-means analysis, with 5000 repetitions and a variety of alternate numbers of clusters. *k*-means analysis identifies clusters by creating random initial data points and calculating distances to these points, using Euclidean distances, then repeating with new cluster centres located at the centre of the groups identified (Mathworks, 2024). Repetition of this process continues until a stable set of clusters is produced; however chronic instability can occur in circumstances including when the number of clusters increases. In this instance, sector analyses with >12 clusters could not obtain a stable grouping. Sectors and indicators have been grouped in the clusters identified where this was consistent across varying numbers of clusters. Where no consistent cluster was identified, sectors were grouped according to the most economically similar grouping – e.g. "Other Services", consistently an outlier, was allocated to Services. "Transport and Trade" was subsumed into "Built Environment and Manufacturing" as the number of clusters decreased but has been retained as a separate grouping here to enable consideration of the individual impacts of this sector.

3. Results and discussion

3.1. Footprints by sector

The highest overall impacting sector was commercial buildings and heavy engineering, with a particularly high impact on greenhouse gases, land use change, air pollution, plastics, phosphate mined and ocean acidification (see Fig. 1). Other high-impact sectors include beef and dairy (land use, biodiversity loss and nitrogen); grains and bulk crops (water use, biodiversity, nitrogen and excess phosphorus); and gas supply (greenhouse gas emissions and ocean acidification).

While GHG footprints (excluding LULUCF) and LULUCF are driven by the "commercial buildings and heavy engineering" sector, GHG from methane only shows the highest footprints from the poultry and beef and dairy sectors (see S5 in supplementary information).

The high proportion of phosphate mined that has been allocated to commercial buildings and heavy engineering compared to excess phosphorus allocated to crops suggests that the application of phosphorus to forestry projects may also need to be analysed for excess application and potential run-off. Given that the amount of phosphorus fertilisers applied to forestry is generally considered to be much less than that applied to croplands (Lun et al., 2018; Nesme et al., 2018; Smethurst, 2010) this may also reflect input-output averaging issues with a relatively small economic sector for phosphate mining and fertilisers.

Pesticide load is most impacted by horticulture and other agriculture sector purchases, compared to water use which is most impacted by purchases of grains and bulk crops, which suggests that while these two sectors are similar in many ways their key environmental challenges are very different.

Highly hazardous pesticides are one of the World Health Organization (WHO) identified 10 chemicals of public health concern (World Health Organization, 2020) (see S6 in supplementary info) causing health problems and fatalities in many parts of the world (World Health Organization, 2019). Some of these are both persistent and bioaccumulative, and in addition to having a significant impact on human health have been implicated in declining wildlife health, including rapidly declining global insect populations (IPBES, 2019). While this research was able to make use of existing datasets for pesticide use, ideally other chemicals of concern should also be studied. Additionally, footprint studies only look at chemicals that are currently being produced, however many previously produced persistent chemicals and other novel entities are currently at toxic levels in the environment (e.g. *Per*- and poly-fluoroalkyl substances (PFAS)), and regeneration and remediation is required to return these areas to a safe state.

Air pollution has been measured in terms of disability-adjusted life

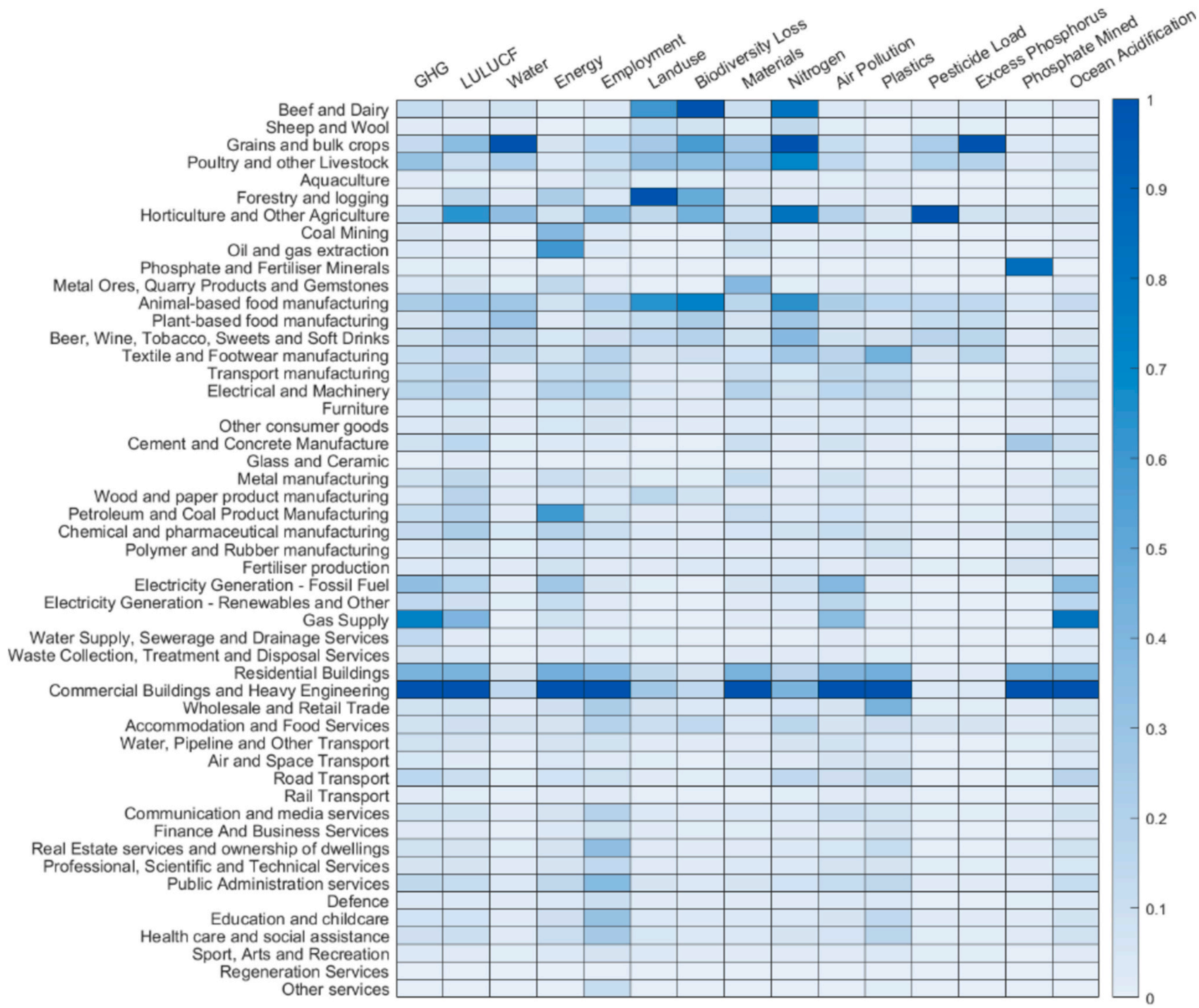

Fig. 1. Heatmap of global footprint contribution by sector for 13 environmental and 2 social impact types (excludes direct end-user emissions).

expectancy (DALY). This is a largely social approach to measuring this indicator (compared with the proposed planetary boundary of inter-hemispheric difference in aerosol optical depth), however gives an initial indication of air pollution-generating sectors, with the construction and energy sectors particularly high impact.

Globally, nitrogen is widely removed from the air to be manufactured into an artificial fertiliser to improve marginal soils, thus helping to underpin the "green revolution" that delivered adequate nutrition to feed the rapidly growing population of the 20th century. Optimal application of nitrogen fertilisers leads to improved growth without runoff but requires close monitoring of soil conditions to ensure appropriate application. The planetary boundary has variously been defined as agricultural nitrogen surplus or total global drawdown of nitrogen, with efforts to determine local and global boundaries (Schulte-Uebbing et al., 2022). The data used here is reactive nitrogen emissions (N_2O, NH_3, NO_x and NO_3^-), including emissions from industry and sewage (Malik et al., 2022b). Despite this the highest impacts are all coming from agricultural products, which would only increase were the input data narrowed down also.

The two separate land use-related indicators measure different aspects of land use change here. LULUCF refers to the carbon emissions (or draw down) from the growth and removal of trees, as measured under the Paris Agreement, while 'Land use' refers to the area of land converted from wild to human use. The differing high intensity sectors for these categories most likely reflect forestry activities that show an ongoing transfer of carbon between sectors but do not formally change the land use as such. Interestingly these results show a clear distinction between agriculture and forestry biodiversity loss and land use footprints with forestry and logging products showing a relatively lower biodiversity loss than horticulture and beef and dairy products.

A high employment footprint is typically seen as a positive social outcome, and our data demonstrates the beneficial employment outcomes from services sectors combined with low environmental footprints.

This work identifies the drivers of global plastic consumption as building and construction, textiles and wholesale and retail trade (see Fig. 1). Interestingly the building and construction sector has not been widely identified as contributing to plastic waste production, which may indicate widespread use of long-lived plastics (e.g. waffle slabs in buildings), but also represent a future area of enquiry for plastic pollution researchers to identify the end-of-life pathways for these products.

The most significant impacts on biodiversity coming from the global economy are due to the food and forestry system, which also has a significant impact on both land-clearing and the application of chemicals and fertilisers that then leak into the environment more broadly. Further threatening processes not linked to the legal economy are not included

Fig. 2. Heatmap of production emissions by sector for 13 environmental and 2 social impact types (excludes direct end-user emissions). Weighting shows the proportion of total emissions for indicator type (0-1).

in the data presented here, such as household use of firewood, invasive species, and illegal wildlife trade (Hinsley et al., 2023; IPBES, 2019).

Well-understood tropes that hark back to past times that are perceived to represent a harmonious balance with nature (such as the rural idyll (Cusworth et al., 2022) and noble savage (Warren, 2017)) propose biodiversity management approaches that may not adequately consider the current realities of degraded environments, higher populations, advanced modern technologies, and the increasing pressure from powerful corporations, countries and organized crime seeking profits from exploiting low-entropy systems such as highly functional natural environments (Galliers et al., 2022; Global Initiative Against Transnational Organized Crime, 2023; Souza et al., 2022).

3.2. Territorial impacts by sector

The footprints calculated can be compared to the direct impacts of industries (as reported under production-based accounting, see Fig. 2), demonstrating the potential for individual industries to target technical substitutions in their own production processes, while the footprints (consumption-based accounting, see Fig. 1) better indicate where there are benefits of changing the consumption of products, thus enabling consideration of alternate and complementary strategies to reduce impacts.

For example, the construction industries (residential and commercial buildings and heavy engineering) have a high footprint of products, but much lower direct impacts, suggesting that effective strategies to reduce impact will rely on targeting material supply chains and level of demand, rather than changing the operational processes directly undertaken by the industry itself. By contrast, grains and bulk crops show both a high production impact and a high footprint, indicating that directly changing industry practices will be needed to reduce the impact of this industry. In both cases substituting consumption with lower-impact products providing the same services or reducing consumption where unavailable is also an option to consider.

Underlying drivers of construction impacts relating to air pollution, greenhouse gases, air pollution and ocean acidification likely relate to the use of fossil electricity to refine and produce material inputs to this sector, while materials use direct impacts sit with metal ores and quarry products. While a 100 % renewable energy sector will address some of these impacts, increasing the durability and efficiency of resource use within this sector, and increasing recycling of metal and quarry products will be needed to reduce the materials use impacts of raw material extraction. The build-out of renewables will be included in built environment footprints.

Food and textiles sectors with high direct impacts (see Fig. 2) include beef and dairy impacting land use, biodiversity and nitrogen fixation, which reflects widespread land clearing to run cattle; grains and bulk crops impacting water use, biodiversity, nitrogen fixation and excess phosphorus applied to crops, reflecting impacts of intensive agricultural practices; and horticulture impacting nitrogen, pesticide use and LULUCF.

Current agricultural policies focused on addressing climate change impacts (such as through changes to ruminant feed and better management of agricultural waste) will not address these concerns, with improvements in agricultural practice to reduce water and nutrient use also required. Land use and biodiversity impacts will need to be addressed through a combination of both better land management and a reduction in the size of the cattle herd to enable regeneration of forest land (Resare Sahlin et al., 2024). Especially critical is the regeneration of the Amazon basin which forms the basis of a climate tipping point (Lenton et al., 2019). Approximately 40 % of global grain supply is currently used to feed livestock, indicating that substituting plant-based for animal-based food intake has the potential to significantly reduce overall environmental impacts, without reducing total calories available for human consumption (FAO and Our World in Data, 2023). 10-30 % of total meat production is then fed to pet dogs and cats in wealthy countries, representing a further avenue to reduce animal-based food impacts (Leenstra, 2024; Okin, 2017).

3.3. Drivers of sector impacts – expenditure vs intensity

Footprint impacts reflect the combination of the value of goods and services bought ('final demand') by government and households, and the intensity of impacts for each dollar spent. Mapping these two aspects of a footprint against each other enables tracking of the relative contribution of these factors to the overall outcomes (see Fig. 3).

Note the logarithmic scale on both axes, showing orders of magnitude variation in impact intensity and spending. Were these split into quadrants, the bottom left quadrant reflects the low-intensity, low-spend sectors, while the top right reflects the high-intensity, high-spend sectors. In terms of actions, the top left (high-spend low-intensity) are likely to be the most promising sectors for low-impact future consumption impacts as they are highly valued but with lower impacts. While the level of spending is to some extent dependent on the precise split of categories chosen (e.g. is all manufacturing added together or split into many smaller categories) the intensity is more independent, and thus reliable, although still subject to averaging effects.

This analysis shows services (purple – excluding construction, trade and transport) are always in the upper left corner meaning that they all have fairly low intensities but large spending. Utilities meanwhile (yellow) show a high intensity of fossil fuel-related impacts (air pollution, GHG, acidification) but low impacts for pesticide load, water, land use and biodiversity. Livestock farming has the greatest intensity of impact on biodiversity, nitrogen, land use and water, while crops and forestry have a greater impact on pesticide load. Built environment impacts were driven by a high total spend but only average intensity.

These scatter graphs show some indicative patterns of relationship between planetary boundaries. Greenhouse gases, ocean acidification and air pollution have similar intensity patterns, due to similar underlying driving processes of high emissions intensity electricity and gas use (see Fig. 1 and Fig. 2). Similarly, biodiversity, land use, pesticides, nitrogen, and water show a lot of congruence, reflecting underlying processes in the forestry and farming sectors (Fig. 1 and Fig. 2). Three indicators - plastics usage, phosphate mined and LULUCF have distinct patterns of intensities, suggesting that the drivers of these indicators do not overlap with other indicators.

3.4. Footprints by region

Assessing footprints by World Bank-defined regions shows significantly higher impacts than global averages for North America (Fig. 4), with consistently below average impacts for Sub-Saharan Africa and South Asia, and impacts approximately around global averages for other regions, consistent with population and affluence measures. East Asia, Middle East and North Africa, and Latin America and Caribbean all sit around global average impacts per capita. This reflects previous work showing patterns of global impacts (Fanning et al., 2022).

Europe and Central Asia, which includes both EU and non-EU countries, demonstrate footprints generally slightly above global averages despite well-above-average GDP, representing a disconnect between wealth and emissions, however further reductions are still required here to sit under planetary boundaries.

Some regions show spikes in particular indicators, suggesting extra attention is required to these impacts, including plastics, pesticides and land use in Europe and Central Asia, Land Use, Land Use Change and Forestry (LULUCF) and biodiversity in Latin America, and blue water extraction in the Middle East and North Africa.

While generally high, North America's lowest relative environmental footprints were from water use, nitrogen, and biodiversity loss, all of which are typically associated with farming practices, and may indicate favourable farming conditions and/or a well-managed agricultural sector, or a possible maximum feasible consumption of food products.

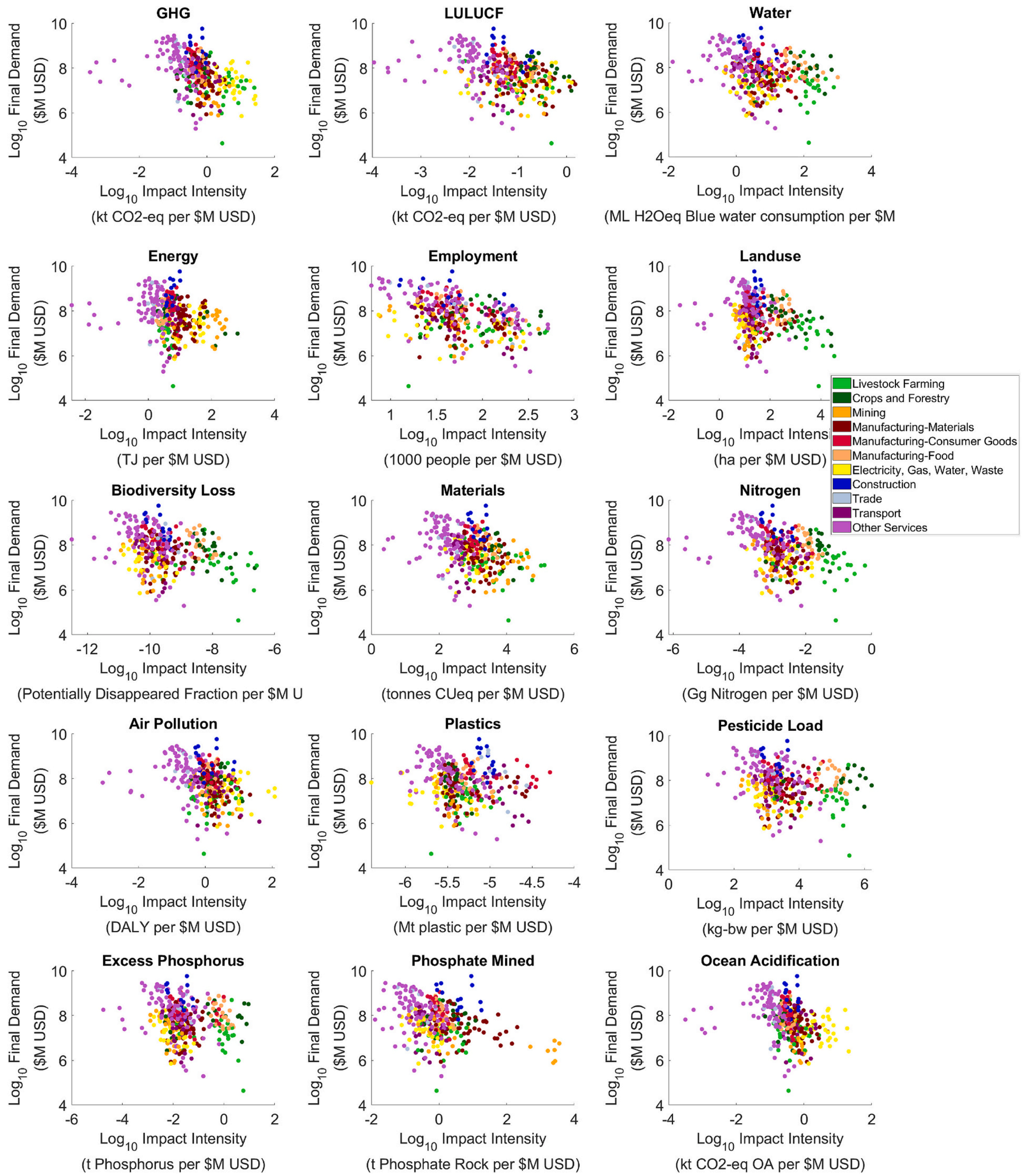

Fig. 3. Scatter plot for major world regions and 51 sectors, showing emissions intensity (Impact per USD) vs total final demand (Million USD) expenditure level, grouped by product type. Note the logarithmic scale on both axes, showing orders of magnitude variation in impact intensity and spending.

Most regions average both high- and low-income countries together, so while the region overall may be average, this should not be taken as implying that all countries within a region will approximate this footprint.

3.5. High-impact sectors by region

A more detailed comparison of the share of each footprint attributable to each sector between regions shows some of the underlying patterns of consumption driving these outcomes (see Fig. 5). For example, looking at greenhouse gas footprints, South Asia and Sub-Saharan Africa both have a similar per capita footprint, however quite different high-impact sectors, with South Asia having a relatively high proportion of (presumably) dairy and grains and bulk crops, but also a relatively high proportion for electricity, reflecting dietary preferences and a high dependency on coal for electricity. Sub-Saharan Africa has a high proportion of footprint across all animal-based food types, but a relatively low proportion attributable to electricity, reflecting low electricity provision in the area.

East Asia has nearly 30 % of their carbon footprint attributable to commercial buildings and infrastructure, while Europe shows a high gas supply footprint, and North America has a relatively low proportion of

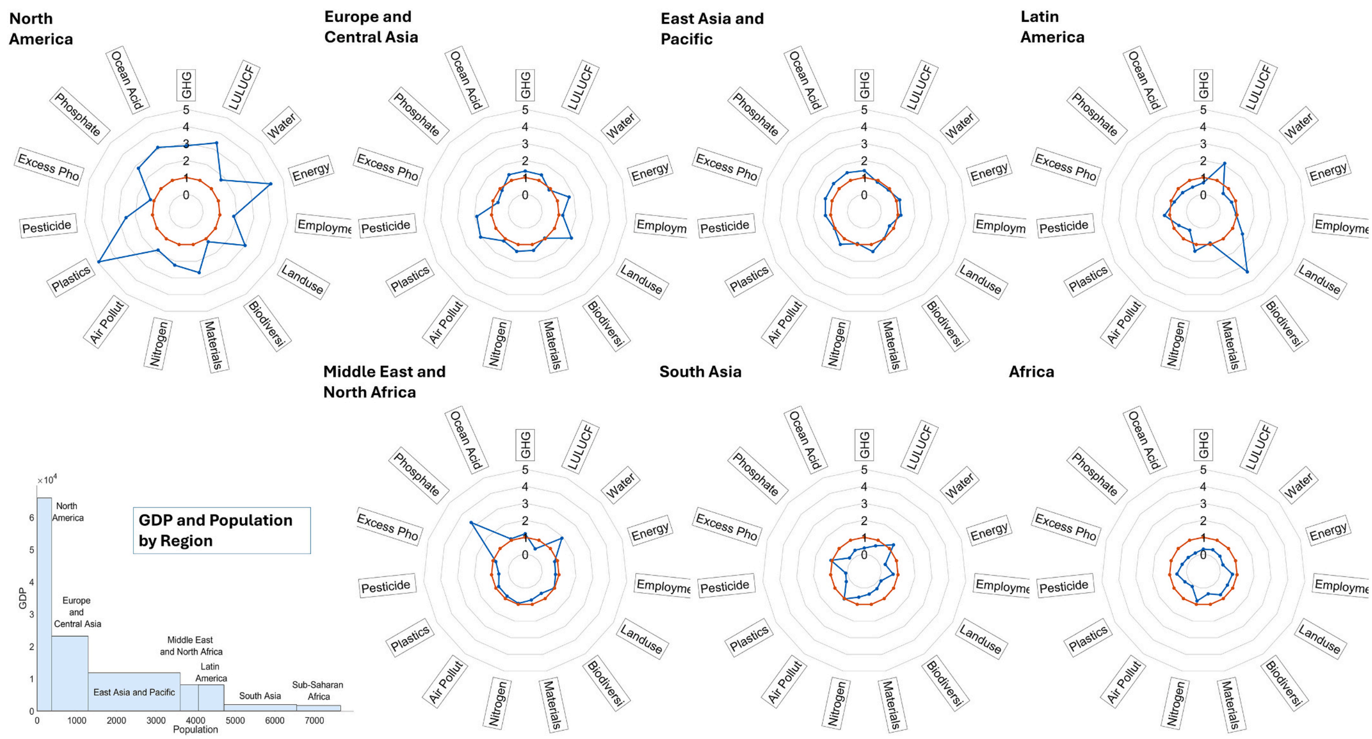

Fig. 4. Regional per capita footprints (blue) relative to global average per capita footprint (red, normalised to 1), for each indicator. GDP and population by region show GDP per capita (USD) vs population (millions of people). GDP = Gross domestic product, GHG = Greenhouse Gases (excluding LULUCF), LULUCF = GHG from land use, land use change and forestry.

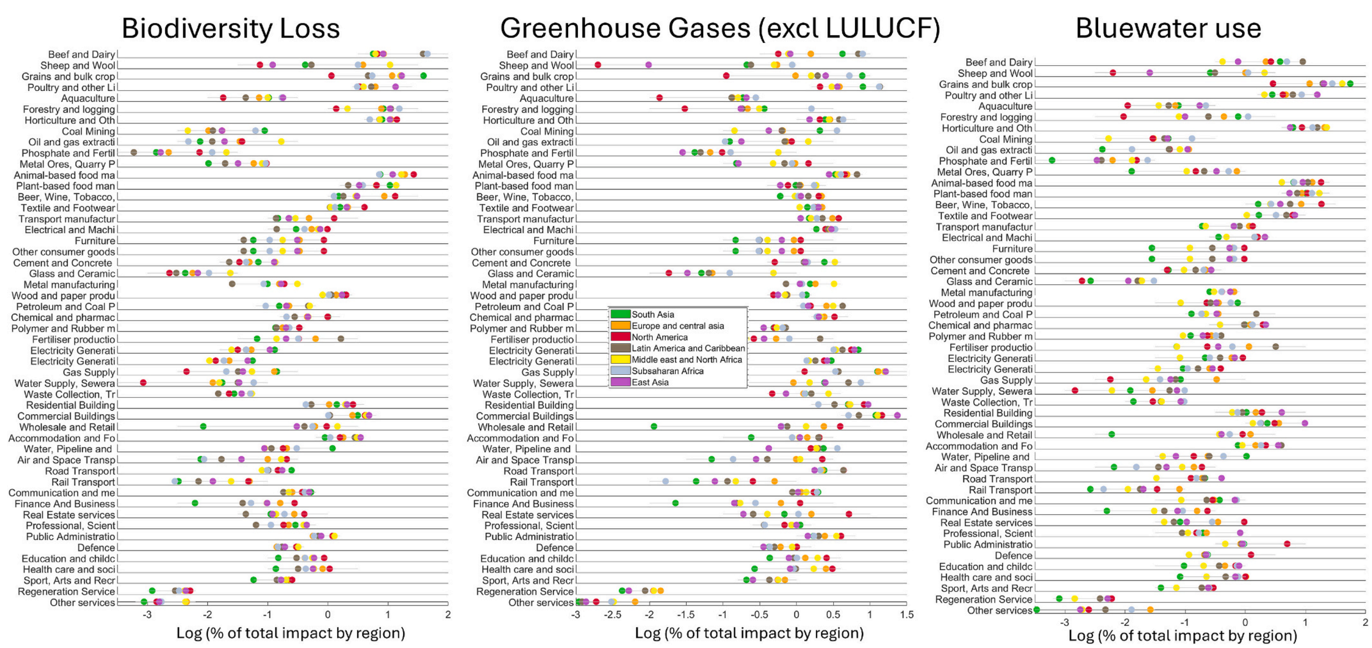

Fig. 5. Percentage of regional footprint by sector for selected indicators. Scale is logarithmic – 0 = 1 %, 1 = 10 %, 2 = 100 % etc.

footprint attached to raw food products and gas supply but a relatively high proportion attributable to most service sectors, especially finance and business and real estate services.

Low-income regions show a relatively high share of impacts from the food sector, suggesting that this is the most necessary area of spending and the least likely to be able to achieve net zero, while high-income areas have a relatively low level of impact, suggesting that there may also be a ceiling on the total amount of food that can be consumed.

A sectoral breakdown of footprints for each region, and the share of footprint for other indicators are shown in Sections S3 and S4 of the Supplementary Information.

3.6. Investigating indicators: wealth vs intensity

A comparison of footprint intensity (total footprint vs total final demand) and per capita final demand for each region shows that as average expenditure increases the impact intensity of each dollar spent decreases for all indicators (see Fig. 6). This result is despite purchase price parity being used in regional comparisons. Simultaneously the per capita footprint also increases with per capita final demand spend across all indicators, also reflecting previously understood relationships. The average slope shows that the per capita footprint increases more quickly than the footprint intensity declines, indicating that increasing efficiencies of resource use are generally being outpaced by increasing spending, as has previously been demonstrated for greenhouse gases (Lamb et al., 2021; Zheng et al., 2023). Biodiversity loss shows the least increase in per capita footprint with wealth, and it may be worth investigating this relationship further to examine the relationship across a broader range of regions and timeframes.

3.7. Environmental impact patterns: similarity of indicators

The similarity of emission patterns has been investigated using a modified Euclidean distance approach. This enables the identification of sectors and indicators that have similar patterns of impacts (see Fig. 7).

Indicator comparisons show two strongly correlated clusters, being firstly GHG, LULUCF, air pollution and ocean acidification ("fossil fuel driven"); and secondly land use, biodiversity loss, water use, and nitrogen ("agriculture driven").

This correlation shows that the sectors that are driving high and low percentages of impacts are more similar for these drivers than others – e.g. "fossil fuel driven" indicators show a high impact from residential and commercial buildings and gas supply, while "agriculture driven" drivers show high impacts from agricultural products, especially grains and bulk crops, and food manufacturing. This suggests that the same fundamental processes are implicated in generating multiple different impacts, as identified here, and therefore multiple environmental benefits can be gained by focusing on just a few sectors. Other indicators, however, will need a unique approach, with phosphate mined, pesticide use and plastics, for example, not aligning well with any other indicators.

Previous work has identified interactions between planetary boundaries as either biophysically mediated (i.e. occurring due to impacts between earth systems) or human-mediated (caused by either parallel processes, such as a single system impacting multiple planetary boundaries, or reactive, where the human response to impacts from one system impact another) (Lade et al., 2020). The economic basis of the analysis here assists in identifying human-mediated parallel processes.

This work only partially supports the analysis of human parallel processes in Lade et al., 2020. A strong relationship between carbon dioxide emissions affecting climate change and ocean acidification is clearly supported. Several relationships with a low correlation in Lade et al., (such as the energy sector driving both carbon dioxide and water use, climate change impacts from energy use due to nutrient production, and carbon emissions from freshwater use) are not significant here, however cluster analysis does locate water supply and waste management impacts as more similar to the energy system than the built environment.

The results shown here support a more nuanced understanding of land clearing for agriculture than is posited by Lade et al., with water and nutrient use being more closely associated with the grains and bulk crops (which feed into poultry and manufactured food products), while land clearing itself is more strongly associated with beef and dairy farming.

The strong association between air pollution and greenhouse emissions shown here is not considered in Lade et al.

3.8. Environmental impact patterns: Similarity of sectors

Sector comparisons (see S2 of Supplementary Information) and cluster analysis showed several highly correlated sectors, notably energy generation (fossil fuels and renewables), and the built environment (residential buildings and commercial buildings and civil engineering), with 1 % and 3 % distance respectively. This indicates that the relative impact of each impact driver is highly similar in each sector, although not necessarily of the same magnitude – e.g. high land and water impacts, but a lower proportion of plastic impacts.

Overall, six main clusters with similar impact patterns could be seen, with two "meta sectors" – 'food, forestry and textiles' (consisting of 2 sub-clusters of beef sheep and forestry, and grains chicken and processed food) and the 'built environment and manufactured products', representing the majority of impacts across most indicators (see Fig. 8). Further clusters identified were 'trade and transport' and the energy system, split into 2 sub-clusters of mining and processing, and utilities.

Note that this does not include direct impacts by end users (households and governments), likely to be high for the energy system nor a split of the environmental footprint of the capital used to produce goods and services (Södersten et al., 2020).

3.9. Footprints informing the "transformations" and "provisioning" agendas

The "six transformations" agenda identifies clusters of SDG interventions that aid government policies, broadly characterised in Table 2 (Allen et al., 2024; Sachs et al., 2019). Similarly, Earth4All have identified Five turnarounds for a Giant Leap (Randers et al., 2023), and also suggesting directly targeting population growth, a key component of the i = PAT impact relationship (Alcott, 2010). The growing call for a degrowth approach has similarly been targeting a sufficiency agenda, with similar target areas (Sandberg, 2021). The "provisioning systems" approach "groups together related ecological, technological, institutional and social elements that interact to transform natural resources to satisfy foreseen human needs" (Bruyninckx et al., 2024). These approaches aim to facilitate the profound changes required to meet SDG and planetary boundary goals by simplifying the many competing objectives and focusing the discussion on critical actions to be taken at a high level.

A comparison to the high-impact footprint clusters identified in Section 3.5 (see Table 2). shows that there is good support for food and energy pillars of sustainability transformations.

Food system change is included in all transformation agendas, although some variations in emphasis can be seen, with a focus on improving living standards (Six transformations/Five turnarounds) or reducing overconsumption (Sufficiency transitions).

The high impacts associated with food consumption here support this focus. Our results show that while a switch from animal-based to plant-based food would reduce impact intensity, plant-based consumption still requires consideration of water, nutrients, pesticides and land use. Food system transformations would benefit from explicitly considering the need to reduce land use intensity by rewilding and regenerating high biodiversity value lands currently being used for agricultural purposes (Gerten et al., 2020).

The energy system is targeted across 3 of 4 transformation agendas, and data supports this with a moderate level of footprint impact, but a high level of production impact. This sector is the most critical for climate change impacts.

The built environment footprint cluster however is not reflected at all in the Five Turnarounds agenda, while the Six Transformations agenda does not consider the fossil fuel and materials use of this sector, which may undermine the outcomes desired given they are the highest footprint sector identified here. The focus on housing in the "sufficiency transitions" approach omits the high footprints being seen here for commercial buildings and civil engineering infrastructure.

Unlike the food, energy and service sectors, which need replenishing frequently, built environment sector products are long-lasting and therefore fundamentally different strategies can be applied to this sector. The maintenance requirements of the built environment, which are well understood to be significantly more expensive than new builds

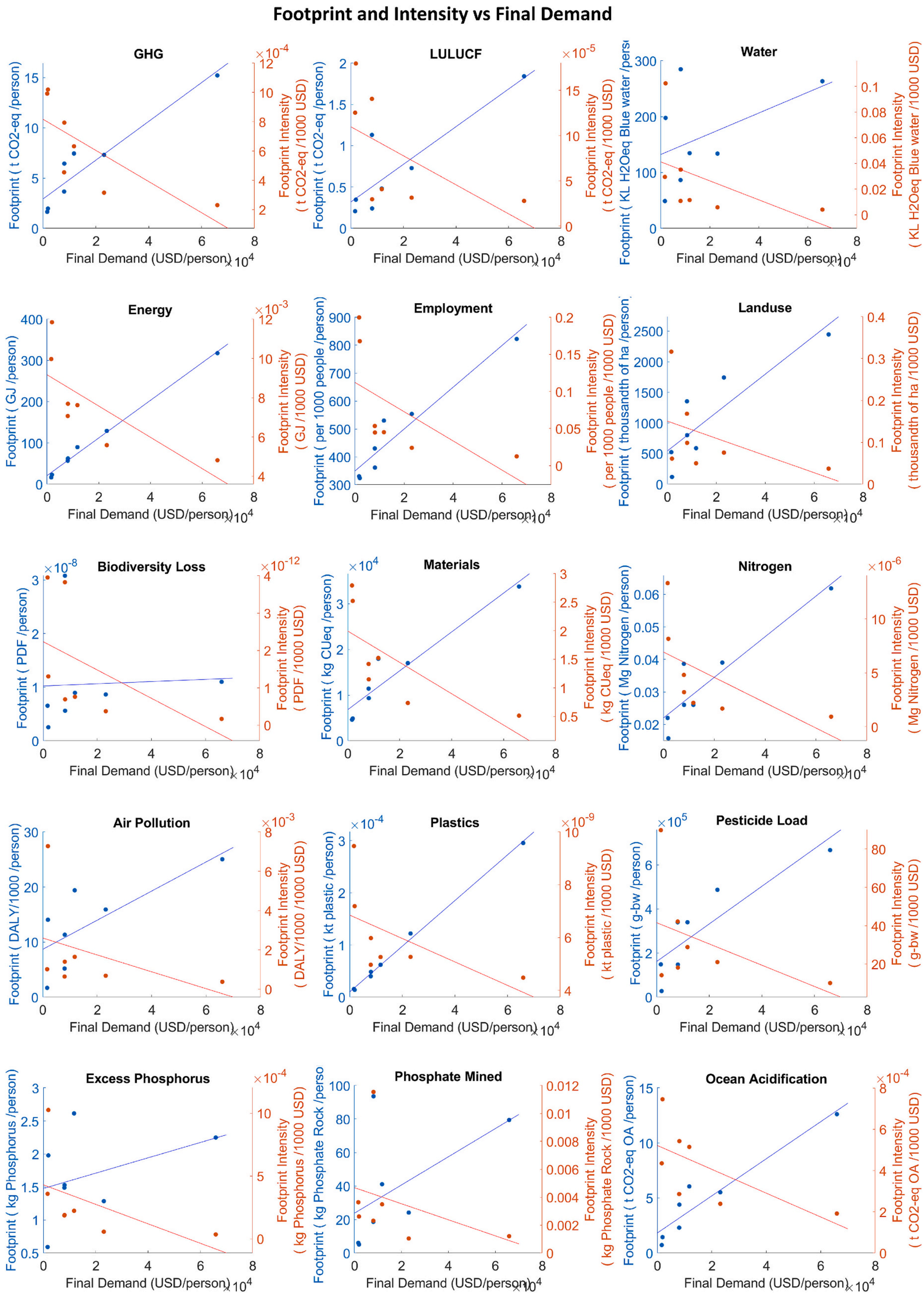

Fig. 6. Footprint and Intensity vs Final Demand comparison by world regions.

GHG	49%	123%	64%	69%	119%	135%	64%	109%	32%	76%	148%	144%	115%	27%
	LULUCF	102%	67%	63%	105%	111%	62%	90%	43%	85%	126%	134%	115%	56%
		Water	147%	120%	96%	73%	110%	48%	120%	136%	83%	49%	155%	143%
			Energy	80%	135%	152%	74%	135%	67%	85%	171%	168%	116%	63%
				Employment	122%	132%	78%	108%	60%	55%	143%	143%	121%	75%
					Landuse	49%	107%	67%	122%	135%	120%	117%	153%	137%
						Biodiversity Loss	120%	52%	136%	152%	91%	96%	164%	154%
							Materials	100%	61%	75%	136%	133%	98%	74%
								Nitrogen	107%	124%	77%	82%	150%	129%
									Air Pollution	65%	145%	141%	105%	30%
										Plastics	160%	147%	105%	68%
											Pesticide Load	88%	173%	166%
												Excess Phosphor	170%	163%
													Phosphate Mined	107%
														Ocean Acidificati

Fig. 7. Similarity between indicators using a modified Euclidean distance formula. Lower distances indicate greater similarity, shown by a stronger green colouration.

(Hauashdh et al., 2022), and ongoing climate adaptation needs, including the possible abandonment of settlements (Hauer et al., 2020; Mach and Siders, 2021), further suggest that this sector may benefit from a radical rethink in the approach taken to meet needs for transport and shelter, with potential for significant wastage of resources under a business-as-usual approach. Known local and forecast global population peaks may represent an opportunity to target a move from the expansion of the built environment sector to a maintenance mode, with associated impact reduction that would otherwise result from building unneeded and stranded infrastructure (He et al., 2023; Silverman, 2020). The global transformation programme itself is likely to require a significant infrastructure build, with cement emissions a remnant issue even in the event of a 100 % renewable energy system (Cavalett et al., 2024). High employment footprints for the built environment will further complicate any efforts to reduce consumption in this space.

The transformation agendas do not explicitly consider novel entities, which represents a significant blind spot considering that this is a large risk factor for the development of future planetary boundary-threatening processes (e.g. ozone depletion, fossil fuels, air pollution, and nitrogen fixation can be seen as novel entity issues).

3.10. Limitations of the study

While every effort has been made to estimate and allocate impacts as accurately as possible, of necessity a study of this breadth and depth relies on a high degree of summation and implication. Results are likely to hold at a high level, however outcomes are a best estimate rather than an exact representation of the underlying processes, and as such should be taken as a starting point for further exploration rather than assumed accurate in every detail.

Limitations, assumptions and uncertainty of input-output analysis are discussed in Section S1.3.

Indicators and data used are limited by the availability of relevant high-quality information. Some of these choices need to be understood when interpreting the results presented.

Examples include:

- indicators chosen approximate drivers of impacts however may only partially represent planetary boundary drivers (e.g. plastic use does not directly determine plastic waste released to the environment, biodiversity considers land-based biodiversity only, blue water use does not consider green water use, human-driven air pollution does not consider e.g. dust storms);
- local environmental conditions (in time and space) will determine the actual level of impact of some planetary boundary drivers, however all uses are assumed to have the same impact here (e.g. water use vs water stress, nitrogen use vs excess nitrogen applied to land, land use vs use of boreal and tropical forest land).
- This work follows the standard economic convention of using gross domestic product (GDP) data that excludes the shadow economy (estimated at 30 % of economic transactions in some economies), and household labour, which represents substantially more, resulting in impacts from these sectors being allocated to other formal economy actors.
- underlying external data used is of itself a best estimate, and may not include all relevant impacts (e.g. greenhouse gas data excludes air and shipping bunker fuel as it is not allocated to any country);
- data does not include the impact of pressures from one boundary on other boundaries (e.g. climate change impacts on biodiversity);

4. Conclusion

These results show that some of the patterns already seen for climate change are repeated across other planetary boundaries – high expenditure regions have the highest per capita footprints despite decreasing intensity of impact per dollar; a few economic sectors have an outsize impact across most indicators. Unlike climate change, which is mostly driven by the energy sector, for other boundaries the highest impacts are ultimately caused by the consumption of goods and services from two major provisioning systems (food, forestry and textiles, and the built environment).

While the built environment product impacts are generally caused indirectly in other sectors, especially the energy system, underpinned by high expenditure, the food system impacts are more likely to be caused by the food industry itself and have a high impact intensity per dollar

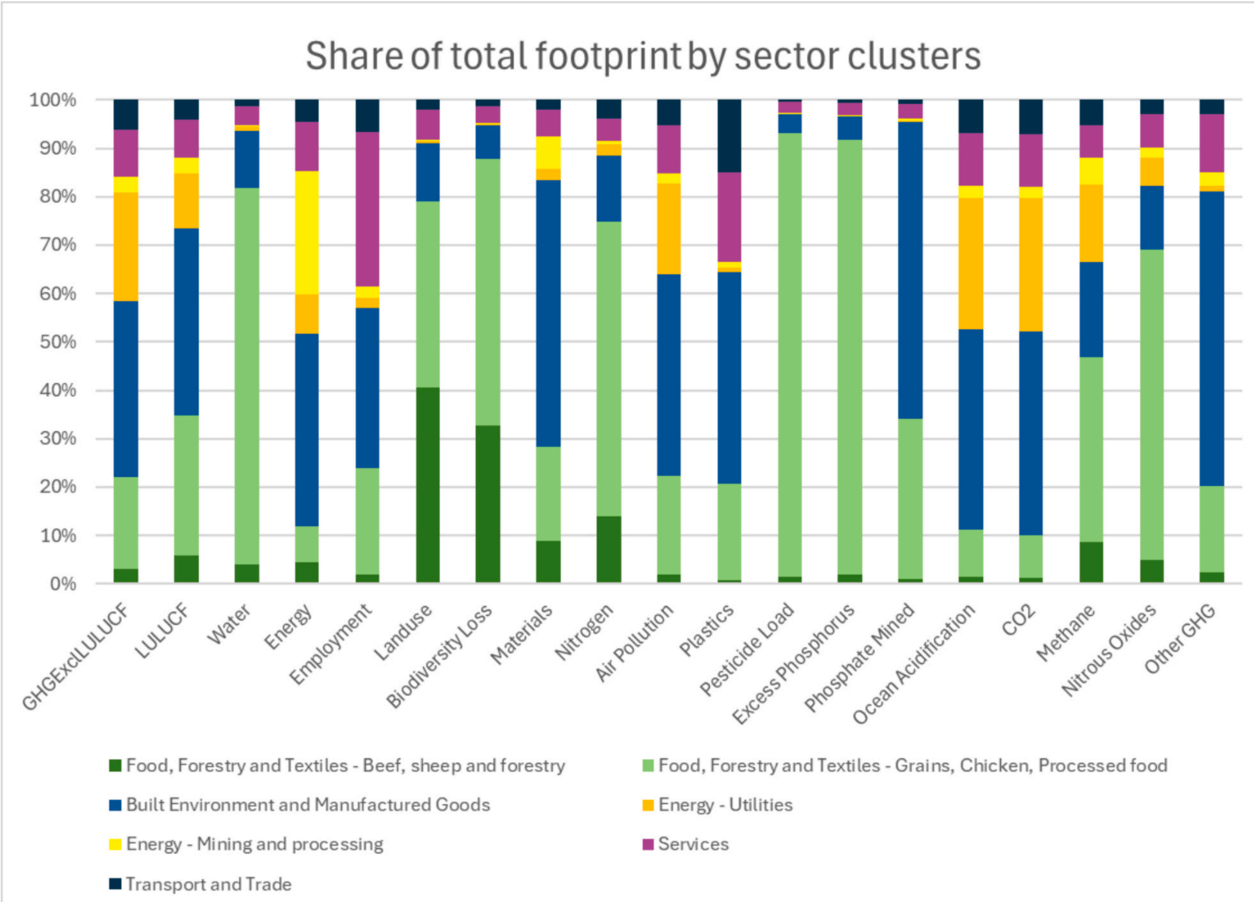

Fig. 8. Share of total footprint by sector clusters. This excludes direct emissions and impacts from households and government. Food, Forestry and Textiles = *Agriculture, Forestry and wood products, Food Manufacturing, Textile Manufacturing, Accommodation and Food Services, Regeneration Services*; Built Environment = *Materials and consumer goods manufacturing (excl wood), Ore and Quarry mining, Residential and Commercial Buildings;* Energy = *Coal, Oil and Gas mining and manufacturing, Electricity Generation, Gas Supply, Water Supply, Waste Management*; Services = *public services, finance, business and media, education, health and social services*; Transport and Trade = *Wholesale and retail trade, water, air, road and rail transport.*

spent. A further contrast is that the built environment provides long-lasting products, while the food system needs to be continually replenished, suggesting that very different strategies will be needed for these two sectors.

These results somewhat support the transformation and provisioning agendas being advanced in broad terms but provide an important check on the focus on residential buildings rather than the impact of commercial buildings and infrastructure in the built environment. They also demonstrate a gap in consideration of impacts from service sectors in some models.

Analysis of similarities between sectors show some new corollaries – textiles can be considered as part of the food system, while wholesale and retail trade align with transport services. Plastics footprints are particularly high in built environment products, as well as trade and textiles.

Energy system products demonstrated only a moderate overall impact on footprints, however production-based emissions for several indicators are high. While the central 2023 United Nations Climate Change Conference (COP28) goal of tripling renewables by 2030 will have important benefits for climate change, air pollution, and ocean acidification, most other planetary boundaries are predominantly impacted by the land use implications of the global food and textiles systems. Food systems need to reduce their impacts while simultaneously feeding an expanding human population on a timely basis, in an increasingly hostile and unpredictable climate system.

Policies that support this include reducing animal-based food consumption and rewilding environmental lands, with regeneration of the Amazon forest identified as especially critical to stabilising the global environment. Plant-based agriculture needs to be better managed to reduce water and nutrient consumption, reduce pesticide use, and support biodiversity.

Novel entities and chemical pollution are widespread and often only loosely controlled and understood. An improved approval system should be in place so that harmful substances are not released to the environment, and cleanup plans are in place globally for harmful chemicals already released. Chemical stewardship requirements would compel companies developing and releasing these substances to take responsibility for end-of-life impacts too complex for communities to manage themselves and ensure that the costs are borne by the company responsible for creating and releasing them.

Planetary boundary indicators offer a compelling vision of overall environmental sustainability and a way of maintaining a stable environment. A narrow focus on key indicators like greenhouse gases, however, can offer a false promise of easy solutions that fails to consider the many synergies and trade-offs involved.

Given these trade-offs, reducing unnecessary consumption and waste represents a conservative approach that will benefit all planetary boundaries and is less likely to have unwanted environmental side-effects than the more experimental consume and then drawdown/regenerate approaches such as that proposed for greenhouse gases.

With increased globalisation, wealthy citizens increasingly aspire to a picture-perfect lifestyle so frequently conveyed in the media but may

Table 2
Relationship between Transformation programs and footprint clusters (grey shading indicates objectives without corollary in footprint clusters).

Footprint cluster (Impact level)	Provisioning System (Bruyninckx et al., 2024)	Sachs – Six transformations for SDGs(Sachs et al., 2019)	Earth for All – Five turnarounds for a Giant Leap (Randers et al., 2023)	Sandberg – Sufficiency Transitions (Sandberg, 2021)	Principle Target Actions proposed	Key indicators (where primary impacting sector)
Food, Forestry and Textiles (High)	Food and nutrition	Sustainable land use, oceans, and food systems	Food System	Nutrition	Food waste, plant-based diet, regenerative agriculture	Water, methane, nitrous oxides, land use, biodiversity, nitrogen, pesticide and excess phosphorus.
Energy (Medium)	Energy	Energy access, decarbonization, clean air and water	Energy System	N/A	Fossil free energy, energy efficiency, electrification,	Energy, CO2, ocean acidification
Built Environment and Manufactured Products (High)	Built Environment	Transport, water and sanitation infrastructure and urban resilience	N/A	Housing	Compact settlements, utility provision, reduced living space	Air pollution, LULUCF, CO2, ocean acidification; materials, phosphate mined; plastics
Services excl. Transport (Medium)	N/A	Education, work, innovation, income Health	Poverty	N/A	N/A	Employment
Trade and Transport Services (Low)	Mobility	N/A	N/A	Mobility	Reduce air travel, car sharing	N/A
N/A		Digital technologies and infrastructure	Empowering women	Miscellaneous Consumption	N/A	N/A
N/A			Inequality	N/A		N/A

not be aware that every single purchase of goods or services has a long supply chain with multiple impacts, often in areas remote from the point of consumption, which are suffering ongoing escalating crises caused by environmental degradation. This work aims to bridge this gap of understanding and make clear the full cost of consumption, in the context of the planetary boundary framework. The availability of footprint data calculated here for a broad range of environmental impacts at a global level enables comparison of alternatives and prioritisation of strategies to create a liveable planet.

CRediT authorship contribution statement

Kylie Goodwin: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mengyu Li:** Writing – review & editing, Data curation. **Thomas Wiedmann:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.10.009.

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