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Implementing the Material Footprint to measure progress towards SDGs 8 and 12

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Abstract

Sustainable development depends on decoupling economic growth from resource use. The material footprint indicator accounts for environmental pressure related to a country's final demand. It measures material use across global supply-chain networks linking production and consumption. For this reason, it has been used as an indicator for two Sustainable Development Goals (SDGs) 8.4 'resource efficiency improvements' and 12.2 'sustainable management of natural resources. Currently, no reporting facility exists that provides global, detailed, and timely information on countries' material footprints. We present a new collaborative research platform, based on multi-regional input-output analysis, that enables countries to regularly produce, update and report detailed global material footprint accounts, and monitor progress towards SDGs 8.4 and 12.2. We show that the global material footprint has quadrupled since 1970 mainly driven by emerging economies in the Asia-Pacific region, but with an indication of plateauing since 2014. Capital investments increasingly dominate over household consumption as the main driver. At current trends, absolute decoupling is unlikely to occur over the next few decades. The new collaborative research platform allows to elevate the material footprint to Tier-I status in the SDG indicator framework and paves the way to broaden application of the platform to other environmental footprint indicators.

Introduction

The Sustainable Development Goals (SDGs) were developed as part of the United Nations' 2030 Agenda for Sustainable Development[1], placing strong emphasis on an integrated approach to reporting on each of the 17 SDGs across economic, social, and environmental dimensions. Within this broad and interrelated framework, the high-level goals tend to be general, and thus it is difficult to quantify them using meaningful metrics. However, at the individual target level quantitative indicators can be defined for monitoring progress towards the respective targets.

Harmonising economic and environmental objectives is a core ambition of the SDGs and best expressed in SDG 12, which aims for sustainable consumption and production. The close link between the economy and natural resource use, and the need to decouple economic development and quality of life from resource use, are also expressed in SDG 8, which requires countries to progressively improve the resource efficiency of production and consumption. The statistical community has agreed on a large set of indicators to monitor progress towards achieving SDG objectives and has adopted the material footprint (MF) – a consumption-based measure of material use – as a core indicator for SDG targets 8.4 and 12.2. The MF measures the full contribution of a country's consumption, across the entire global supply-chain network, on the extraction and use of primary materials[2]. It provides a direct link between the harvesting of biomass and extraction of resources from the ground (minerals, metal ores and fossil fuels) and the final goods and services ultimately consumed elsewhere (for details see SI 1). In a globalised economy with increasingly complex supply-chain networks, understanding this link is crucial for designing effective policies for resource efficiency, such as consumption-based climate mitigation policies. A supply-chain wide indicator such as the MF is also robust against outsourcing, i.e., countries cannot reduce their material use by simply relocating material-intensive production stages to other countries [3-5].

The United Nations (UN) has established an inter-agency expert group, which has classified all indicators used in the context of the SDGs into three tiers[6]. Currently, the MF indicator features in Tier II, a status where the indicator is conceptually clear and based on an established methodology, but for which data is not yet regularly produced. To achieve Tier-I status, MF data would need be regularly produced by '*at least 50% of countries and of the population in every world region where the indicator is relevant*'[7].

The first comprehensive, global assessment of MFs was based on a multi-region input-output (MRIO) analysis of 35 material categories[2], using the Eora database[8,9]. The MRIO approach already provides the MF with an established methodology, governed by United Nations standards[10] that are adhered to by national statistical bureaux. Since then, several updates and methodological advances have been presented, mostly aimed at comparing and refining the methods, and increasing our knowledge about trends, drivers, trade exchanges and the global distribution of resource use. Some studies have focused on comparing Eora with other MRIO databases (including GTAP[11], WIOD[12,13] and EXIOBASE[14-17]), or comparing MRIO analysis with other methods, for example based on life-cycle assessment, physical input-output analysis or hybrid methods[18-21]. Other studies have employed decomposition analysis to assess changes over time[13,14] or international inequalities[22,23]. More recently, the role of capital investment in driving raw material consumption was investigated in a global study[24], and national studies on the US[25] and China[26,27]. All studies confirmed that substantial amounts of mineral materials are embodied in capital infrastructure. MFs, especially those of a rapid renewable energy expansion, and the possibility of their decoupling from economic growth, have recently become topical in critiques of the IPCC's technology-focused mitigation pathways[28-31].

Despite these advances, no study has presented global MF trends more recent than 2011. Also, no MF database currently exists that reflects timely and detailed material supply chains, as a continuous time series, and for many individual countries. Most existing databases are either not continuous, not timely, or too aggregated. The latter problem leads to material exchanges that are implausible, or to incorrect attribution that occurs for example for agricultural products where these are aggregated across domestic and exported crops[32-34]. In addition, there is no MF database that offers quantitative measures of information reliability to support decision-making. Finally, no facility exists to enable countries to regularly produce, update and report MF data, and to monitor their progress towards SDGs 8.4 and 12.2.

Here we address these knowledge gaps by providing a framework that allows raising the MF to Tier-I status, featuring a regularly updated and detailed data foundation that is readily accessible to decision-makers in many countries. This is achieved through two innovations. First, we develop a computational collaborative research platform that harnesses comprehensive information on domestic and international trade, and material extraction, for each country. In unison with the established methodology of MRIO analysis, these two datasets combine into a powerful capability for tracing materials embodied in a multitude of commodities, starting from raw materials extraction and conversion into products, proceeding via domestic and international trade, and ending with final consumer items. Second, we utilise an online web portal that allows decision-makers to access a wealth of information for analysing, reporting and monitoring MFs of their countries, and to submit their own data. This MF framework cannot be provided by a single country, because no single country can produce a footprint account without domestic extraction data from every other country and representation of industry-to-industry relationships among countries (i.e. an MRIO database). It therefore requires a global agent – such as the UN – to establish and host an MF framework. This work has been realised by a collaboration including members of the International Resource Panel (IRP) and the Life Cycle Initiative and its Sustainable Consumption and Production Hotspot Analysis Tool (SCP-HAT, scp-hat.lifecycleinitiative.org), both UNEP initiatives. As a proof-of-utility of the new MF framework, we present selected trends of the MF indicator across the past five decades as well as results from a detailed global assessment of decoupling material use and economic growth.

Results

To demonstrate the utility of the new MRIO and MF databases for supporting the monitoring and reporting of progress towards SDG targets 8.4 and 12.2, we present several new findings. We start with the first 50-year time series depiction of the overall material balance (see Methods), where domestic material extraction (DE) equals the material footprint (MF) plus the materials embodied in exports (Raw Material Equivalents, RME_{ex}) minus those embodied in imports (RME_{im}), then extract top-ranking importers, exporters, and trade routes of embodied materials, and finally offer insights into the drivers of MFs, and evidence for the decoupling of material use from economic growth.

Material footprint trends

Between 1970 and 2019, global material extraction ('domestic extraction', *DE*) increased from 32 to 95 Gigatonnes per year (Gt, Fig. 1). This increase was predominantly carried by non-metallic construction materials, and mainly by upper-middle income countries in the Asia-Pacific region (left column). During the same period, materials embodied in the international trade of products (centre column) grew from 11 to 37 Gt. This trend was mostly facilitated by construction materials in the Asia-Pacific region, which is currently the main exporter of materials embodied in products, as these materials are used to build new infrastructure needed for production and processing. Prior to 2000, the main importers of these materials were situated in Europe and the Americas, but these have been overtaken by Asian nations such as China, Japan, India, South Korea, and Indonesia. The product breakdown (4^{th} row) shows the transition from extracted primary commodities (biomass and mine/quarry outputs; left panel), to consumer goods (food, energy, vehicles, houses; right panel). The breakdown into final demand (5^{th} row) shows that initially households were the main agents driving the increase in global MF. However, since 2000, the development of upper-middle income countries (mainly in the Asia-Pacific region) has spurred a boost in investment in capital goods that is clearly reflected in the increasing role of non-metallic minerals used for construction and manufacturing of durables[27].

China plays an important role in all of these trends. Between 1990 and 2019, its MF increased from 5 to 32 Gt, currently representing 60% of the Asia-Pacific region. The main driver was construction of public infrastructure, making up three quarters of China's MF[26]. Remarkably, its status as significant net materials exporter started reversing from 2009 onwards, caused in part by burgeoning imports of iron ore, crude oil and coal, to supply its steel mills, refineries and power stations. In addition, between 2005 and 2015, Chinese consumers' expenditure on imported cars, meat and international tourism increased 5-, 10- and 10-fold, respectively (SI 4).

A salient feature of global MF in recent years is that its growth has slowed markedly since 2014. Global year-on-year growth rates averaging only 0.9% p.a. between 2014 and 2019, less than one third of the year-on-year rates experienced between 2000 and 2013 (which averaged 3.2%). The major driver of this trend is declining DE growth rates in China. By 2013 China accounted for one third of global DE, and for 57% of the growth in global DE tonnage between 2000 and 2013. China's change from rapid year-on-year increases in DE (6.4% between 2000 and 2013), to slight contraction (–0.5% from 2014 to 2019), explains most of the reduction in observed total global MF growth. Ongoing reductions in China's DE would be consistent with strategies to move into more high-tech driven manufacturing areas, as flagged, for example, in the 'Made in China 2025' strategic plan released in 2015.

(INSERT FIGURE 1)

Fig. 1: Evolution of the world's MF between 1970 and 2019. All figures in Gt.

Left column: domestic extraction DE; centre column: raw material equivalents of imports and exports RME_{im} and RME_{ex}; right column: material footprint MF. Top row: Breakdowns by four aggregate material types (SI 2.4), 2nd row by seven broad regions (SI 2.5), 3rd row by regional income groups (SI 2.6), 4th row by broad product classes (SI 2.7), bottom row by final demand destinations. The bottom left panel is empty because extraction by final users (for example subsistence agriculture) is negligible. The envelopes of net trade by commodity (4th row) are different, because net exports are shown at extraction (as all other trade panels), while net imports are shown at final sale (compare Eq. 6). The fact that the remaining envelopes of RME_{im} and RME_{ex} are equal in absolute values reflects that the global sums over exports and imports are equal: $\sum_r RME_{\text{ex}}^r = \sum_r RME_{\text{im}}^r$, because whatever gets exported gets imported somewhere else. For the same reason, the global sums of DE and MF are equal: $\sum_r DE^r = \sum_r MF^r + RME_{\text{ex}}^r - RME_{\text{im}}^r = \sum_r MF^r$, because whatever gets extracted, gets finally consumed somewhere else.

Trade balances

The evolution of material trade by region (centre panel 2nd row in Fig. 1) can be further disaggregated to identify top-ranking net importers and net exporters of embodied materials (Fig. 2). As expected, high-income countries (USA, Japan, the EU) are net importers of a relatively evenly distributed mix across the main four material types, because they import mainly composite manufactured goods. In contrast, net exporters are often developing or emerging economies, specialising in primary materials extraction. Brazil features large biomass embodied in its soybean and meat exports. Australia and Chile are significant exporters of metal ores and their derivatives. Russia, Kazakhstan, Saudi Arabia, Australia, South Africa, and Indonesia export primary fossil fuels. Note China's position as a significant importer after 2010, caused by major imports of iron ore, crude oil, coal, soybeans, meat, timber, pulp, palm oil and livestock products (SI 4).

(INSERT FIGURE 2)

Fig. 2: Selected top-ranking net importers and net exporters of embodied materials, $RME_{\text{im}}^r - RME_{\text{ex}}^r$, averaged over the periods 1990–1999 (top bar for each country), 2000–2009 (middle bar) and 2010–2019 (bottom bar), for four aggregate material types.

Material flows embodied in global trade

As the new MF database distinguishes 97 sectors in 164 regions (SI 2), it maps material flows onto $97 \times 164 = 15{,}908$ bilateral relationships. The resulting MRIO matrix – sized $15{,}908 \times 15{,}908 > 250$ million elements – is dense (i.e. non-sparse), meaning that every single sector in the global economy is connected through the flow of materials to all other sectors. A depiction of just the top 250 bilateral relationships of material flows embodied in traded products (out of a total of $15{,}908^2 \times 62 > 15$ billion) already connects every continent (Fig. 12 in SI 7.3).

A Structural Path Analysis at the detailed level of 62 material types (SI 7.1) reveals that these international flows are quite varied, and include straw embodied in US cereals for China, Russian and Norwegian oil and gas for Germany, Australian coal for the UK, Iranian oil for UAE stockpiles, and Azeri natural gas for Georgia. China is the recipient of important international material flows such as Brazilian soybeans, copper from the Lao PDR, natural gas from Uzbekistan, Australian gold, and South African ruminant meat. Important domestic material flows (SI 7.2) are often for local food production, such as fodder residues and grazed biomass from livestock (Brazil: ruminants, India: poultry, China and Indonesia: pigs), and straw and bagasse from crops (India: rice and sugar cane, Russia: wheat, USA: maize). Some metal ores and fuels are extracted for temporary stockpiling (USA: gold, Iraq, Iran and UAE: oil, Australia: coal, Lao PDR: copper).

Significant differences can be observed in the shares of global material extraction embodied in international trade between the different material groups: for biomass and non-metallic minerals these shares are low at only around 30%, indicating that these materials are used predominantly for domestic purposes. For fossil fuels and metal ores, these shares are higher at around 55% and 70%, respectively (see SI 5, reflecting the concentration of these materials in a few world regions).

Decoupling of material use and economic growth

Previous assessments of the MF of nations[2,35,36] did not find any evidence for the decoupling of material use and economic growth. We revisit the question here, using a new dataset up to the year 2019. Subjecting the time series panel data of per-capita MFs to a multiple regression against explanatory variables of per-capita GDP, material intensity, and time (see Methods), we are able to calculate the GDP elasticity η of the world-average MF, and detect relative decoupling ($0 < \eta \leq 1$) and absolute decoupling ($\eta \leq 0$).

Tab. 1: Results of an OLS regression of per-capita MFs as a function of per-capita GDP, material intensity, and time. Stars denote statistical significance obtained from a Student's *t*-test, and delineate 99% (***), 95% (**), and 90% (*) levels of confidence. The regression parameters are the GDP elasticity $\eta(x) = \frac{\mathrm{d}F/F}{\mathrm{d}x/x} = \eta_0 + \theta x[\ln(x) + 1]$ (see Eq. 9), the material intensity coefficient $\rho = \frac{\mathrm{d}F}{\mathrm{d}q}$, and the temporal derivative $\tau = \frac{\mathrm{d}F}{\mathrm{d}t} = \dot{F}$.

Variable	Biomass	Fossil fuels	Metal ores	Non-metallic minerals
η_0	0.37 ***	0.98 ***	0.81 ***	0.96 ***
$\theta \times 10^6$	-0.62 ***	-0.74 ***	-0.84 ***	-1.32 ***
ϱ	-0.03 ***	0.25 ***	0.17 ***	0.32 **
τ	-0.02 ***	-0.03 ***	-0.01 ***	-0.01 ***
$\ln(k)$	-1.22 ***	-7.62 ***	-6.63 ***	-6.58 ***
R^2	0.49	0.88	0.77	0.83

We find the GDP elasticity of the biomass footprint to be about 0.37, and between 0.8 and 1.0 for fossil fuels, metals and minerals (Fig. 3, Tab. 1, SI6, indicating clear relative decoupling from GDP for the biomass footprint. All elasticities are significantly larger than 0, meaning that there is no evidence of absolute decoupling in recent decades. For the metal ore footprint our results ($\eta_0 = 0.81$) agree with a recent study[37] that found in a panel analysis of 43 large economies that a 1% rise in GDP increases the metal ore footprint by 1.9%, but only if GDP is measured in constant purchasing power parities (SI 9).

A new finding is how GDP elasticity changes with GDP, which has previously not been reported[2]. Here, we find that all θ coefficients are negative, indicating that elasticities are decreasing towards larger per-capita GDP. However, these coefficients are small, so that elasticities would remain positive even if world-average per-capita GDP increased to well beyond US$40,000 (regression curves in Fig. 3 and SI 6). At the post-2000 GDP growth rate, this would take more than 50 years. We experimented with weighted-least-squares formulations using different weights (SI 6.1–6.2), and with fixed-effects models (SI 6.3–6.4), but none of these yielded any indication of elasticities decreasing to below zero for per-capita GDPs close to the current world average of about US$11,000. Therefore, widespread near-future absolute decoupling appears unlikely. Despite the material intensity of production having decreased in recent decades (Fig. 3 right column), a corresponding mitigating effect of improved technology on footprints is not discernible (Fig. 3 left column), because of increasing affluence. Finally, we find a weak decreasing trend of MFs over time (Tab. 1 coefficients for τ), which must be ascribed to variables not included here.

(INSERT FIGURE 3)

Fig. 3: Per-capita MF (left column) and material intensity (right column) as a function of per-capita GDP, for the four aggregate material types (rows). Despite China's plateauing MF (see especially bottom left panel), absolute decoupling of all material types is not projected to occur until well beyond per-capita GDPs of US$40,000; most countries are currently situated in areas of increasing MF. Shown are data points for all 164 regions, and for 28 years. Circle shade represents year (pale = 1990, black = 2019), circle size represents population. The solid black lines in the left column graphs are the result of the multiple regression (Eq. 8).

Discussion

Successful implementation of the UN SDGs requires complementary and collective actions from policy makers, businesses, and civil society. To this end, data and monitoring tools are vital for understanding and informing policies and processes aimed at meeting the 2030 Agenda. The framework presented here constitutes an advance over the prior state-of-affairs, because it establishes a UNEP-overseen foundation for reporting and monitoring progress of countries world-wide towards the UN SDGs. Specifically, it advances our capability through a) timely, detailed and continuous data streams and a unified methodology, and b) a participatory reporting platform for tracking indicators in SDGs 8.4 and 12.2.

Data and unified methodology (Advance I)

We discuss the importance of headline indicators for reporting progress towards SDG objectives and highlight the improvements required for calculating MF at a standard that is sufficient for supporting policy formulation at country and sector levels. Use of data for regular monitoring is vital for ensuring that countries do not simply 'improve' by outsourcing impacts to other countries. SDG 12 specifically requires countries to implement sustainable production and consumption processes, which includes accounting for negative impacts of consumption. Such accounting needs to be goal-specific to enable assessment of countries' trajectories towards meeting the 2030 Agenda. In the context of SDGs 8 and 12, this study is the first to use a novel Virtual Laboratory to develop an MRIO database to operationalise MF. The unified input-output (IO) methodology supported by the UN[10] and business accounting[38] standards is especially suitable for informing policy making at various levels, paving the way for applying the global principles acquired in this work to future subnational and city-level SDG assessments.

Timeliness, detail, continuity and reliability (Advance II)

The data foundation developed in this work achieves a comprehensive representation of MFs by introducing a detailed sector structure tailored to material supply logic, by applying engineering knowledge to avoid implausible attributions, and by solving aggregation problems for biomass use of sectors that conflate domestic and export crops. In doing so we yield a convincing MF result, comparing favourably to previous assessments. The Global MRIO Laboratory offers the ability to automate the process of updating MRIO data as new information becomes available, thus ensuring timeliness and continuity. The Lab also encompasses processes for quality assurance of primary and derived information and provides the means to take reliability and uncertainty into consideration when making decisions.

Country participation (Advance III)

No single country can produce a footprint account without domestic extraction data from every other country and a detailed representation of trade relationships among countries (i.e. a global MRIO database). In other words, given that countries need access to global data, the new MRIO-MF framework presented in this study is the core of a global capability that will allow countries to undertake their own MF analysis by employing national domestic extraction satellite datasets and utilising the global MRIO and satellite data to capture impacts embodied in international trade of goods and services. This global capability will be hosted and maintained by the United Nations Environment Programme (UNEP), allowing countries to upload their domestic satellite accounts for domestic extraction of materials or greenhouse gas emissions, and calculate the associated footprints. UNEP's online tool SCP-HAT, which also features the material footprint indicator presented in this study, provides three modules to analyse hotspot areas of sustainable consumption and production. Module 3 will allow users to compare their own data on domestic material extraction or greenhouse gas emissions retrieved from their national sources with the Module's default data, and insert new data that will alter the results. Module 3 will serve as an entry point for high-quality national data, replacing estimated information from global databases. However, such an approach will require comprehensive quality assurance of the inserted data, as well as solving potential confidentiality issues.

Decision-making support

As a result, implementing the new MRIO-MF database in UNEP's SCP-HAT tool will create the conditions to lift the MF indicator to Tier I in the United Nations SDG indicator system, and to incorporate other footprint indicators (for example, greenhouse gas emissions, biodiversity, air pollutants, water) into the SDG framework. This opens the way for developing and implementing sustainable material policies aimed at reducing the absolute level of material consumption[39]. Targets for absolute reduction in material use are being debated in the policy arena. For example, in February 2021, the European Parliament adopted a resolution that urges the European Commission to propose binding targets for EU countries for the year 2030 to significantly reduce the EU's material and consumption footprints[40]. The MRIO-MF framework presented here can become a key knowledge base for designing policies to achieve such reduction targets by providing information on hotspot materials, products, industries, and supply chains that contribute to the material footprint of countries. Based on the detailed insights from the material footprint calculations, policy makers can elaborate specific policy responses[41], for example, increased taxation of highly material-intensive products, setting resource efficiency standards for specific product groups, or adapting product policy frameworks, such as the EU Ecodesign Framework, to consider material use in addition to energy consumption. Also, policies on sustainable public and private procurement can be informed by material footprint results, indicating material efficient supply chains.

On a more strategic level, decision-makers can also draw on material footprint results following strategies adopted by consumption-based greenhouse gas accounting, including [4,5,42-45]. The features that can be used to guide evidence-based policy making include complementary national-level accounting for material use; accounting for and understanding of inequality and shared responsibility in material management, both nationally and internationally; and trade policies addressing materials embodied in trade and international supply chains (e.g. border tax adjustments or agreements with international suppliers). The material footprint results can also inform science-based target setting for material extraction; raise awareness and increase understanding of the material implications of consumption; provide incentives to change consumption patterns or reduce consumption; and provide accounting for and understanding of materials embodied in trade and outsourcing of MF across countries.

These strategies have synergies with the objectives of the Sustainable Development Solutions Network, hosted by the United Nations, which produces the annual Sustainable Development Report, documenting performance of world nations towards all 17 SDGs. The improved MRIO-MF framework showcased in this study paves the way for inclusion of a comprehensive MF dataset in the Sustainable Development Report, and to extend this work to a broader suite of environmental, social and economic indicators that can be coupled to SDGs.

Methods

The narrow scope of the MF-based indicators within the overall SDG framework understates their relevance as both relatively hard, objective measures of large-scale physical impacts on the environment, and one of only a few indicators that link economic development in individual countries to resource use globally. We focus here on the MF instead of DMC, because as a territorial measure DMC fails to trace impacts beyond national borders. DMC, used for targets 8.4.2 and 12.2.2, is therefore arguably more important at a local level than MF. In any case, the new approach developed in this work can include DMC. A discussion of the differences between MF and DMC, their uses, and why they are both necessary for the same SDG targets appears in SI 1 and serves as background to the description of the MF methodology in this 'Methods and data' section.

Basic input-output theory

Input-output-assisted footprint calculations utilise the fundamental input-output balance:

$$\mathbf{x} = \mathbf{T}\mathbf{1}^N + \mathbf{y}\mathbf{1}^K =: \mathbf{A}\mathbf{x} + \mathbf{y}\mathbf{1}^K \qquad (1)$$

to derive Leontief's demand-pull formulation[46]:

$$\mathbf{x} - \mathbf{A}\mathbf{x} = \mathbf{y}\mathbf{1}^K \Leftrightarrow \mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}\mathbf{1}^K =: \mathbf{L}\mathbf{y}\mathbf{1}^K \;, \qquad (2)$$

where $\mathbf{x}$ is $N \times 1$ total output of N sectors of the economy, $\mathbf{T}$ is $N \times N$ intermediate demand of products supplied by these N sectors for use by the same N sectors, $\mathbf{y}$ is $N \times M$ final demand of products from N sectors for use by K finally demanding entities (household, the government, the capital sector and – in single-region input-output (IO) databases – the rest of the world), and $\mathbf{1}^N = \{\underbrace{1, \dots, 1}_{N}\}$ and $\mathbf{1}^K = \{\underbrace{1, \dots, 1}_{K}\}$ are $N \times 1$ and $K \times 1$ summation operators. $\mathbf{x}$, $\mathbf{T}$ and $\mathbf{y}$ are expressed in monetary (for example dollar) values. $\mathbf{A} = \mathbf{T}\hat{\mathbf{x}}^{-1}$ is the $N \times N$ matrix of unit-less input coefficients (the hat symbol denotes vector diagonalisation), which captures an economy's 'production recipe', in that it holds the inputs T_{ij} of $i = 1,\dots,N$ supplying sectors into $j = 1,\dots,N$ using sectors, per unit of total output x_j of the using sector. Finally, $\mathbf{I}$ is an $N \times N$ identity matrix, with diagonal elements equalling 1, and zero entries elsewhere, and $\mathbf{L}$ is the Leontief inverse.

Multiple regions

In single-region databases, $\mathbf{T}$, $\mathbf{A}$, $\mathbf{L}$, $\mathbf{y}$ and $\mathbf{x}$ cover the sectors of one national economy. In multi-regional (MRIO) databases[47-49], these quantities cover the sectors of many economies. Global MRIO databases cover the entire world economy[50-53]. In a multi-region context, the transactions matrix $\mathbf{T}$ (and as a consequence, also $\mathbf{A}$, $\mathbf{L}$, $\mathbf{y}$, and $\mathbf{x}$) can be understood as being indexed by sector and region, as T_{ij}^{rs} etc., where products flow from supplying sectors $i = 1,\dots,I$ in regions $r = 1,\dots,R$, to be used by sectors $j = 1,\dots,J$ or final demand entities $k = 1,\dots,K$ in regions $s = 1,\dots,S$, and where matrices are of sizes $IR \times JS$ ($\mathbf{T}$, $\mathbf{A}$, $\mathbf{L}$), $IR \times KS$ ($\mathbf{y}$), or $IR \times 1$ ($\mathbf{x}$). Typically, MRIO tables contain square matrices, so that $I = J =: N$, and $R = S$. In what follows, we adopt previously used notation[54], and use indices r, s and t for supplying, selling and consuming regions, and i and j for the supplying and using sectors. In this notation, quantities appear as multidimensional tensors, and their products can be sliced in multiple ways. For example, equation 2 can be written as:

$$x_i^r = \sum_{j,st} L_{ij}^{rs} y_{jk}^{st} \,. \tag{3}$$

Physical extensions

Call $\mathbf{Q}$ a $1 \times RN$ satellite account, holding the physical factor inputs or pollution outputs of $i = 1,\ldots,N$ supplying sectors in $r = 1,\ldots,R$ regions[55,56]. Then,

$$Q = \mathbf{Q}\mathbf{1}^N = \mathbf{Q}\hat{\mathbf{x}}^{-1}\mathbf{x} =: \mathbf{q}\mathbf{x} = \mathbf{q}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y} =: \mathbf{q}\mathbf{L}\mathbf{y} =: \mathbf{m}\mathbf{y} =: F \tag{4}$$

is Leontief's demand-pull formulation in physical units, where $\mathbf{q} = \mathbf{Q}\hat{\mathbf{x}}^{-1}$ is the $1 \times RN$ vector of satellite coefficients, $\mathbf{m} = \mathbf{q}\mathbf{L} = \mathbf{q}(\mathbf{I}-\mathbf{A})^{-1}$ is a $1 \times RN$ vector of so-called multipliers. While $\mathbf{q}$ holds physical quantities per unit of total output in the using, or polluting sectors, $\mathbf{m}$ holds physical quantities per unit of final demand. In contrast to $\mathbf{q}$, $\mathbf{m}$ includes the entirety of upstream supply-chain contributions that are ultimately needed to satisfy the final demand bundle $\mathbf{y}$, which is reflected in the Leontief inverse appearing in the definition of $\mathbf{m}$. $Q = F$ has two interpretations: from a production perspective Q is the total factor content of $\mathbf{x}$, and from a consumption perspective F is the factor footprint of $\mathbf{y}$. In equation 4 above, the satellite $\mathbf{Q}$ was introduced as having one row or representing one indicator. Of course, $\mathbf{Q}$ can have multiple rows, and thus Leontief's calculus is carried out simultaneously for multiple indicators.

Trade balance

In index notation, and omitting the final demand entity index k for the sake of brevity and clarity, equation 4 becomes:

$$Q = \sum_{ij,rst} q_i^r L_{ij}^{rs} y_j^{st} = F \,. \tag{5}$$

The domestic extraction for a country r is:[1]

$$\begin{aligned} Q^r &= \underbrace{\sum_{ij,st} q_i^r L_{ij}^{rs} y_j^{st}}_{\text{domestic extraction of } r} = \sum_{ij,s} q_i^r L_{ij}^{rs} y_j^{sr} + \sum_{ij,t\neq r,s} q_i^r L_{ij}^{rs} y_j^{st} \\ &= \underbrace{\sum_{ij,ts} q_i^t L_{ij}^{ts} y_j^{sr}}_{\text{consumption footprint of } r} - \underbrace{\sum_{ij,t\neq r,s} q_i^t L_{ij}^{ts} y_j^{sr}}_{\text{total imports of } r} + \underbrace{\sum_{ij,t\neq r,s} q_i^r L_{ij}^{rs} y_j^{st}}_{\text{total exports of } r}. \end{aligned} \tag{6}$$

The imports term includes both intermediate imports (for example $q_i^t L_{ij}^{tr} y_j^{rr}$) and final imports (for example $q_i^t L_{ij}^{ts} y_j^{sr}$). The only criterion limiting the imports term is that factor use may not

[1] An alternative derivation is

$$\begin{aligned} Q^r &= \underbrace{\sum_{ij,st} q_i^r L_{ij}^{rs} y_j^{st}}_{\text{domestic extraction of } r} \\ &= \sum_{ij,st} q_i^s L_{ij}^{ts} y_j^{sr} - \sum_{ij,st} q_i^t L_{ij}^{ts} y_j^{sr} + \sum_{ij,st} q_i^r L_{ij}^{rs} y_j^{st} \\ &= \sum_{ij,st} q_i^t L_{ij}^{ts} y_j^{sr} - \sum_{ij,t\neq r,s} q_i^t L_{ij}^{ts} y_j^{sr} - \sum_{ij,s} q_i^r L_{ij}^{rs} y_j^{sr} + \sum_{ij,s} q_i^r L_{ij}^{rs} y_j^{sr} + \sum_{ij,t\neq r,s} q_i^r L_{ij}^{rs} y_j^{st} \\ &= \underbrace{\sum_{ij,st} q_i^t L_{ij}^{ts} y_j^{sr}}_{\text{consumption footprint of } r} - \underbrace{\sum_{ij,t\neq r,s} q_i^t L_{ij}^{ts} y_j^{sr}}_{\text{imports of } r} + \underbrace{\sum_{ij,t\neq r,s} q_i^r L_{ij}^{rs} y_j^{st}}_{\text{exports of } r}. \end{aligned}$$

occur in the region r under consideration. Similarly, the exports term includes both intermediate exports (for example $q_i^r L_{ij}^{rs} y_j^{st}$) and final exports (for example $q_i^r L_{ij}^{rr} y_j^{rt}$). The only criterion limiting the exports term is that final demand may not occur in the region r under consideration. Since the international trade terms include both intermediate and final transactions, equation 6 mirrors a conventional monetary trade balance.

Equation 6 is derived by splitting y_j^{st} into $y_j^{sr} + y_j^{s,t\neq r}$, that is by splitting out the region r of factor use. Kanemoto *et al.*[54] suggest an MRIO trade balance through splitting y_j^{st} into $y_j^{ss} + y_j^{s,t\neq s}$, that is by splitting out the region s of final sale, with the factor embodiment F by selling region s and consumed product j:

$$\begin{aligned} F_j^s &= \sum_{i,rt} q_i^r L_{ij}^{rs} y_j^{st} = \sum_{i,r} q_i^r \left[L_{ij}^{rs} y_j^{ss} + \sum_{t\neq s} L_{ij}^{rs} y_j^{st}\right] \\ &= \sum_{i,r} q_i^r \left[\sum_t L_{ij}^{rt} y_j^{ts} - \sum_{t\neq s} L_{ij}^{rt} y_j^{ts} + \sum_{t\neq s} L_{ij}^{rs} y_j^{st}\right] \\ \Leftrightarrow F^s = \sum_j F_j^s &= \underbrace{\sum_{ij,rt} q_i^r L_{ij}^{rt} y_j^{ts}}_{\text{consumption footprint of } s} - \underbrace{\sum_{ij,r,t\neq s} q_i^r L_{ij}^{rt} y_j^{ts}}_{\text{final imports into } s} + \underbrace{\sum_{ij,r,t\neq s} q_i^r L_{ij}^{rs} y_j^{st}}_{\text{final exports out of } s}. \end{aligned}$$

In contrast to equation 6, the imports term includes only final imports (for example $q_i^r L_{ij}^{rt} y_j^{ts}$). Since $t \neq s$, intermediate imports into region s such as $q_i^r L_{ij}^{rs} y_j^{ss}$ are not included. Similarly, the exports term includes only final exports (for example $q_i^r L_{ij}^{rs} y_j^{st}$). Since the destination index of L_{ij}^{rs} is s, intermediate exports out of region s such as $q_i^s L_{ij}^{st} y_j^{tt}$ are not included.

Standard SDG reporting variables in a global MRIO framework

For the purpose of reporting on the United Nations' Sustainable Development Goals 8.4/12.2[57], the MF indicator is used[58,59]. The United Nations' System of Environmental-Economic Accounting (SEEA[60]) provides the context in which the SDGs[61] and input-output analysis[62] are linked. In an MRIO context, the MF and related trade balance quantities are defined in analogy to equation 6 as:

$$MF^r = DE^r + RME_{\mathrm{im}}^r - RME_{\mathrm{ex}}^r, \qquad (7)$$

where $DE^r \coloneqq Q^r$ is Domestic Extraction, and $RME_{\mathrm{im}}^r \coloneqq \sum_{ijk,t\neq r,s} q_i^t L_{ij}^{ts} y_{jk}^{sr}$ and $RME_{\mathrm{ex}}^r \coloneqq \sum_{ijk,t\neq r,s} q_i^r L_{ij}^{rs} y_{jk}^{st}$ are the raw material equivalents of imports and exports of region r, respectively. From this fundamental trade balance and its four quantities, a number of standard reporting variables for the Sustainable Development Goals 8.4/12.2 can be derived.

First, Domestic Extraction satellites Q^r are available for 62 different material types (SI 2.3), and as such, the trade balance and its components can be expressed in either of those types. Second, DE, MF, RME_{im} and RME_{ex} can be broken down:

- by extracting sector i, for example as $MF_i^r = \sum_{jk,ts} q_i^t L_{ij}^{ts} y_{jk}^{sr}$,
- by consumed product j, for example as $MF_j^r = \sum_{ik,ts} q_i^t L_{ij}^{ts} y_{jk}^{sr}$,
- by final demand destination k, for example as $MF_k^r = \sum_{ij,ts} q_i^t L_{ij}^{ts} y_{jk}^{sr}$,
- or by any combination of the six dimensions i, j, k, r, s and t.

MRIO and MF data foundation development

In order to enable the MF to be raised to Tier-I status, the underlying data foundation must be comprehensive and detailed; geographically, over time, and with respect to economic sectors and material types. Second, it must be flexible in terms of being able to change geographical, sectoral and material classifications as user needs and the global economy change. Third, it must enable timely updates as data availability progresses. Fourth, it must incorporate mechanisms of data quality reporting and assurance, and enable uncertainty analysis, so that findings can be put into contexts of likelihood and support decision-making. Finally, results must be readily accessible to users world-wide.

Given these multiple requirements, the Global MRIO Virtual Laboratory[63] was selected as the platform to construct MRIO tables, to integrate these with material flow accounts provided by the UNEP IRP[64], and to use Leontief's input-output calculus to derive comprehensive MF accounts for the world (see Methods and Data section). Virtual Laboratories are a new and innovative development within the input-output field[65] based on high-performance cloud computing environments[66], as they allow the timely and flexible streamlining of (MR)IO data for collaborative use of a wide range of users and research questions[67,68].

In meeting these requirements, the new framework offers detail on 97 economic sectors, 164 regions and 62 material types (SI 2), as a continuous time series for the 1990–2019 period. The 97-sector structure is tailored to reflect material supply logic, rather than just monetary value flows, because while primary extraction and early processing stages of the world economy account for a relatively small portion of value flows, they dominate material flows. Appropriate allocation of material flows thus depends on having adequate disaggregation of these high-mass, low-value flow sectors[21]. To address this, 15 crop production sectors and 17 mining sectors (coal, metal ores, industrial and construction minerals) are disaggregated, accounting for a third of all sectors (far exceeding their share of value added). In addition to this improved disaggregation, considerable effort has been invested in applying engineering-knowledge-based constraints, to avoid implausible inter-sectoral links between these primary and early processing sectors. This avoids, for example, copper ore extraction linking directly to aluminium smelting, or conflation of low-value biomass mainly consumed domestically, e.g. grains, with high value crops typically for export e.g. coffee. This cannot be achieved using more aggregated primary data structures, e.g. where copper and aluminium ores and processed metals are lumped together as 'non-ferrous ores and metals', or pumpkins, sorghum and coffee together as 'crops'.

A Virtual MRIO Lab uses an innovative classification bridge between primary source and MRIO data called the root classification[66], which enables flexibility in adapting to new geographical and sectoral structures. A large degree of automation and implementation in a cloud-based high-performance computation environment facilitates rapid updating (SI 3.1). Data quality reporting and uncertainty analysis are in-built in every MRIO Lab, as every dataset is created with accompanying standard deviations tables (SI 3.4 and 3.5). The data and results from this study will feature in UNEP's open-source platform SCP-HAT (http://scp-hat.lifecycleinitiative.org), presenting findings per country at national and sector levels, along with an analysis of hotspot areas for interventions towards more sustainable consumption and production patterns.

Data sources

To operationalise the MF framework for SDGs 8 and 12, the variables $\mathbf{Q}$, $\mathbf{T}$ and $\mathbf{y}$ need to be populated with data. An initial global dataset for SDG reporting was established by the United

Nations Environment Programme (UNEP) International Resource Panel (IRP), reporting MF data for most countries globally (UNEP 2016).

Domestic extraction (DE) of materials

The basic material flow data required to establish the DE satellite accounts **Q** for the material footprinting were created using standard methodology[69]. In summary, data for DE are compiled into 62 detailed subcategories (referred to as the common compilation categories of CCC level, see SI 1.3 of UN-IRP 2018[69]), which are nested within four overarching major materials groups (biomass, fossil fuels, metal ores, non-metallic minerals). Where possible, data is sourced directly from authoritative, centralised international databases and simply concorded and aggregated into the relevant CCC categories. This approach covers most of the crop biomass time series (using UN FAO data), and most fossil fuels (using IEA data).

In some cases, the raw data need adjustments, e.g. conversion from energy (GJ of fuels) or volume (m^3 of timber) into mass units. For some biomass components, notably crop residues and grazed biomass, more complex manipulations need to be applied. In the case of crop residues, estimates for both the residue produced per tonne of crop, and for the percentage of that residue which is actually recovered from the field for economic use (as DE only counts materials which are extracted from the environment and enter into some form of economic activity/processing), are applied to calculate crop residue tonnages from recorded crop production tonnages.

Tonnages of ores mined for most metals, excluding iron ore, are not generally available from a centralised source. Refined metal production statistics, however, are much more readily available, so metal ore tonnages are typically calculated from metal production figures from BGS or USGS, multiplied by a grade factor (metal concentration in the extracted ore). Production of non-metallic minerals is typically very poorly recorded for most countries, especially for the high volume / low value construction aggregates which dominate total tonnages. These are thus modelled by applying conversion factors to better recorded, closely associated proxies, notably production / apparent consumption of cement, bitumen, and bricks, and railway network extensions.

Monetary MRIO data

Currently a small number of MRIO frameworks are available to establish global MFs[51]. There have been efforts toward database comparison[70], demonstrating general convergence of footprints[71], but some deviations in country and sector detail. While these MRIO databases have clear advantages over other MF approaches[18], no MRIO database currently exists that reflects detailed material supply chains, as a continuous time series, and for a large number of individual countries. Existing databases are either not continuous, not timely, or too aggregated. The latter problem leads to material exchanges that are implausible, or to incorrect attribution that occurs for example for agricultural products where these are aggregated across domestic and exported crops. In addition, information on data reliability is highly desirable to enable analysts to quantify the reliability of findings for policy applications.

A continuous time series of high-resolution MRIO tables for the 1990–2019 period (**T** and **y** matrices), including accompanying tables with standard deviations for every element, was constructed in the Global MRIO Virtual Laboratory[63], distinguishing 164 regions and 97 economic sectors (see SI 2.1 and 2.2). For the 1970–1989 period, where national and global input-output information is increasingly sparse or non-existent, we combine the 1990 production recipe (the **A** matrix, see Methods) with year-specific DE satellite accounts.

Multiple regressions

We follow Lenzen *et al.*[72] and subject the time series data of per-capita MFs F to a multiple regression against explanatory variables of per-capita GDP x, material intensity q (as in Eq. 4), and time t, as:

$$F = kx^{\eta_0+\theta x}\mathrm{e}^{\varrho q}\mathrm{e}^{\tau t} \Leftrightarrow \ln(F) = \ln(k) + \eta_0 \ln(x) + \theta x \ln(x) + \varrho q + \tau t\ . \qquad (8)$$

In this formulation, the influence of per-capita GDP on per-capita MFs is characterised by an elasticity:

$$\eta(x) = \frac{\mathrm{d}F/F}{\mathrm{d}x/x} = \eta_0 + \theta x[\ln(x) + 1]\ . \qquad (9)$$

A decoupling of the MF from economic growth would imply that $\eta(x) \leq 0$. We experimented with ordinary least-squares regression (OLS), a number of weighted least-squares (WLS) regressions (SI 6.1–6.2), individual-country trends (see Supplementary Data), and fixed effects (SI 6.3–6.4). Separating individual-country trends from the panel yields fixed effects (SI 6.3) that follow an elastic relationship that is similar to that exhibited by the entire panel. Thus, the regression in Eq. 8 combines structurally similar within- and between-country trends (SI 6.4).

Data availability

All data have been deposited at https://ielab.info/resources/datasets. Material footprint data are freely available. Multi-region input-output data are available on request only, because of the large file sizes.

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Author contributions

HS and MaL designed the study, MaL, AG, JW, JF, MyL performed the analysis, SL, SG, PP reviewed the analysis, MaL, AM and HS wrote the manuscript, JP, IT, LMC, MVV, MS, KN and TW reviewed the manuscript and contributed to the manuscript.

Competing interests

We declare that none of the authors have competing financial or non-financial interests as defined by Nature Research.

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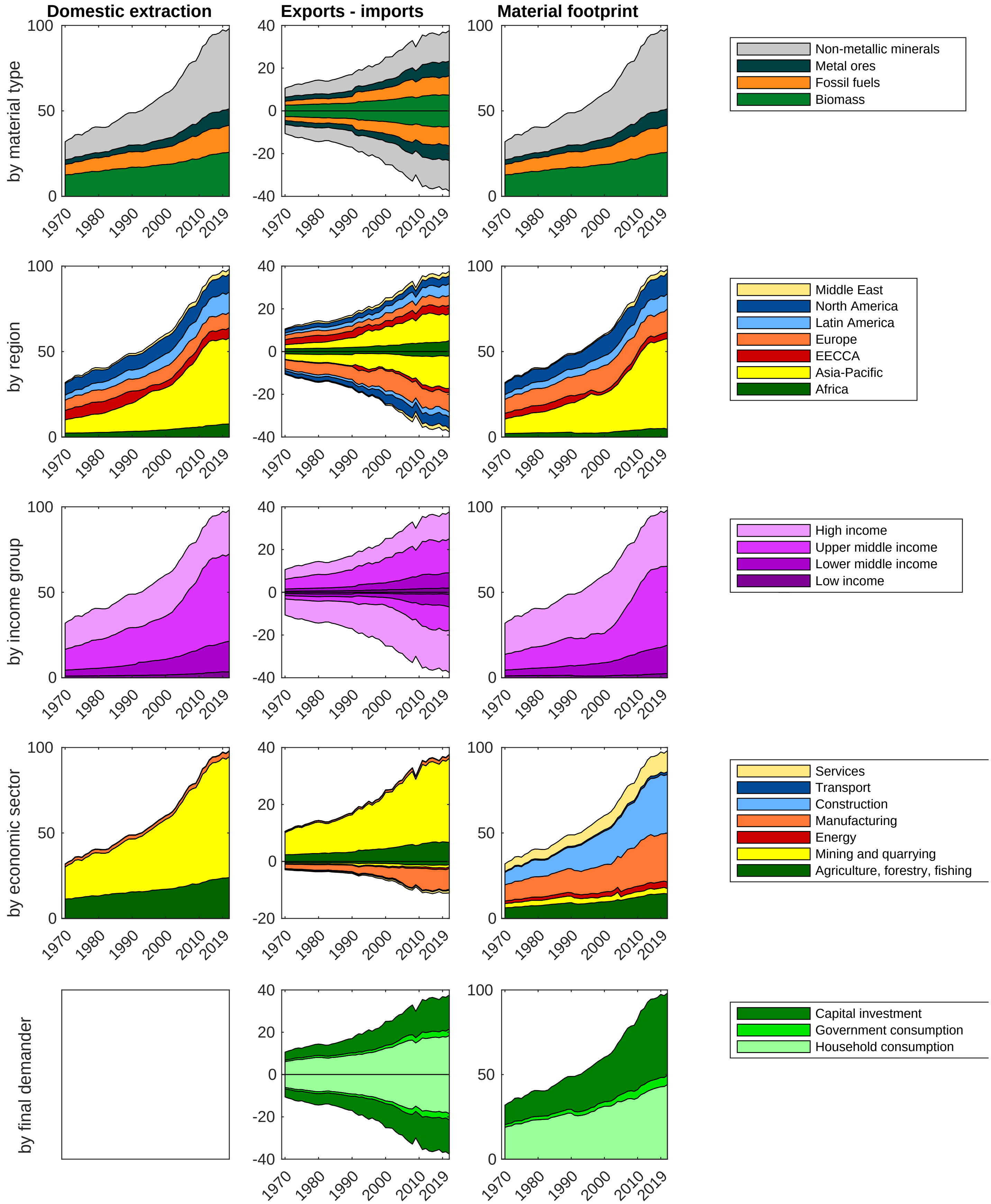
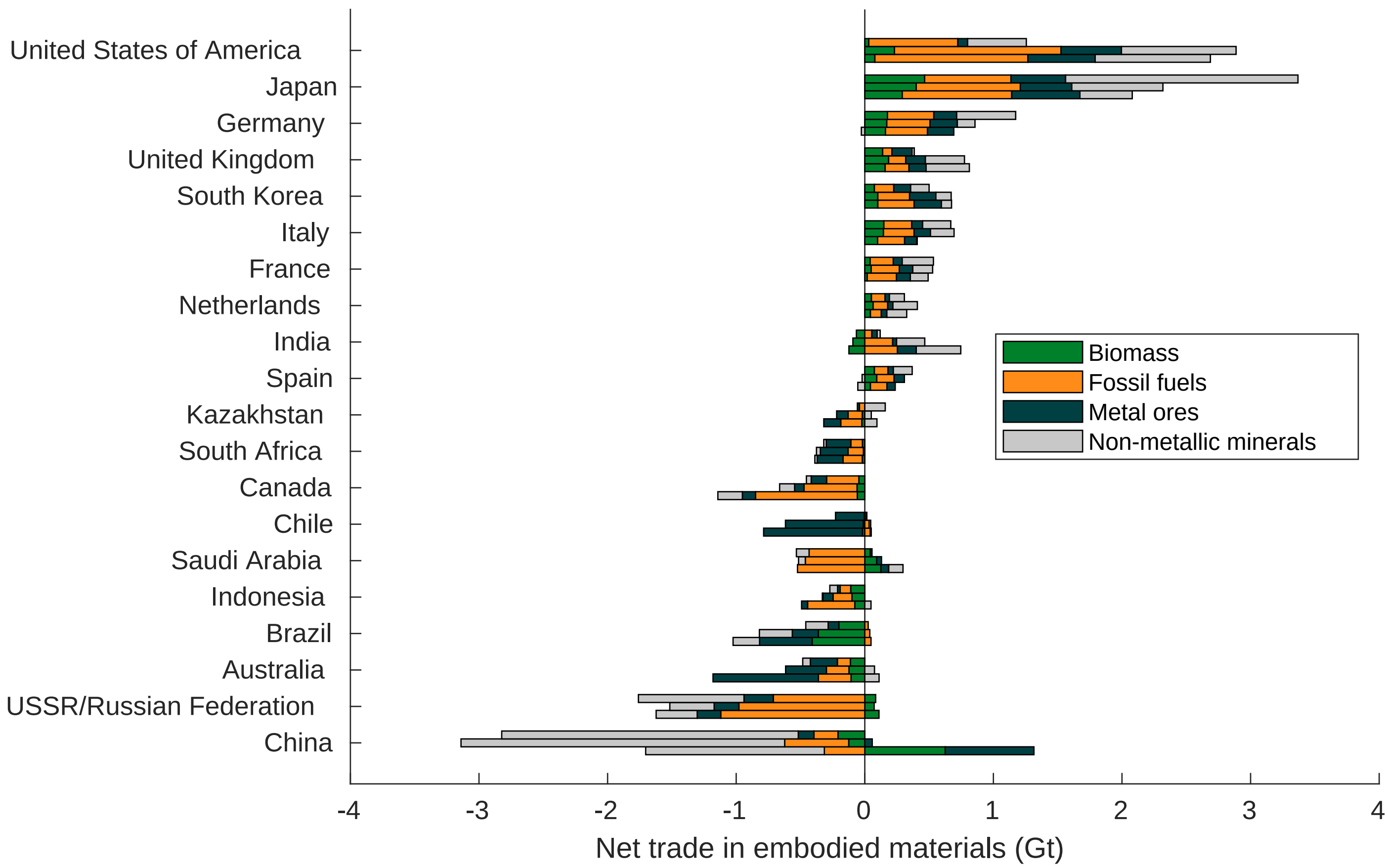
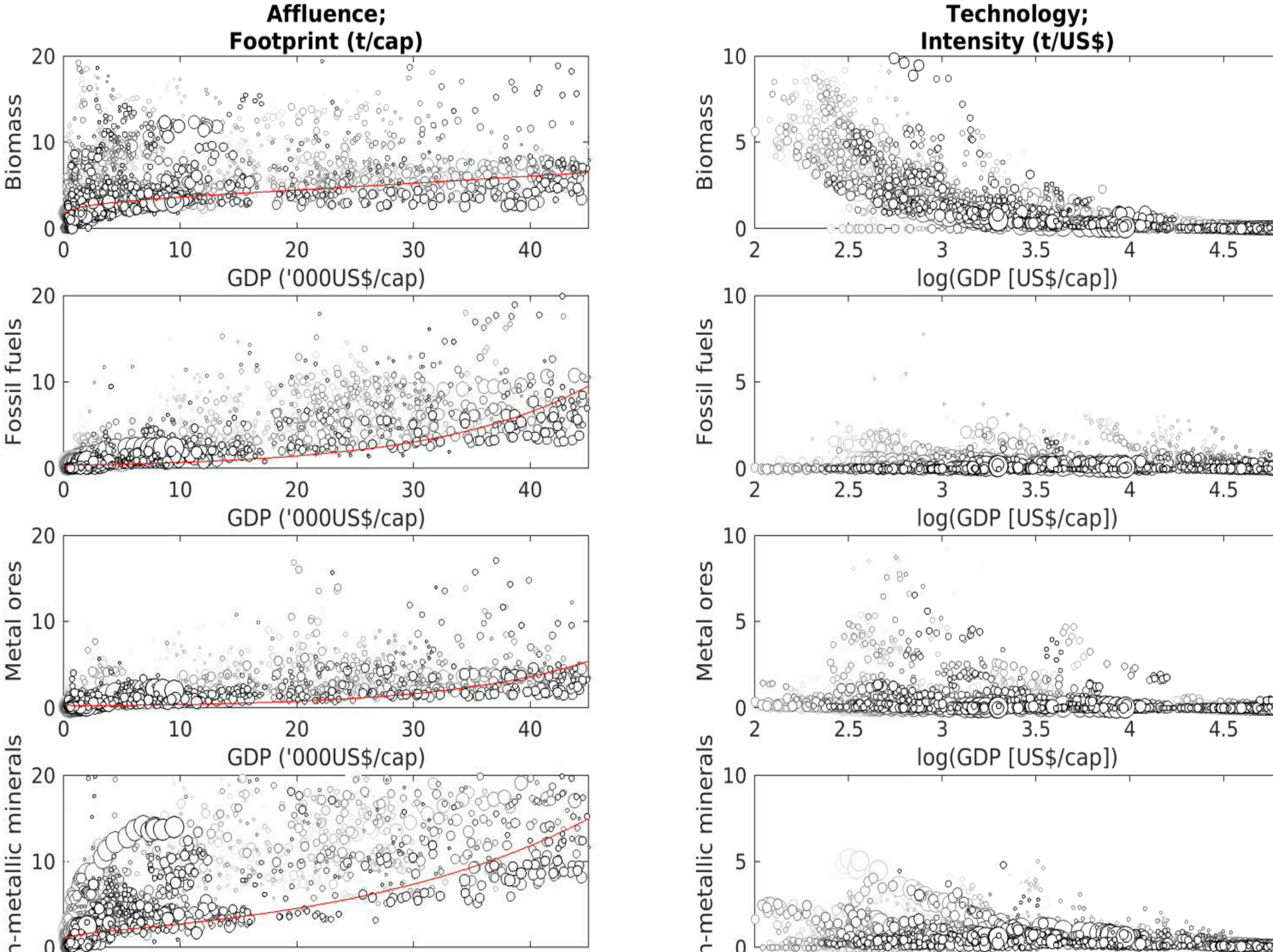


Domestic extraction
Exports - imports
Material footprint
by material type
by region
by income group
by economic sector
by final demander
Non-metallic minerals
Metal ores
Fossil fuels
Biomass
Middle East
North America
Latin America
Europe
EECCA
Asia-Pacific
Africa
High income
Upper middle income
Lower middle income
Low income
Services
Transport
Construction
Manufacturing
Energy
Mining and quarrying
Agriculture, forestry, fishing
Capital investment
Government consumption
Household consumption
1970
1980
1990
2000
2010
2019



United States of America
Japan
Germany
United Kingdom
South Korea
Italy
France
Netherlands
India
Spain
Kazakhstan
South Africa
Canada
Chile
Saudi Arabia
Indonesia
Brazil
Australia
USSR/Russian Federation
China
Biomass
Fossil fuels
Metal ores
Non-metallic minerals
-4
-3
-2
-1
0
1
2
3
4
Net trade in embodied materials (Gt)


Affluence;
Footprint (t/cap)
Technology;
Intensity (t/US$)
Biomass
Fossil fuels
Metal ores
GDP ('000US$/cap)
log(GDP [US$/cap])