Global end-use inventory of the anthropogenic mass

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ABSTRACT

Human-made objects and the built environment, comprising together the anthropogenic mass, form the basis of physical wealth and provide many services to the population, from shelter and food production to mobility and comfort. However, the production and accumulation of this anthropogenic mass have altered the Earth in such ways that we are jeopardizing local and global sustainability and pushing planetary boundaries to their limits. Global economy-wide material flow accounting (ew-MFA) has been a valuable top-down approach to track material stocks and flows through national economies, but does not offer a clear picture of how these materials are employed in our societies and for what purpose they are used. Hence, the transition to sustainable patterns of resource use calls for a more complete understanding of the impact materials have on the human experience. Here, I lay out a complementary perspective on global material flows for nine material types by putting together a bottom-up assessment of infrastructure, machines, and consumer products, grouped in a way which is consistent with their ultimate relevance for human activities and experiences. The 23 classes of human-made artifacts and structures assessed account for 66 ± 33% of total anthropogenic mass evaluated by top-down ew-MFA studies, with stock estimates for six out of nine material types agreeing within their uncertainty range. This holistic, end-use outlook on material stocks provides a bird's eye perspective on the resource intensities of different end-use sectors.

RÉSUMÉ

Les objets fabriqués et l'environnement bâti par l’humain, constituant la masse anthropogénique, forment la base de la richesse matérielle et fournissent de nombreux services à la population, allant de l'abri et de la production alimentaire à la mobilité et au confort. Cependant, la production et l'accumulation de cette masse anthropogénique a modifié la Terre de telle sorte que nous compromettons désormais la durabilité locale et mondiale et poussons les frontières planétaires à leurs limites. L’analyse des flux de matières à l'échelle de l'économie mondiale (ew-MFA) a été une approche précieuse pour suivre les stocks et les flux de matériaux à travers les économies nationales, mais n'offre pas une image claire de la manière dont ces matériaux sont employés dans nos sociétés et dans quel but ils sont utilisés. Par conséquent, la transition vers des modèles durables d'utilisation des ressources nécessite une compréhension plus complète de l'impact des matériaux sur l'expérience humaine. Ici, je présente une perspective complémentaire sur les flux mondiaux de matériaux pour neuf types de matériaux en établissant une évaluation des infrastructures, des machines et des produits de consommation, regroupés de manière cohérente avec leur ultime pertinence pour les activités et les expériences humaines. Les 23 classes d'artéfacts et de structures fabriqués par l'homme évaluées représentent 66 ± 33% de la masse anthropogénique totale déterminée par les études ew-MFA, avec les estimations de stock pour six des neuf types de matériaux concordant dans leur plage d'incertitude. Cette perspective sur l'utilisation finale des stocks de matériaux offre une vue d'ensemble de l'intensité des ressources à travers différents secteurs d'utilisation finale.

1. INTRODUCTION

Global material extraction has been expanding consistently since the beginning of the 20th century, reaching about 78 Gt/yr in 2010 — nearly ten times more than in 1900 — and continues to grow at an annual rate of 3% per year (Krausmann, et al., 2020). Driven at global scale by increasing affluence, economic growth, and population, the in-use stock of materials has reached a total mass of approximately 1100 Gt, equivalent to all global living biomass on a dry-weight basis (Elhacham, et al., 2020). Large amounts of materials are required to build, maintain, and refurbish these stocks, consequently driving environmental pressures and pushing the limits of ecological systems (Wiedmann, et al., 2020). In 2017, the industries transforming raw materials into semi-finished products were responsible for nearly 40% of total final energy consumption and about a quarter of direct carbon dioxide emissions (IEA, 2019a). Manufacturing of new construction materials for buildings alone accounted for 11% of global energy- and process-related greenhouse gas (GHG) emissions in 2018 (IEA, 2019b). If climate change is to be globally contained within 2°C or less, "material demand must be reduced and in-use stocks be at least stabilized" (Haberl, et al., 2017; IPCC, 2022).

Despite the environmental risks that rising material stocks represent, this anthropogenic mass is composed of essential immovable structures (e.g. buildings, transport infrastructure) and artifacts (e.g. machines, tools, objects) forming the material basis of wealth. Not only does it offer end-uses including shelter, mobility, and communication, it also provides the physical foundation for production, manufacturing, and consumption (Krausmann, et al., 2018), thus justifying further stock build-up. At the same time, it has been argued that following rapid gains in human development with increasing material and energy use, saturation occurs and human well-being no longer improves with greater resource use (Mayer, et al., 2017; Martínez and Ebenhack, 2008). Evidence has suggested there was no clear correlation between a person's emissions and subjective well-being. It was also proposed that materialistic personal values correlate with lower subjective well-being and to some extent to higher GHG emissions (Andersson, et al., 2014). Vita, et al. (2019) connected global emissions from 200 economic goods to nine fundamental human needs and their satisfaction. The study pointed out that generally greater gains in objective quality of life indicators (ex : protection, leisure, identity) were achieved when moving from low to moderate emissions but eventually diminished or stagnated at high emissions, while most subjective quality of life indicators (ex : affection, participation, understanding) did not vary consistently with carbon emissions, except for freedom and creation. Undoubtedly, technological changes will play an important role in limiting carbon emissions. However, changes in lifestyle and decoupling between economic growth and resource use and carbon emissions, most notably in affluent societies, will also be a crucial component to limit global warming (Capstick, et al., 2014; Jackson, 2005; Hickel and Kallis, 2020). While implementing degrowth and behavioural changes may appear difficult, individual well-being will not necessarily be affected in a negative way, suggesting the possibilty of living better while consuming and emitting less (Druckman and Gatersleben, 2019; Wiedenhofer, et al., 2018). Since the demand for goods and services is a significant driver of global environmental impacts (Ottelin, et al., 2019), it is imperative to gain a broad understanding of how material flows relate to human well-being via end-uses, meaning the goods and services delivered by in-use material stocks.

1.1. LITERATURE REVIEW

Many recent studies have used the well-established framework of economy-wide material flow accounting (ew-MFA) to reflect the relationship between the economy and the environment. EW-MFA traces materials flow in a mass-balance approach from extraction, including imports, to their exports and end-of-life discharge as waste or emissions (Eurostat, 2018), making it a top-down method. In dynamic ew-MFA research, a model can either be inflow-driven, where the annual difference between inflows (consumption) and outflows (e.g. exports, emissions) accumulates in stocks, or stock-driven, where material quantities embedded in a particular entity for a given time are summed. For instance, by using relevant factors linked to floor area, the mass of building stock can be estimated as it is the case in Pauliuk and Müller (2014). Hence, most ew-MFA studies focus on compiling extraction data, trade, and consumption of materials and only quantify outputs and emissions by applying the mass-balance principle, where inputs must always equal to outputs and changes in accumulated material stocks in the system. The harmonized top-down framework allows country comparisons across time and has been widely used as a policy indicator (Krausmann, et al., 2017a; Schaffartzik, et al., 2014; Giljum, et al., 2014; Wiedenhofer, et al., 2019). Krausmann, et al. (2018) investigated global development of ten material stocks for the period 1900-2015, with Elhacham, et al. (2020) projecting the results to 2020. Plank, et al. (2022a) completed the perspective by evaluating the 1900-2016 gross addition to stocks (GAS) in terms of the annual amount of primary new materials entering the in-use anthropogenic mass, after processing losses and excluding the contribution of recycled materials.

Yet, the relationship between stocks, flows, and services provided are not captured in such ew-MFA studies. Desired end-uses and services can be seen as the motivation for undertaking any human activity, which directly influence the biophysical impact humans have on the Earth (Galbraith, 2021). In this sense, it is ultimately the demand for end-use functions and services to society provided by various items of anthropogenic mass that drives the accumulation of materials (Chen and Graedel, 2015; Haberl, et al., 2017). Therefore, in-use stock of artifacts and immovable structures can serve as a bridge to link material cycles to the anthropogenic mass and the functions and services demanded by society.

The subdivision of material stocks into specific end-use products or infrastructures is more often done when focusing on one material at a time. Under this scope, most studies include the secondary inputs of recycled or down-cycled materials. For example, Hatayama, et al. (2010), Müller, et al. (2011), Cullen, Allwood, and Bambach (2012) modelled global steel flows into various end-use goods (e.g. vehicles, construction). Cullen and Allwood (2013) mapped the 2007 global aluminium flows from liquid metal to 13 categories of final products. The production, use, and fate of global plastic in 2015 was estimated by Geyer, et al. (2017) and a global review of data sources for plastic stocks and flows was conducted by Wang, et al. (2021). Westbroek, et al. (2021) estimated the global glass flow from raw extraction to six end-use categories for the year 2014. Isolated sectors have also been analyzed, like the global electricity network (Kalt, et al., 2021), the Internet services in Switzerland (Müller, et al., 2013), and the transport sector of the United Kingdom (Carmona, et al., 2021) to better represent the role of the stock-flow-service nexus and the increasing importance of the services delivered by in-use stocks of materials.

As opposed to the top-down methodologies of ew-MFA, different bottom-up approaches have been explored to assess the environmental impact of end-use goods and the materials required to manufacture them. The material footprint of individual products may be evaluated using data from supply-use and input-output tables, such as the ones provided on the platform EXIOBASE, a global and detailed multi-regional environmentally extended supply-use and input-output tables. Life-cycle analysis (LCA) is another analytic tool that examines all stages of a product (i.e. manufacturing, usage, maintenance, and end-of-life). It also provides a quantitative evaluation of the associated environmental impact from energy and material consumed, as well as wastes and emissions generated, for a product to be functional. This approach is applied to specific artifacts, like airplanes (Jemiolo, 2015) or heavy-duty off-road equipment (Kwak, et al., 2012). Due to its time-consuming methodology, LCA analysis cannot be employed on a large scale. The resource efficiency of a product or service can also be evaluated through the concept of the ecological rucksack and material inputs per service unit (MIPS), which is a variation of the LCA approach and was developed in 1992 by researchers at the Wuppertal Institute in Germany. Here, quantification focuses on the materials moved from nature to create the product but not directly used in the product itself, including material flow required for energy input (Ritthoff, et al., 2002). This method highlights the importance of hidden flows and is again generally applied to a specific good, like high-definition TVs (Aoe and Michiyasu, 2005), or a small localized sample such as participating households in southern Finland (Lähteenoja, et al., 2008). A more direct method to assess material requirements to build a product or provide a service is to determine material intensities per product, specifically the mass of material(s) used to build one functional unit. Such information can be extracted from comparative LCA studies, by compiling tear-down data, models, personal communications, and literature reviews, or from reports that provide data on a typical standard product, which is an average estimate that considers the variations of one product. For example, seven material intensities for a typical standard small/ mid-size car, pick-up truck, and sports utility vehicle (SUV) were detailed in various reports intended to support a US-based model that evaluates fuel-cycle energy use and emissions of various transportation technologies (Burnham, Wang, and Wu, 2006; Burnham, 2012; Kelly, et al., 2015).

1.2. SCOPE OF THIS STUDY

Although research on in-use stocks and materials flowing into end-use products has increased substantially in recent years, there is still no global assessment quantifying multiple in-use materials stored in the anthropogenic mass with a detailed disaggregation into end-use products. There has also been no known prior attempt to construct a database specifying the composition of the anthropogenic mass, in terms of artifacts and immovable structures, which would give a new perspective on the spatio-temporal coupling between global materials flows and underlying societal needs for functions and services (Wiedmann, et al., 2020). A more complete picture of humans' engagement with the Earth system might be obtained by comparing the findings of such an endeavour to existing top-down ew-MFA estimates. This paper seeks to take a step toward a global and comprehensive database on material stocks embedded in various human-made artifacts and infrastructures through a bottom-up approach, grounded on inventory numbers and material intensities, and is oriented toward a holistic understanding of the human-Earth system. Considering that this research aims to resolve the geographic distribution of the anthropogenic mass, a location-based approach is taken, where materials embedded in artifacts and immovables are attributed to the country where they are being used or registered, instead of the country where materials are extracted or produced. Due to the nature of the data used to undertake this project, it is not possible to distinguish the percentage of recycled materials used to make the end-use goods. However, it is assumed that the contribution of recycled materials is moderately low as Haas, et al. (2015) pointed out in their study that recycled materials contributed only 6% of global material inputs in Europe.

Considering that desired end-uses and services can serve as the motivation for undertaking any human activity, a novel classification of items, or classes, comprising the anthropogenic mass is proposed. Centred on end-use applications, this activity-oriented perspective highlights whether items of the anthropogenic mass enhance the speed of processes, including the creation of new functions, or alter the physical context, most often the comfort level, in which humans spend their time. This activity-oriented classification is intended to be compatible with state variables of an Earth system that would completely integrate the human component in physical quantities, as proposed by Galbraith (2021).

2. METHODS

The database is built following a bottom-up approach, using inventory numbers and material intensities. The state variables considered here are the masses of each class comprising the anthropogenic mass, and the materials comprising them, such as the mass of agricultural machinery and the mass of steel embedded within the agricultural machinery. These state variables quantified at a point in time can then be spatially distributed according to a set of appropriate factors.

Overall, the in-use mass of nine material categories (aggregates, asphalt, concrete, iron/steel, aluminium, copper, plastic, glass, and wood/paper) embedded in 23 end-use classes of anthropogenic mass was estimated in 187 countries. Altogether, these materials comprises more than 90% of global stock-building materials in terms of mass (Krausmann, et al., 2017b). Bricks were the only material of global importance (91 Gt out of 1154 Gt as estimated in 2020 by Elhacham, et al., 2020) that was not considered due to its sole application in buildings construction. The current database does not yet include a class made of paper (e.g. books, graphic papers).

2.1. CONCEPTUAL FRAMEWORK

Each class of anthropogenic mass has been labeled with a two-level nested classification based on the end-use, or outcome, provided by the item. The first level, either functional or contextual, reflects whether the use of the class makes an impact on a state variable through an activity, including the production of new outcomes that wouldn't be possible without the item considered. For instance, the functional category includes roads and vehicles since they increase the rate of change of location resulting from an activity, just as machinery increases the production rate of manufacturing activities. Factory buildings are also included in the functional category since their purpose is to specifically host and facilitate manufacturing activities. However, non-factory buildings do not have a clear function under the activity-oriented perspective. Instead, they change the physical context in which people spend their time, frequently elevating the comfort level, so this category is deemed contextual. Cathedrals, shops, and houses may host diverse activities (e.g. praying, shopping, sleeping), but the nature of non-factory buildings is not related to a specific human activity, as compared to factory buildings, and the activities that take place in these premises could be done outside of them at a lower level of comfort. Other classes, like textiles and furniture, are also under the contextual category because they do not enhance the rate of any particular activity and simply alter the environment in which humans live. The second level of classification is related to the movability of an item. Functional classes can either be considered as *infrastructure* like railways, pipelines, factories, and industrial buildings if immovable, or as *activity modifiers* such as tools, vehicles, machines, and electronics if movable. Contextual classes if immovable are similarly subdivided into *non-factory buildings* (i.e. residential and service-sector buildings) and *comfort and decoration* if movable, which includes textiles and furniture. This systematic classification of the anthropogenic mass, consistent with Galbraith (2021), is intended to emphasize what roles each class serves and how they impact the human experience. By putting forward the functionality and movable attribute of a class, we can differentiate how much of a specific material contributes to enhancing the rate of human activities and how much is used for other purposes. It then becomes possible to point out the services rendered by the different materials, a perspective not possible from traditional top-down ew-MFA studies. A conceptual diagram of the nested classification is presented in figure 1. Table 1 provides an overview of the anthropogenic mass end-use classes appraised in this project, their corresponding two-level classification, and the spatio-temporal coverage of each dataset within the database.

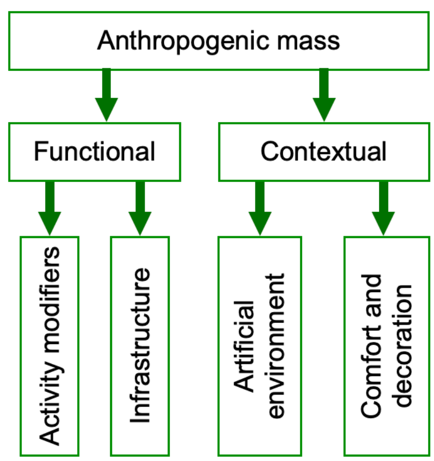

Fig. 1. Schematic representation of the main categories within the classification of the anthropogenic mass

Table 1. End-use categorization of anthropogenic mass and spatio-temporal coverage of datasets. Bottom-up approach refers to the use of inventory numbers and material intensities, while top-down allocates a portion of the global stock to the class.

Label	Category	End-use class	Time-series	Spatial resolution		Approach	
				Country-level	Global	Bottom-up	Top-down
Functional	Activity modifier	Passenger cars	x	x		x	
Functional	Activity modifier	Commercial vehicles	x	x		x	
Functional	Activity modifier	Rolling stock		x		x	
Functional	Activity modifier	Merchant fleet	x	x		x	
Functional	Activity modifier	Shipping containers			x	x	
Functional	Activity modifier	Commercial aircrafts		x		x	
Functional	Activity modifier	Military equipment		x		x	
Functional	Activity modifier	Manufacturing and construction machinery			x		x
Functional	Activity modifier	Agricultural machinery	x	x		x	
Functional	Activity modifier	Domestic appliances			x		x
Functional	Activity modifier	Food and beverage packaging			x		x
Functional	Activity modifier	Other packaging			x		x
Functional	Activity modifier	Consumer electronics			x		x
Functional	Activity modifier	Medical equipment			x		x
Functional	Infrastructure	Roads		x		x	
Functional	Infrastructure	Railways		x		x	
Functional	Infrastructure	Pipelines		x		x	
Functional	Infrastructure	Electricity network		x		x	
Contextual	Artificial environment	Residential buildings	x	x		x	
Contextual	Artificial environment	Service-sector buildings	x	x		x	
Contextual	Comfort and decoration	Tableware			x		x
Contextual	Comfort and decoration	Furnitures			x		x
Contextual	Comfort and decoration	Textiles			x	x	

2.2. DATA COLLECTION AND PROCESSING

Publicly available inventory numbers, material-specific data, and material intensities from international organizations, business leaders, and peer-reviewed studies were compiled and harmonized. Data availability and quality vary greatly across years, sources, materials, and coverage. Out of the 23 classes, country-specific information was found for more than half, with the remaining being global estimates. Consistent with consumption-based accounting, objects were allocated to countries where the classes are used (e.g. agricultural machinery, military equipment) or are registered (e.g. airplanes, merchant fleet) rather than where they are manufactured. Time-series were downloaded when available for future use, although the main goal of the database is to portray the composition of the anthropogenic mass in 2020. Time-series were available for six classes. Datasets were visually inspected to filter poor quality information, fill gaps, and adjust values when necessary by comparing estimates from alternative sources. In general, when averages had to be calculated, the arithmetic mean between the geometric and arithmetic mean of the datapoints was taken, following Bar-On, et al. (2018). Missing entries in time-series were filled by linear regression. If datasets provided information prior to but not including year 2020, it was assumed the proportion of each material embedded in the items of interest, out of global stocks for the latest year available, was the same in year 2020 (eq.1).

$$S_{m,i,2020} = S_{m,i,y} * \frac{G_{m,2020}}{G_{m,y}} \tag{1}$$

S : Stock of material *m*, in item *i*, for year *y*

G : Global stock of material *m*, for year *y*

For the analysis, country-level information on population, income classes, and gross domestic product per capita, in purchasing power parity 2017 international dollar, (GDP_{capita}) were gathered from World Bank and the International Money Fund (World Bank, 2021a.b.c; IMF, 2021).

2.3. UNCERTAINTY ASSESSMENT

None of the inventory numbers collected were published with error estimates or an evaluation of their accuracy. Moreover, additional data uncertainty was introduced through the anlaysis by assumptions and category-specific parameters (e.g. material intensity in different products). Systematic uncertainty assessment was therefore done following a method described in Plank, et al. (2022b), and originally developed by Laner, et al. (2015). The reliability of the data sources and estimation procedures to construct the database was evaluated by translating ordinal scoring of data quality into normally distributed uncertainty ranges. The scoring of reported data was conducted along five independent quality indicators (reliability, completeness, temporal correlation, geographical correlation and other correlation) and for expert judgments (Laner, et al., 2015) (Fig.2). Section U of the Supplementary Information (SI) presents in detail the uncertainty assessment conducted in this project.

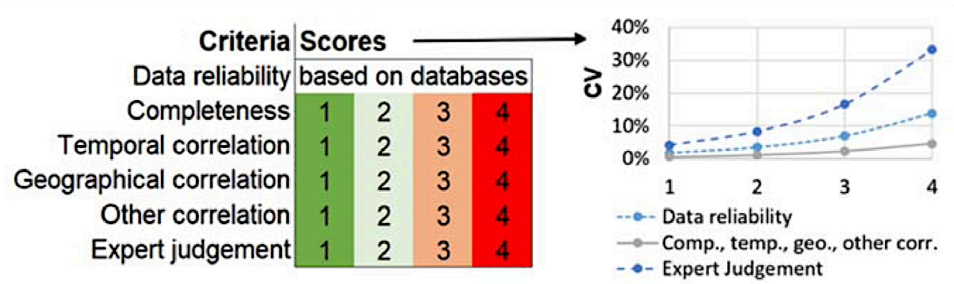

Fig. 2. Uncertainty assessment framework presented in Plank, et al. (2022a) and based on Laner, et al. (2015) where scoring of six criteria is used to assess the reliability of final results and determine a coefficient of variation (CV).

2.4. EXAMPLE : GLOBAL RAILWAY ASSESSMENT

A thorough documentation of data sources, processing, and estimation procedures for each class considered is fully described in the SI. Here, an overview of the approach is provided, using the mass of railways as an example (details in section E of the SI).

- Three datasets on total national railway length (km), irrespective of the number of parallel tracks, were found (UNECE, 2021; CIA, 2021; World Bank, 2021d). The year of reporting for the three sources was assumed to be representative of the year 2017.
- Each source was plotted against the others to highlight important discrepancies between the three sources (Fig. S5). Data for nine countries were inconsistent and were individually investigated. The final value in each case was determined by finding an alternative source of information, usually from official statistical portals or governmental reports. For example, World Bank and CIA data significantly disagree on the length of railways in China. Since it was possible to retrieve the length of the network in 2018 from China Statistical Yearbook published by the Chinese government, the latter value was used in the subsequent analysis.
- The estimate of railway length for 132 countries was determined according to the number of sources :
    - One source of information : the value was used directly after being checked for a possible inconsistency (e.g. large railway network in a small isolated country)
    - Two or three sources available, with no significant gap between data points (less than 10% difference) : arithmetic mean between the data points

- Two or three sources available, with a significant gap between data points but not addressed in Fig. S5 : alternative sources were used to determined which value was more likely representative of the reality.

• The length of double tracks (or more) was reported in 40 countries by UNECE (2021), none of which was classified as a low-income country. It was assumed there would be a maximum of two parallel tracks in a network. Out of the 132 countries considered, 92 were attributed a double track ratio (R), based on a linear regression using population density (R = 0.00125*Pop.Density + 0.156, adjusted R^2 = 0.5106). However, if a country was classified in the low-income group, the value 0 was assumed. Unusually high values for three countries were manually adjusted. Final railway lengths were then corrected to account for the presence of two parallel tracks at most.

• Material requirement for railway tracks was determined after reviewing construction practices and reports from global manufacturers and a seminal study (AGICO, 2017; Indian Railways Institute, 2019; Huang, 2013). It was assumed one kilometre of functional railway required 117.7 metric tonnes of steel. Materials for railway sleepers and gravel for ballast could not be quantified at the time of this paper.

• Lengths of railways determined as explained above were multiplied by the estimated material intensity. In this case, the mass of railway tracks and the mass of steel were quantified and scaled to the year 2020 based on eq.1.

3. RESULTS

Figure 3 shows how the bottom-up estimates of material stocks embedded in end-use classes across all countries compares to global stocks evaluated through the ew-MFA framework by peer-reviewed studies (data from literature reported in Table S1, section A). Globally, more than 80% of the global mass of aggregates, glass, iron/steel, and wood/paper is accounted for by the end-use classes listed in Table 1. In fact, out of the nine material categories, six are equal within their respective uncertainty range. Only for concrete and plastic is there a significant portion that has not been covered by the database. While most stocks are incompletly accounted for, the stock of aluminium is 60% greater than the global estimate. Copper is slightly overestimated as well, although falling within the limits of uncertainty ranges. Table 2 reports the absolute mass accounted for, as well as the global stocks estimated by ew-MFA studies, for each material category. Details for estimates from global ew-MFA studies (e.g. sources, standard deviations) are summarized in the SI, section A and Table S1. Out of the 699 Gt of materials accounted for, 54% (377 Gt) was embedded in roads and 35% (246 Gt) in residential buildings. Most of the missing anthropogenic mass is concrete (291 Gt), which is thought to be stored in various functional infrastructures that are poorly documented, such as industrial buildings, energy and food storage facilities, as well as marine and road infrastructure.

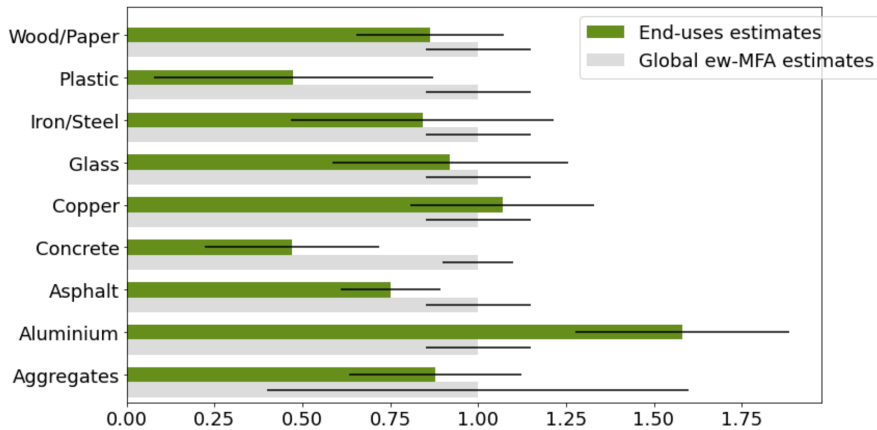

Fig.3. Fraction of total material stocks accounted in the end-use approach (green) out of ew-MFA estimates (light grey) in 2020. Uncertainty bars are ±2 standard deviations (95% confidence interval). Uncertainty for end-use estimates corresponds to the total coefficient of variation calculated between sources contributing to each material stock (Table S12).

Table 2. Absolute mass of material stocks in 2020 accounted for in the end-use approach compared to global stock estimations from ew-MFA studies.

	Concrete	**Aggregates**	**Asphalt**	**Iron/ Steel**	**Wood/ Paper**	**Plastic**	**Glass**	**Aluminium**	**Copper**
2020 Stock (Mt)	548 566	386 345	64 677	35 434	16 400	3 630	2 042	1 000	486
Mass accounted for (Mt)	257 696	339 535	48 520	30 144	14 156	1 846	1 878	1 581	519

The composition of each material stock within the database, under the perspective of the activity-oriented classification, is presented in figure 4. On an absolute scale, the mass embedded in infrastructure comprises 56% of total mass accounted for in the database, and the artificial environment 42%, while activity modifiers and comfort and decoration classes make only 2% and 0.1% respectively. The artificial environment, composed solely of residential and service-sector buildings, requires the majority of each following stock: wood, concrete, glass, and all metals. The infrastructure category, made of functional immovable structures, accounts most of the aggregate stock and global asphalt, the two main materials employed in roads[1]. Activity modifier items require 57% and 37% of in-use plastic and aluminium stock accounted for respectively (Fig. 4)

[1] Road surfaces specifically, as road infrastructures (e.g. bridges, tunnels, protection walls, sidewalks, etc.) have not yet been included in the database.

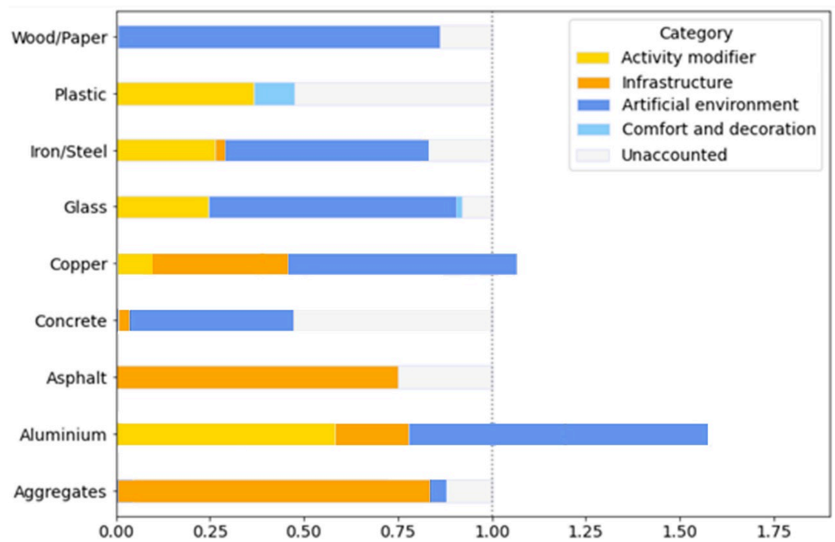

Fig. 4. Fraction of total material stocks accounted for in the end-use approach out of global ew-MFA estimates in 2020 with relative contribution of each category of end-use classes.

The data compilation shows how the well-known increase of material use with income differs by end-use category (Fig. 5). The comfort and decoration category is not represented due to poor country-level data. The other three resolved categories all increase with per-capita GDP. Largely dominated by concrete and aggregates, there are roughly 200 t/capita of materials that form the artificial environment and infrastructure in the highest income countries, which is an order of magnitude greater than in the lowest income countries. Activity modifiers, accelerating the rate of change of human activities, span across almost four orders of magnitude in terms of

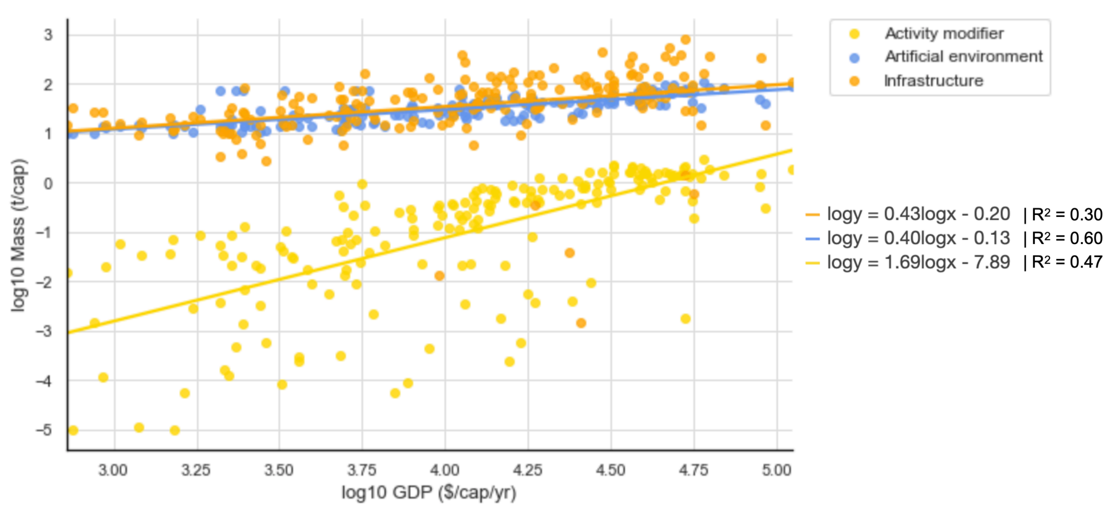

Fig. 5. Correlation between per capita total anthropogenic mass embedded in end-use categories and per capita GDP, for all countries in 2020. Regression equations are specified on the right. Additional figures for each material are shown in SI, section V (Fig. S6-S8).

anthropogenic mass per capita between the highest and lowest income countries (Fig. 5). Plastic mass per capita, followed by aluminium and iron/steel, in activity modifier items are the materials the most coupled to per-capita GDP, despite a high variance in the lowest income group (Fig. S9-S10).

Materials of importance for functional items are iron/steel and aggregates, with the former embedded in activity modifiers, such as manufacturing machinery, vehicles and domestic appliances, and the latter used in road construction. Plastic is another notable material for activity modifiers (Fig. 5 and 6). The comfort and decoration category seems to be mainly made of plastic, but this is skewed representation because very few items were appraised in this category. The main use of concrete is for the construction of the artificial environment (i.e. non-factory buildings), showcasing the importance of residential and service-sector buildings (Fig. 6).

Figure 7 shows the per-capita mass of concrete embedded in the artificial environment and infrastructures around the world in 2020. Most of the material accounted for is stored in residential buildings (Fig. S11) and further research is needed to determine where the unaccounted concrete mass is used. High mass per capita correlates well with location of high

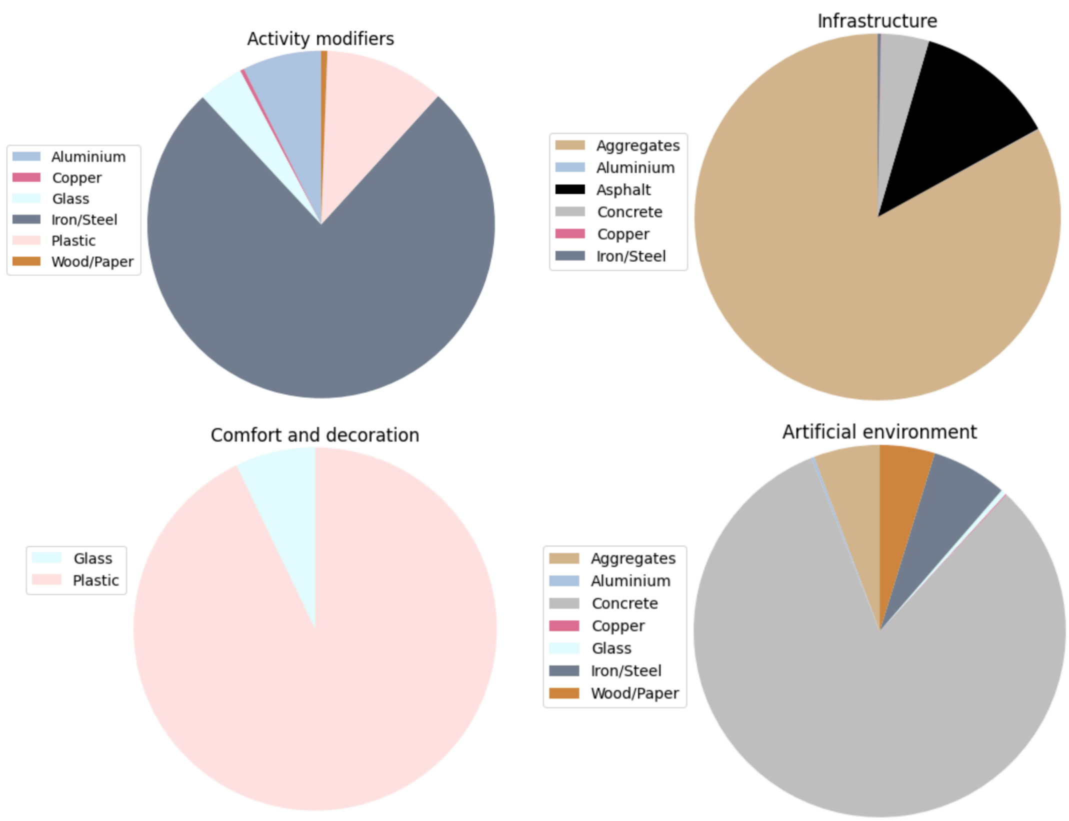

Fig. 6. Material composition of the anthropogenic items appraised within each functional (top) and contextual (bottom) categories

income countries, most notably in the USA, Canada, and Australia. China's use of concrete per capita is about the same as European countries.

In additional figures presented in SI (Fig. S12-S14), trends in the level of material consumption per capita mostly stay the same in a country across all materials examined; there aren't countries with a high level of material consumption for one material and not for the others. However, on a per-capita basis, the US distinguished itself from all other countries by having the highest per-capita mass for all materials (Fig. S12-S14), except for iron and steel. The per-capita mass of iron/steel mass is quite similar around the world, with a global average of 4t/capita (Fig. S12). The exceptions to this are the Bahamas, Panama, and Liberia, with a per-capita value over 100 metric tonnes due to the large concentration of the merchant fleet being registered in those countries, for legal and financial advantages, and relatively small population size (Fig. S12-S14 for material specific maps).

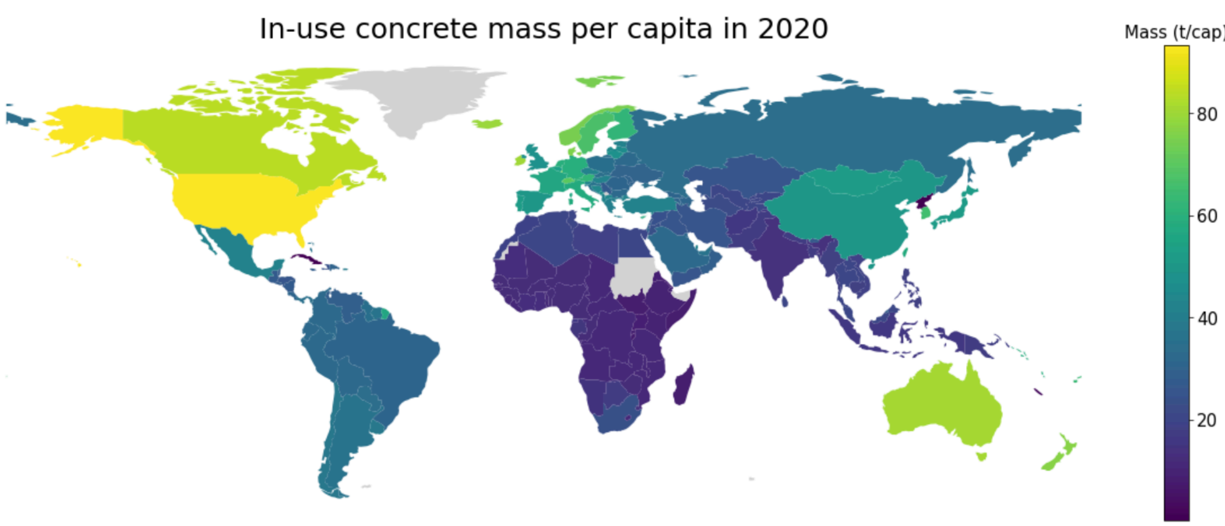

Fig. 7. Per capita mass of in-use concrete in 2020 across countries. Grey areas have no data

4. DISCUSSION

A novel database of 23 end-use classes forming the anthropogenic mass was presented in which nine global material stocks within end-use classes were quantified. The 23 classes investigated sum to 66% (699 Gt) of the total anthropogenic mass (1060 Gt) estimated in top-down ew-MFA studies. Six out of nine material stocks were appraised within 20% of their current ew-MFA estimates. Only concrete, plastic, and aluminium did not align closely with top-down values (Fig. 2-3). Out of the 699 Gt of materials accounted for, 54% (377 Gt) was embedded in roads, and 35% (246 Gt) in residential buildings. On an absolute scale, 24% of the 699 Gt was located in China, 13% in the United States, and 7% in India (Fig. S14), while on a per-capita basis, the United States had the greatest mass per capita for all materials, except iron/steel.

The analysis has focused on material standing stocks, rather than material fluxes, as a first step. Despite not storing much materials, activity modifiers and comfort and decoration categories were usually defined by classes with shorter lifetimes. With 51% (1.9 Gt) of global plastic stock (3.6 Gt) stored in those two categories, higher turnover rates of end-use classes can create dramatic environmental problems worldwide (Geyer, et al., 2017). Expanding the current database should not only consider adding end-use classes that store a significant mass of materials, but also classes of importance for the human experience that have a higher turnover rate.

Most of the missing anthropogenic mass was concrete (291 Gt), which is thought to be stored in various functional infrastructures that are poorly documented, such as industrial buildings, energy and food storage facilities, as well as marine and road infrastructure. Therefore the per-capita mass of concrete was likely underestimated by approximately half (Fig. 6). The same goes for plastic as only 51% of global stock from ew-MFA was accounted for, hence the per-capita mass was also underestimated by half (Fig. S13).

The activity-oriented classification allowed for a better understanding of the purpose of material stocks, an angle not possible under the top-down ew-MFA approach. Aluminium, iron and steel, and plastic were important materials for activity modifier classes, while the majority of copper, concrete, and aggregates were used in immovables structures (e.g. infrastructures and non-factory buildings). Almost all of the global wood stock could be accounted for by non-factory buildings specifically. This classification can help identify the priorities in climate mitigation actions as the inventory of the anthropogenic mass allows to put in perspective what really matters in terms of mass and with more information on the fluxes, what artifacts or immovables have the most impact on the environment. Such analytic tool could be an additional argument to support why advocate for some environmental choices and political decisions and not for others.

A systematic assessment of data reliability by ordinal scoring of data quality for each source was translated into a continuous coefficient of variation (CV) based on the framework by Laner, et al. (2015) and application by Plank, et al. (2022b). Resulting CVs are a reflection of data availability and compilation procedures. Although the general reliability of initial datasets was evaluated, many intermediary parameters (e.g. material intensities, fractions of global stock, lifetimes) were poorly constrained and it was not possible to evaluate the error carried in each of them. Future work may be able to improve on this by developing a Bayesian framework, however this was beyond the scope of this study.

Scarcity of data was the main obstacle that limited the inclusion of more classes in the database. It was also the main reason why all materials used within an end-use class could not always be assessed. For instance, due to lack of information, the plastic, aluminium, and glass embedded in domestic appliances may only be roughly estimated, thus carrying a greater uncertainty.

Poorly constrained values of material intensities intensities added significant uncertainty to our estimates. For instance, most of the aluminium stock accounted for was stored in residential buildings (Fig. 2 and S9), with an average aluminium content of 2.91 kg/m^2 (Table S3). This material intensity was based on 16 sources mostly from high income industrial countries. Dwellings and informal housing in the Global South are most likely less aluminium intensive, highlighting the need for more geographically diverse estimates of material intensities. The high aluminium intensities in wealthy countries may explain our high global estimate of aluminium stock. At the same time, it is worth mentioning that the rapid rise in global aluminium demand that has occured over the last 60 years, and still ongoing (Cullen and Allwood, 2013), may not be captured well enough by stock-flow models from ew-MFA studies. From 1950 to 2007, there has been a 30-fold increase in global aluminium demand, reaching 47 Mt/yr in 2007 (Cullen and Allwood, 2013). Fifteen years later, aluminium production, assumed to be equivalent to the demand, has now reached 65 Mt (Government of Canada, 2022), an increase of 40%. It is therefore tentatively suggested that the global in-use stock of aluminium may be significantly higher than estimates from existing ew-MFA studies (Elhacham, et al., 2020; Krausmann, et al., 2018; Plank, et al., 2022a).

The database presented here is intended as the first step in an ongoing compilation effort. Further development in satellite data and image processing will refine estimates of material stocks embedded in the artificial environment and provide the data needed to include more end-use classes within the functional infrastructure category. Also, as in-use stocks are just one perspective on material uses, the database proposed here should be further developed to integrate material fluxes and emissions by end-use classes.

5. CONCLUSION

This paper has presented what is, to our knowledge, the first initiative towards a comprehensive global end-use oriented assessment of the material stocks embedded in the anthropogenic mass. The anthropogenic mass was classified according to end-uses which are consistent with a generalized human activity framework (Galbraith, 2021), so that coupling between global material flows and functions and services offered by the manufactured capital can be better understood.

As a first step towards a comprehensive accounting, this work assessed nine material types within 23 end-use classes. Overall, 66 ± 33 % of the total anthropogenic mass estimated by top-down ew-MFA studies was accounted for. Encouragingly, most of the missing mass can be attributed to concrete. Despite limitations of publicly available data for other materials, our global estimates of six out of nine material stocks (i.e. aggregates, asphalt, iron/steel, copper, glass, wood/paper) fell within uncertainty ranges of top-down ew-MFA studies. This reasonable agreement between top-down and bottom-up estimates shows that the numerous end-use types that still remain to be assessed are likely to comprise only a small fraction of global material stocks. Per-capita trends depicted the US as the country with one of the highest mass per person for eight out of the nine material types, which can be attributed to decades of mass consumption and production (Freudenberg, 2021).

The functions and services delivered by human-made artifacts and immovables are a key component of social progress (Haberl, et al., 2017; Chen and Graedel, 2015; Mayer, et al., 2017). Understanding how the anthropogenic mass influences human well-being, via the functions and services offered to society, and how it contributes to material flows would provide a new narrative for further investigations on the impact of human activities. It is hoped that future work can build upon the foundations laid here to eventually provide a complete end-use accounting of the anthropogenic mass.

REFERENCES

AGICO (2017) “Chinese Steel Rails Overview”, visited 13 December 2021. http://www.railway-fasteners.com/news/steel-rails-overview.html

Andersson, D. et al. (2014) “Greenhouse gas emissions and subjective well-being: An analysis of Swedish households”, Ecological Economics, 102, pp. 75–82. doi: 10.1016/j.ecolecon.2014.03.018.

Aoe, T. and Michiyasu, T. (2005) “ 'Ecological rucksack' of high-definition TVs”, Materials Transactions, 46(12), pp. 2561–2566. doi: 10.2320/matertrans.46.2561.

Bar-On, Y. M., Phillips, R. and Milo, R. (2018) “The biomass distribution on Earth”, Proceedings of the National Academy of Sciences of the United States of America, 115(25), pp. 6506–6511. doi: 10.1073/pnas.1711842115.

Capstick, S. et al. (2014) “Prospects for radical emissions reduction through behavior and lifestyle change”, Carbon Management, 5(4), pp. 429–444. doi: 10.1080/17583004.2015.1020011.

Carmona, L. G. et al. (2021) “The use of steel in the United Kingdom’s transport sector: A stock–flow–service nexus case study”, Journal of Industrial Ecology, 25(1), pp. 125–143. doi: 10.1111/jiec.13055.

Chen, W. Q. and Graedel, T. E. (2015) “In-use product stocks link manufactured capital to natural capital”, Proceedings of the National Academy of Sciences of the United States of America, 112(20), pp. 6265–6270. doi: 10.1073/pnas.1406866112.

CIA — Central Intelligence Agency (2021) “The World Factbook — Railways”. Electronic dataset, visited 2 December 2021. https://www.cia.gov/the-world-factbook/field/railways/

Cullen, J. M. and Allwood, J. M. (2013) “Mapping the global flow of aluminum: From liquid aluminum to end-use goods”, Environmental Science and Technology, 47(7), pp. 3057–3064. doi: 10.1021/es304256s.

Cullen, J. M., Allwood, J. M. and Bambach, M. D. (2012) “Mapping the global flow of steel: From steelmaking to end-use goods”, Environmental Science and Technology, 46(24), pp. 13048–13055. doi: 10.1021/es302433p.

Druckman, A. and Gatersleben, B. (2019) “A time-use approach: high subjective well-being, low carbon leisure”, Journal of Public Mental Health, 18(2), pp. 85–93. doi: 10.1108/JPMH-04-2018-0024.

Elhacham, E. et al. (2020) “Global human-made mass exceeds all living biomass”, Nature, 588(7838), pp. 442–444. doi: 10.1038/s41586-020-3010-5.

Eurostat (2018) “Economy-wide material flow accounts — Handbook”, Eurostat Manuals and Guidelines. Publications Office of the European Union, Luxembourg.

Freudenberg, N. (2021) “At what cost: modern capitalism and the future of health”, Oxford University Press, New York. USA. pp.3-35

Galbraith, E. D. (2021) “Earth system economics: A biophysical approach to the human component of the Earth system”, Earth System Dynamics, 12(2), pp. 671–687. doi: 10.5194/esd-12-671-2021.

Geyer, R., Jambeck, J. R. and Law, K. L. (2017) “Production, use, and fate of all plastics ever made”, Science Advances, 3(7), pp. 25–29. doi: 10.1126/sciadv.1700782.

Giljum, S. et al. (2014) “Global patterns of material flows and their socio-economic and environmental implications: A MFA study on all Countries world-wide from 1980 to 2009”, Resources, 3(1), pp. 319–339. doi: 10.3390/resources3010319.

Government of Canada (2022) “Aluminium Facts”, visited 6 June 2022. https://www.nrcan.gc.ca/our-natural-resources/minerals-mining/minerals-metals-facts/aluminum-facts/20510#L1

Haas, W. et al. (2015) “How circular is the global economy?: An assessment of material flows, waste production, and recycling in the European union and the world in 2005”, Journal of Industrial Ecology, 19(5), pp. 765–777. doi: 10.1111/jiec.12244.

Haberl, H. et al. (2017) “The material stock-flow-service nexus: A new approach for tackling the decoupling conundrum”, Sustainability (Switzerland), 9(7). doi: 10.3390/su9071049.

Hatayama, H. et al. (2010) “Outlook of the world steel cycle based on the stock and flow dynamics”, Environmental Science and Technology, 44(16), pp. 6457–6463. doi: 10.1021/es100044n.

Hickel, J. and Kallis, G. (2020) “Is Green Growth Possible?”, New Political Economy, 25(4), pp. 469–486. doi: 10.1080/13563467.2019.1598964.

Huang, N. (2013) “Infrastructure” in “Living with a fair share ecological footprint”, editors : Robert and Brenda Vale, 1st edition, publisher : Routledge, London, UK. pp.120. doi : 10.4324/9780203126448

IEA — International Energy Agency (2019a) “Material efficiency in clean energy transitions”, International Energy Agency, Paris. https://iea.blob.core.windows.net/assets/52cb5782-b6ed-4757-809f-928fd6c3384d/Material_Efficiency_in_Clean_Energy_Transitions.pdf

IEA — International Energy Agency (2019b) “2019 Global status report for buildings and construction”, International Energy Agency, Global Alliance for Buildings and Construction, United Nations Environment Programme. https://www.unep.org/resources/publication/2019-global-status-report-buildings-and-construction-sector

IMF — International Money Fund (2021) “World Economic Outlook Database - October 2020 Edition”, electronic dataset, downloaded 29 June 2021. https://www.imf.org/en/Publications/WEO/weo-database/2020/October

Indian Railways Institute (2019) “Rail steels and stresses”, Institute of Civil Engineering, visited during December 2021.https://www.iricen.gov.in/iricen/books_jquery/railsteel.pdf

IPCC — Intergovernmental Panel on Climate Change (2022) “Climate Change 2022 - Mitigation of Climate Change”, Working Group III contribution to the IPCC Sixth Assessment Report, Summary for Policymakers, Cambridge University Press. UK.

Jackson, T. (2005) “Live better by consuming less? Is there a 'double dividend’ in sustainable consumption?”, Journal of Industrial Ecology, 9(1–2), pp. 19–36. doi: 10.1162/1088198054084734.

Jemiolo, W. (2015) “Life cycle assessment of current and future passenger air transport in Switzerland”, (February-December), p. 103.

Kalt, G. et al. (2021) “Material stocks in global electricity infrastructures – An empirical analysis of the power sector’s stock-flow-service nexus”, Resources, Conservation and Recycling, 173, p. 105723. doi: 10.1016/j.resconrec.2021.105723.

Krausmann, F. et al. (2017a) “Material Flow Accounting: Measuring Global Material Use for Sustainable Development”, Annual Review of Environment and Resources, 42, pp. 647–675. doi: 10.1146/annurev-environ-102016-060726.

Krausmann, F. et al. (2017b) “Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use”, 114(8), pp. 21–26. doi: 10.1073/pnas.1613773114.

Krausmann, F. et al. (2018) “From resource extraction to outflows of wastes and emissions: The socioeconomic metabolism of the global economy, 1900–2015”, Global Environmental Change, 52(April), pp. 131–140. doi: 10.1016/j.gloenvcha.2018.07.003.

Krausmann, F., Wiedenhofer, D. and Haberl, H. (2020) “Growing stocks of buildings, infrastructures and machinery as key challenge for compliance with climate targets”, Global Environmental Change, 61(January), p. 102034. doi: 10.1016/j.gloenvcha.2020.102034.

Kwak, M. et al. (2012) “Comparative life cycle assessment of complex heavy-duty off-road equipment”, Proceedings of the ASME Design Engineering Technical Conference, 5, pp. 425–433. doi: 10.1115/DETC2012-70547.

Lähteenoja, S., Lettenmeier, M., Kotakorpi, E. (2008)“The ecological rucksack of households: huge differences, huge potential for reduction”, Chapter 22 of “Sustainable consumption and production: framework for action : 2nd conference of the Sustainable Consumption Research Exchange (SCORE!) network”, Editor : Theo Geerken. Flemish Institute for Technological Research, Brussels, Belgium. pp.319-337

Laner, D. et al. (2015) “A Novel Approach to Characterize Data Uncertainty in Material Flow Analysis and its Application to Plastics Flows in Austria”, Journal of Industrial Ecology, 20(5), pp. 1050–1063. doi: 10.1111/jiec.12326.

Martínez, D.M. and Ebenhack, B.W. (2008) “Understanding the role of energy consumption in human development through the use of saturation phenomena”. Energ Policy 36: 1430–1435. doi: 10.1016/j.enpol.2007.12.016.

Mayer, A., Haas, W. and Wiedenhofer, D. (2017) “How Countries’ Resource Use History Matters for Human Well-being – An Investigation of Global Patterns in Cumulative Material Flows from 1950 to 2010”, Ecological Economics, 134, pp. 1–10. doi: 10.1016/j.ecolecon.2016.11.017.

Müller, D. B., Wang, T. and Duval, B. (2011) “Patterns of iron use in societal evolution”, Environmental Science and Technology, 45(1), pp. 182–188. doi: 10.1021/es102273t.

Müller, E. et al. (2013) “Material and energy flows and environmental impacts of the internet in Switzerland”, Journal of Industrial Ecology, 17(6), pp. 814–826. doi: 10.1111/jiec.12056.

National Bureau of Statistics of China (2022) “China Statistical Yearbook 2019”, Table 16-3 and Table 16-4, visited 11 January 2022. http://www.stats.gov.cn/tjsj/ndsj/2019/indexeh.htm

Ottelin, J. et al. (2019) “Household carbon footprint patterns by the degree of urbanisation in Europe”, Environmental Research Letters, 14(11). doi: 10.1088/1748-9326/ab443d.

Pauliuk, S. and Müller, D. B. (2014) “The role of in-use stocks in the social metabolism and in climate change mitigation”, Global Environmental Change, 24(1), pp. 132–142. doi: 10.1016/j.gloenvcha.2013.11.006.

Plank, B. et al. (2022a) “From resource extraction to manufacturing and construction: flows of stock-building materials in 177 countries from 1900 to 2016”, Resources, Conservation and Recycling, 179(September 2021). doi: 10.1016/j.resconrec.2021.106122.

Plank, B. et al. (2022b) “Compilation of an economy-wide material flow database for 14 stock-building materials in 177 countries from 1900 to 2016”, MethodsX, 9, p. 101654. doi: 10.1016/j.mex.2022.101654.

Ritthoff, M., Rohn, H., Liedtke, C. (2002) “Calculating MIPS : Resource productivity or products and services”, Wuppertal Spezial no. 27e, Wuppertal Institute for Climate, Environment and Energy. ISBN : 3929944561. https://www.econstor.eu/handle/10419/59294

Schaffartzik, A. et al. (2014) “The global metabolic transition: Regional patterns and trends of global material flows, 1950-2010”, Global Environmental Change, 26(1), pp. 87–97. doi: 10.1016/j.gloenvcha.2014.03.013.

UNECE — United Nations Economic Commission of Europe (2021) Electronic dataset, downloaded 16 November 2021. https://w3.unece.org/PXWeb2015/pxweb/en/STAT/STAT__40-TRTRANS__11-TRINFRA/ZZZ_en_TRRailInfra1_r.px/

Vita, G. et al. (2019) “Connecting global emissions to fundamental human needs and their satisfaction”, Environmental Research Letters, 14(1). doi: 10.1088/1748-9326/aae6e0.

Wang, C. et al. (2021) “Critical review of global plastics stock and flow data”, Journal of Industrial Ecology, 25(5), pp. 1300–1317. doi: 10.1111/jiec.13125.

Westbroek, C. D. et al. (2021) “Global material flow analysis of glass: From raw materials to end of life”, Journal of Industrial Ecology, 25(2), pp. 333–343. doi: 10.1111/jiec.13112.

Wiedenhofer, D. et al. (2018) “Household time use, carbon footprints, and urban form: a review of the potential contributions of everyday living to the 1.5 °C climate target”, Current Opinion in Environmental Sustainability, 30, pp. 7–17. doi: 10.1016/j.cosust.2018.02.007.

Wiedenhofer, D. et al. (2019) “Integrating Material Stock Dynamics Into Economy-Wide Material Flow Accounting: Concepts, Modelling, and Global Application for 1900–2050”, Ecological Economics, 156(April 2018), pp. 121–133. doi: 10.1016/j.ecolecon.2018.09.010.

Wiedmann, T. et al. (2020) “Scientists’ warning on affluence”, Nature Communications, 11(1), pp. 1–10. doi: 10.1038/s41467-020-16941-y.

World Bank (2021a) “Population, Total”, electronic dataset, World Development Indicators, downloaded on 19 February 2021. https://data.worldbank.org/indicator/SP.POP.TOTL?end=2019&start=1990

World Bank (2021b) “Urban population (% of total population)”, electronic dataset, downloaded on 19 February 2021. https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS

World Bank (2021c) “World Bank Country and Lending Groups”, electronic dataset, downloaded on 30 September 2021). https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups

World Bank (2021d). “Rail lines (total route-km)”, electronic dataset, downloaded 16 November 2021. https://data.worldbank.org/indicator/IS.RRS.TOTL.KM?view=map&year=2018

SUPPLEMENTARY INFORMATION

The primary goal of this paper was to produce global estimates, resolved by country where possible, of the most important classes of anthropogenic mass as defined by end-uses and relate them to stocks of materials. Multiple studies and reports were compiled and harmonized to arrive at the results presented in the main paper. For each class appraised, data sources and assumptions are detailed, followed by the method for quantifying the mass of materials embedded in those artifacts and immovables. Fitting methods and general considerations are also included. Uncertainty assessments are specifically addressed in section U. The resulting database can easily be updated and all code written (Python v.3.8.1) is made available.

Overview

A. ECONOMY-WIDE ESTIMATES OF GLOBAL STOCKS FROM LITERATURE

Results from ew-MFA model of stock accumulation in the anthropogenic mass developed by Krausmann, et al. (2018) were extrapolated from 2015 to 2020 by Elhacham, et al. (2020). Plank, et al. (2022) evaluated the 1900-2016 gross additions to stocks per year (GAS), or the amount of primary materials entering global in-use phase of the anthropogenic mass, after processing losses and excluding input of secondary materials. The results were projected to 2020 in this paper according to the steps described in the next section. Global material stocks from top-down ew-MFA studies used in this project are summarized in Table S1.

Table S1. Gross additions to stocks and global stocks of materials accumulating in the anthropogenic mass in 2020, with their respective standard deviations. GAS and stocks are from Elhacham, et al. (2020), Plank, et al. (2022) and other sources. n.d. … no data

Material	**Description**	**2020 GAS (Mt/yr)** ± 2 StdDevs	**2020 Stock (Mt)** ± 3 StdDevs
concrete	cement and aggregates (sand/gravel) mostly used in building and infrastructure construction	29 059.8 ± 8.1%	548 566.2 ± 10%
sand/gravel	mainly used as bedding for roads and buildings — aggregates used for concrete and asphalt production are accounted in those categories and not here	n.d.	386 344.7 ± 60%
asphalt	bitumen and aggregates (sand/gravel) used mainly for road construction/pavement	* 2 686.8 ± 8.7%	64 676.6 ± 15%
iron/steel	main in-use metal	1 001.5 ± 8.3%	35 433.5 ± 15%
aluminium	second most used metal	[1] 65.3 ± 14.2%	1 000.0 ± 15%
copper	third most used metal	[2] 25.0 ± 14.2%	485.5 ± 15%
container glass	mainly used in food and beverage sector	* 91.7 ± 38%	* 398.1 ± n.d
flat glass	architectural and window glass	* 82.4 ± 38%	1 643.5 ± 15%
other glass	tableware, reinforced fibres, others	* 17.0 ± 38 %	n.d.
plastic	different kind of plastic composites	422.1 ± 16.2%	3 629.8 ± 15%
wood and paper	solidwood products, books, newspaper, cardboard	722.0 ± 7.7%	16 400.4 ± 15%

[1] 2020 data from Government of Canada (2022) because GAS from Plank, et al. (2022) also included copper and other metals. Uncertainty was assumed to be the same as estimated by Plank, et al. (2022)

[2] 2020 production of refined copper from USGS (2021). Uncertainty was assumed to be the same as estimated by Plank, et al. (2022)

* derived from other assumptions and sources, details in section below

Scaling of GAS from 2015 to 2020

Two approaches were employed to scale material-specific gross addition to stocks (GAS) from Plank, et al. (2022a) to year 2020. Method 1 multiplied the 2015 GAS of material *m* by the overall increase in global stock of material *m* from 2015 to 2020 (eq.S1). Method 2 assumed GAS of material *m* increased by 2.9% each year, based on the 2010-2016 average growth of global GAS, all materials combined (eq.S2). Difference in results between the two methods was less than 2%; the arithmetic mean was taken and reported in Table S1.

$$GAS_{m,2020} = GAS_{m,y} * \frac{G_{m,2020}}{G_{m,y}} \quad \text{(S1)}$$

$$GAS_{m,2020} = GAS_{m,y} * (1 + 0.029)^{2020-y} \quad \text{(S2)}$$

GAS : gross addition to stock of material *m*, in year *y*

G : global stock of material *m*, in year *y* (from Elhacham, et al., 2020)

Special modifications for asphalt and glass

Asphalt. Initially, GAS from Plank, et al. (2022a) did not include input of secondary materials. However, a significant portion of asphalt is being recycled and re-use for the same purpose (i.e. road pavement). By taking this flow into account, global in-use stock of asphalt was more accurate and allowed for better estimates of mass allocation between 224 countries (see Section C). It was assumed asphalt road pavement had a 25 year lifetime and a global recycling rate of 27%. It was also estimated that 72% of recycled asphalt was being used as road pavement (Krausmann, et al., 2018). Hence, 377 Mt of recycled asphalt was added to the 2020 GAS extrapolated from Plank, et al. (2022a).

Glass. There was a significant difference in results for container glass between Elhacham, et al. (2020) and Westbroek, et al. (2021). Elhacham, et al. (2020) estimated the 2014 global stock of container glass to be about 1560 Mt with a 4 year lifetime, meaning a production flow under steady-state condition of 390 Mt/yr. The global glass supply chain was investigated by Westbroek, et al. (2021) and it was determined the production of container glass in 2014 was equivalent to 79 Mt/yr, with less than one year lifetime, implying an in-use stock of less than 79 Mt. By means of parsimony, the geometric mean between 79 Mt and 1560 Mt was taken as the value for global in-use stock of container glass in 2014. The value was scaled to 2020 by the growth of global glass stock from 2014 to 2020 (+13.42%), based on Elhacham, et al. (2020) results. Production rates in 2014 from Westbroek, et al. (2021) for container and flat glass were scaled to 2020 according to eq. S1 and eq.S2 (y = 2014). Production of other types of glass was determined assuming that container and flat glass production amounts to 91% of global glass production, with the rest allocated to tableware (4%) and other products such as reinforced fibres (Harder, 2018; Westbroek, et al., 2021). No lifetime assumption for other types of glass was taken, so no in-use stocks could be estimated.

B. RESIDENTIAL AND SERVICE-SECTOR BUILDINGS

Residential area

Residential floor areas from 2000 to 2020 were easily accessible for 28 countries in Europe, Canada, USA, China, India, and Russia. Table S2 compiles the sources used in each case. Together, these countries covered 50% of the world population and 53% of the housing stock in 2020. Housing floor areas for the rest of the world were interpolated with a global dynamic stock model developed by Marinova, et al. (2020; henceforth M2020). Below, the method applied to each source is further detailed.

Table S2. Compilation of data sources on residential floor area for different regions or countries.

Location	Source	Value found
Europe	ENTRANZE Project (2008)	2008 housing floor area per capita for 28 European countries
Canada	Natural Resources Canada (2020)	total residential floor space for period 2000-2019 based on residential end-use model created by the government of Canada
USA	Moura, Smith, and Belzer, (2015)	2010 total residential area estimated with a model based on data from national survey
India	Kacchawa, Singh, and Kumar (2019)	housing floor area per capita from a model
China region	CEIC (2022) — extracted from China National Bureau of Statistics	urban and rural floor area per capita for period 2006-2020 (including Taiwan, Macau, Hong Kong)
Russia	Federal State Statistics Service (2022)	total residential floor area for period 2000-2015
Rest of the world	Marinova, et al. (2020)	total floor area for 26 world regions from 1970 to 2050 based on a dynamic stock model

Europe. To project forwards to 2020, it was assumed that the 2008 average floor area per capita was constant in time and was the same in urban and rural settings (ENTRANZE Project, 2008). The per capita value was multiplied by urban and rural population in each corresponding countries. The resulting residential area in 2020 for those 28 countries was 18% smaller than what was estimated in M2020.

Canada. Total residential area in 2020 was not reported by Natural Resources Canada (2020), so it was estimated with the average floor area increase between 2015 and 2019 (39 km^2/yr). The total housing area for each year was split between urban and rural setting according to the share of population in each case. This method led to an increase in residential floor area in 2020 by 18% compared to M2020 estimates.

USA. With the 2010 total housing area from Moura, et al. (2015), per capita residential floorspace was determined (70.70 m^2/capita). It was again assumed the per capita value remained constant in time and stayed the same in urban and rural settings. Multiplied with urban and rural population, the residential area was 24% greater than what was reported in M2020.

India. Per capita residential floor area (11.9 m^2/capita) estimated by Kacchawa, et al. (2019), as evidence for governmental energy policies in India, was used. It was also assumed it would be static in time and would not change between urban and rural areas. The per capita value was multiplied with urban and rural population each year. It led to a 14% increase in 2020 housing area compared to M2020.

China region. Urban and rural floor area per capita for year 2000 to 2005 and year 2020 were missing (CEIC, 2022). Year 2000 to 2005 per capita values were estimated by the average increase in per capita floor area between 2006 and 2011 (urban = + 0.735 m^2/capita/yr ; rural = + 1.073 m^2/capita/yr). Year 2020 was estimated with the average increase between 2013 and 2019 (urban = + 0.987 m^2/capita/yr ; rural = + 1.588 m^2/capita/yr). The total residential areas in China, Taiwan, Hong Kong, and Macau in 2020 was 2% smaller than estimates from M2020.

Russia. Average floor area per capita from 2016 to 2020 was missing, so it was estimated by the average increase between 2010 and 2015 (+ 0.4 m^2/capita/yr) (Federal State Statistics Service, 2022). It was also assumed the per capita floor area stayed the same between urban and rural settings. The values were multiplied by the corresponding population in urban and rural areas each year. This led to a 1% increase in Russian residential floor area compared to M2020 results.

Rest of the world. Following M2020, residential floorspace for 26 world regions (Fig. S1) was based on the per capita floor area generated by the integrated assessment model IMAGE[2] and assumed to be a function of population density and income levels (described in Daioglou, et al., 2012 and proposed by Isaac and van Vuuren, 2009). The IMAGE sub-model TIMER[3] was also used for its population number and division between urban and rural settings. The regional urban and rural residential floor areas

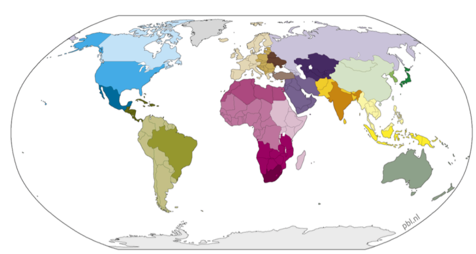

Fig. S1. The 26 world regions from IMAGE[1] version 3.0.

[2] Integrated Model to Assess the Global Environment (IMAGE) https://models.pbl.nl/image/index.php/Welcome_to_IMAGE_3.2_Documentation

[3] The IMage Energy Regional model (TIMER)

from M2020 were then distributed amongst countries according to each country's contribution to the total urban and rural population within their given region. An example of the urban residential disaggregation for region 14 in 2020 is presented below.

- Urban population in region 14 : Belarus (18.9%), Moldova (4.4%), Ukraine (76.7%)
- 2020 urban residential area of region 14 from M2020 : 1 022.293 km^2
- Final 2020 urban housing area (km^2): Belarus (193.493), Moldova (44.531), Ukraine (784.270)

Service-sector floor space

Deetman, et al. (2020) evaluated floorspace of service-sector buildings, also referenced as commercial buildings, for the 26 world regions depicted in Fig. S1. They derived regional floor areas of four different building types based on a regression analysis over a paid database published in 2018 by Guidehouse Insights (Machinchik and Freas, 2018), which reported the global building stock of eight commercial and two residential building types. The resulting four service-sector building categories in M2020 are as follows :

1. offices
2. retail, shops, and warehouses
3. hotels and restaurants
4. others (educational buildings, hospitals, governmental edifices, public transportation, and assembly buildings)

Regional commercial floor areas for each building category were allocated between countries based on their contribution to their respective region's total GDP. This was grounded on the premise from Harvey, et al. (2014) that commercial floor area varies in direct proportion to GDP. This method was applied to each of the four service-sector building category.

Comparison of floor areas with literature

The resulting time-series of residential areas agrees well with previous global estimates. For instance, the IEA's Energy Technology Perspectives scenarios (IEA, 2020) estimated there was roughly 245 000 km^2 of building floor area in 2019, of which 80% were residential buildings. The results presented here led to a residential floorspace for the same year of about 197 649 km^2, which is less than 1% difference from the IEA estimates. Moreover, in 2010, Harvey, et al. (2014) approximated the residential area to 152 000 km^2 and the IEA (2012) to 180 000. The time-series produced here led to a 2010 floorspace of 161 154 km^2, which falls in the middle of the two independent estimates.

As for the total commercial area, the values presented here are between 20 and 10% smaller than what can be found in other independent studies. In 2019, the global commercial area was 17% smaller than the IEA (2020) estimates. For the year 2010, it was 22% smaller than Harvey et. al. (2014) results and again 17% smaller than the 2012 IEA report (IEA, 2012). Moreover, the US Energy Information Administration (2021) projected US commercial floorspace to be about 8 690 km^2 in 2020, which was 11% greater than the resulting floor area estimated in this paper.

Material intensities

Marinova, et al. (2020) compiled data found in the literature on material intensities (kg/m^2), with regional specificity, for six materials (concrete, steel, aluminium, copper, glass, and wood) and four residential building types (detached house, semi-detached house, apartment, and high-rise building). However, due to the great variety in housing architecture and construction around the world, material intensities were poorly constrained, with an uncertainty varying by at least a factor of 2 (Fig. S2). Moreover, there was an overrepresentation of developed countries in the data compiled and few values were recorded overall (less than 16 values for aluminium and copper; 25-40 values for glass, wood, steel, and concrete). Global average material intensities regardless of region and building type are reported in Table S3. For commercial buildings, global

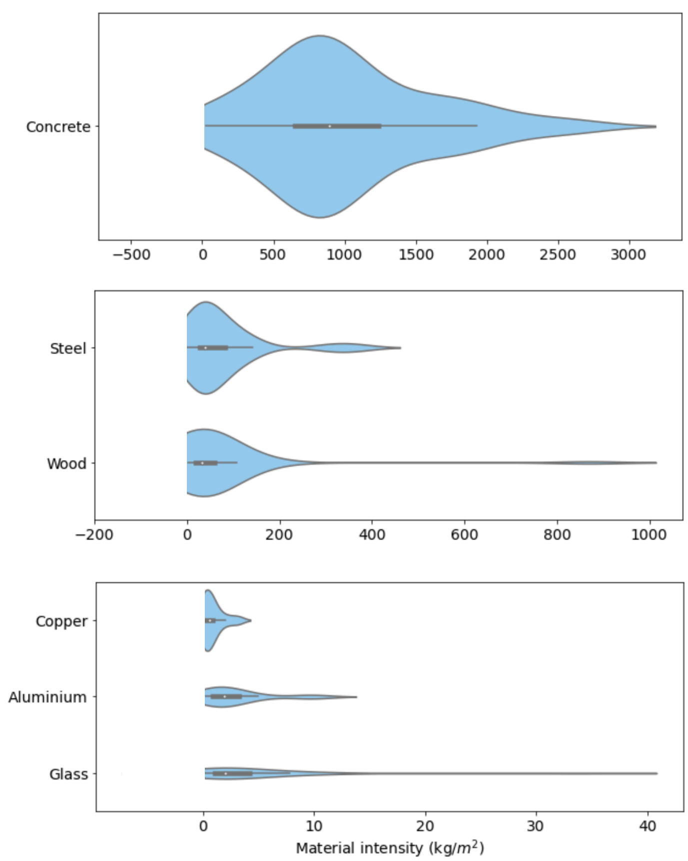

Fig. S2. Violin plots of material intensities (kg/m^2) in residential buildings compiled by Marinova, et al. (2020). Each scale is different.

average intensities of the six materials and the four building types were also compiled from the literature by Deetman, et al. (2020) (Table S3).

Table S3. Global average values of material intensities in residential housings and four service-sector building types for six materials, all based on data compilation from the literature by Marinova, et al. (2020) and Deetman, et al. (2020)

Materials (kg/m²)	Residential	Offices	Retail, shops, and warehouses	Hotels and restaurants	Others
Concrete	1,001.82	905.10	700.10	724.20	1,029.10
Steel	75.44	115.00	78.50	84.40	101.90
Wood	65.58	6.70	11.20	18.50	25.50
Aluminium	2.91	4.80	2.40	4.40	5.80
Copper	0.78	3.90	2.30	3.50	3.40
Glass	4.33	6.50	5.90	3.90	14.50

To appraise the amount of aggregates (i.e. sand and gravel) required as sub-base layers of residential and commercial buildings, the multiplier from Krausmann, et al. (2018) and derived from Miatto, et al. (2016), of 70 kg of aggregates per tonne of concrete, was used.

Informal dwellings not taken into account

Many informal dwelling types, which are typical in developing countries, were excluded from M2020 model due to lack of data, although these homes are usually made of scrap materials found close by. The commercial database of buildings from Guidehouse Insights did not include industrial and agricultural edifices. It is also likely that the following constructions have not been considered either : water supply buildings, sheds, industry garages, federal armed forces, fire stations, monasteries, churches, freight handling buildings, police stations, prisons, sewage and mining facilities, energy supply buildings, cemetery, greenhouses, power stations, waste facilities, and gas stations.

C. ROAD SURFACES

Country-level information on road length was taken from two sources. Meijer, et al. (2018) combined 66 geospatial datasets on road lengths, including the crowdsourced project OpenStreetMap, into one global dataset called the Global Roads Inventory Project (GRIP). GRIP covered 222 countries and estimated the world road network to be about 21.6 million km for the "present day". For each country, road length was split into four categories :

1. Main roads (grouping highways and primary roads)
2. Secondary roads

3. Tertiary roads
4. Local roads

The CIA World Factbook also provides estimates of road length online for 224 countries and/or territories as well as the fraction of paved roads. Date of information was around 2013, with total road length adding up to 38 million km (CIA, 2021b). The CIA's data source was not specified although some values agreed well with a 2014-2019 report from the World Road Statistics, which is a paid product from the International Road Federation (2021). Most countries had longer road networks in the CIA data than in GRIP database, but the opposite occurred too, such as in Mexico, where the CIA reported about 50% less roads. Overall, there was 30% difference between GRIP and the CIA data, so to minimize the discrepancies, the average total road length for each country was determined as described below, following Bar-On, et al. (2018):

1. Calculated the arithmetic mean between CIA and GRIP data
2. Calculated the geometric mean between CIA and GRIP data
3. Took the arithmetic mean between results from steps 1 and 2

With this manipulation, the global road network was evaluated at 28 341 345 km. The same proportions of different road categories within a country from GRIP results were kept. It is likely there was an underestimation of local roads as they are less well reported in GRIP, but the order of magnitude is assumed to be the same. Table S4 records global length of roads by road types from different sources and final averages used in this paper.

Table S4. Present day estimation for global road length by types of road, with GRIP dataset from Meijer, et al. (2018), the CIA World Factbook (2021b) and the final average values after data manipulation.

	GRIP (2018)	CIA World Factbook (2021b)	Final average values	
Total road length (km)	21,548,054	38,016,463	28,341,345 *	100%
Main roads (km)	3,214,253		4,599,933	16.2%
Secondary roads (km)	4,863,992		7,017,633	24.8%
Tertiary roads (km)	8,513,570		9,919,629	35%
Local roads (km)	4,956,239		6,797,118	24%

Percentages correspond to the coverage of each road category in regards to the final total average value.

* Small countries and islands have no specification on types of roads that make up their network. Hence, the total road length is 7,032 km greater than the sum of the different road categories.

Percentage of paved roads

The pavement ratio from the CIA dataset was available for 173 countries and absent for 51. Missing values were estimated based on a regression analysis over per-capita GDP and population density (Fig. S3). For the 15 countries without economic or demographic information, the arithmetic mean of the paved road proportion within the total network of a country, according to its income class, was attributed. The average proportions of paved road by income class are as follows:

- high income countries = 0.860
- upper-middle countries = 0.679
- lower-middle countries = 0.314
- low income countries = 0.155

This approach gave a total of 16 864 239 km of paved roads (59.5% of global roads). Since higher order type of roads are the most likely to be paved first, this would be consistent with all main and secondary roads being paved since their contribution to the global network amounts to 41% (Table S4).

```
Coefficients:
                           Estimate Std. Error t value Pr(>|t|)
(Intercept)                -1.38059    0.12315 -11.211  < 2e-16 ***
log10(GDP.capita)           0.38928    0.03017  12.905  < 2e-16 ***
log10(Pop.density..sq.km.)  0.17142    0.02450   6.997 4.91e-11 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.2103 on 181 degrees of freedom
  (40 observations deleted due to missingness)
Multiple R-squared:  0.5862,    Adjusted R-squared:  0.5816
F-statistic: 128.2 on 2 and 181 DF,  p-value: < 2.2e-16
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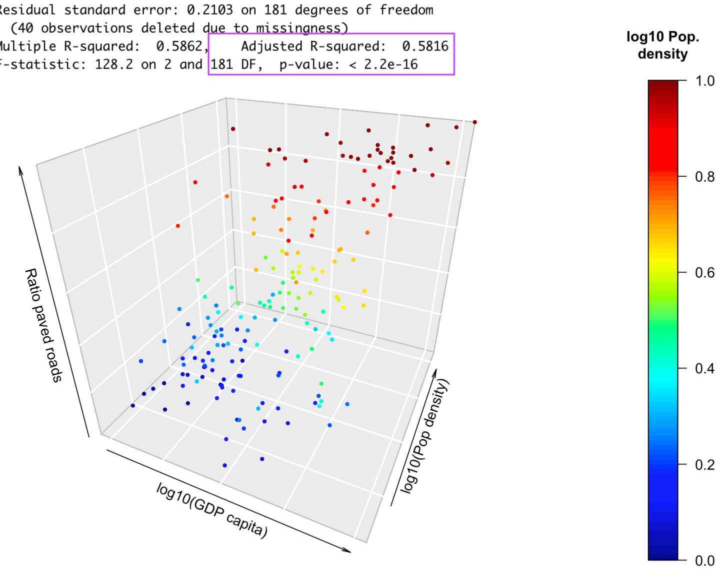


Fig. S3. 3D plot of paved roads ratio according to GDP per capita (PPP, constant 2017) and population density (people per km²), both expressed over a log_{10} scale. Regression model used is described above the graph.

Global asphalt stock and concrete stock for surface pavement

Krausmann, et al. (2018) estimated the asphalt stock, with data on bitumen production, to be about 59.013 gigatonnes (Gt) in 2015 with a net addition to stock (NAS) of 0.938 Gt/year and an uncertainty of 5% (Table S7 in Krausmann, et al., 2018). NAS was assumed constant and asphalt stock was projected until 2021. Because data on road lengths were not specific to a year, the arithmetic mean of asphalt stock between 2016 and 2021 was taken to determine a "present day" in-use value (62.296 Gt with a standard deviation of 1.755 Gt)

The vast majority of asphalt is used for road surfacing, but there are a variety of other applications (ex: waterproofing, dam facings, etc.) (European Asphalt Pavement Association, 2021). The Asphalt Institute and EuroBitume are two prominent associations, representing respectively international and European producers of refined bituminous products and affiliated businesses. In a report, they stated that 85% of bitumen production was directed towards asphalt preparation for pavement (Asphalt Institute and EuroBitume, 2015). Furthermore, it was conservatively estimated that parking lots, airport routes, and driveways require at most 10% of the asphalt used for surface pavement. This was based on Davis, et al. (2010a) and Davis, et al. (2010b) which estimated that 4-5% of a typical US midwestern county urban land was covered by parking lots. Without additional information, here are the relative proportion of asphalt end-use applications :

- 75% of asphalt for road pavement
- 10% for pavement of parking lots, airport routes, etc.
- 10% for roofing
- 5% for waterproofing and other uses, in small volume

A portion of a country's road network can also be paved with concrete instead of asphalt. According to a report sponsored by the US Department of Transportation, concrete pavement can vary from 0.51% of the total road network for the United Kingdom to 17% for The Netherlands and Belgium, with an average of 7% (Hall, et al., 2007). Most of these roads were part of a highway network or classified as primary roads. Hence, it was considered that 7% of the main roads (highway and primary) were paved with concrete, which has a density of 2400 kg/m^3. This implies the in-use asphalt stock embedded in road pavement was about 47 Gt for the present day calculation.

Road dimensions

Minimum thickness of asphalt layers varies depending on traffic load, speed limit, and climate to name just a few. Also, asphalt density varies between 2250 and 2500 kg/m^3 (Pavement Interactive, 2021), corresponding to an average of 2350 kg/m^3. Combined with road length and average width and thickness based on various sources (Table S5), this bottom-up approach gave a global in-use asphalt stock of 37.683 Gt, 20% smaller than the top-down value estimated in a section above (46.734 Gt). It was believed the bottom-up estimates on road width and thickness were too narrow and must carry more uncertainty than the top-down approach. Therefore, to be consistent with the top-down estimate, the asphalt stock of each country was adjusted by a multiplicative factor of 1.2402[4] .

Thickness of concrete paved roads varied between 20 and 30 cm according to Hall, et al. (2007), so the average value was taken. The widths were assumed to be the same as of asphalt roads (Table S5). Because of the uncertainty in roads dimensions, the concrete stock used for road pavement was also adjusted with the same factor of 1.2402. The resulting global stock of concrete embedded in road pavement was about 5.6 Gt.

As for unpaved roads, thickness of gravel layer for different road categories was based on a thorough report sponsored by the Swedish National Road Administration (Alzubaidi, 1999). Again, the width of the roads were the same as for asphalt (Table S5) and the factor was applied to minimize the large uncertainty of road dimensions. This led to a global aggregates stock in unpaved roads of 49.326 Gt, when considering an average gravel density of 1690 kg/m^3.

Table S5. Road dimensions used in the bottom-up approach to determine the stock of asphalt, concrete, and gravel embedded in road surfaces

Road category	**Surface type**	**Width (m)**	**Thickness (cm)**
Main	Asphalt	23.2 [1]	11.1 [3,4,5]
Main	Concrete	23.2 [1]	25.0 [6]
Secondary	Asphalt	10.9 [2]	6.35 (5.08 — 7.62) [1,5]
Secondary	Gravel	10.9 [2]	45 [7]
Tertiary	Asphalt	6.0 [2]	3.81 (2.54 — 5.08) [1,5]
Tertiary	Gravel	6.0 [2]	30 [7]
Local	Asphalt	6.0 [2]	2.54 [1,3,5]
Local	Gravel	6.0 [2]	20 [7]

Sources :
[1] APAI, 2006
[2] Whitelegg, 1994
[3] Hoxha, et al., 2021
[4] Teilmann and Böhm, 2016
[5] Kollaros and Athanasopoulou, 2017
[6] Hall, et al., 2007
[7] Alzubaidi, 1999

[4] Top-down stock / Bottom-up stock = 1.240187883

Sand and gravel in base-course layers of paved roads

To account for aggregates used in base-course layers of paved roads, the ratio from Krausmann, et al. (2018) of 2.56 tonnes per tonne of asphalt (or concrete) was applied, which was founded on technical construction standards for roadways, some assumptions, and coefficients from Miatto, et al. (2016). The multiplier carried a 30% uncertainty. Overall, it was estimated there was 261.421 Gt of sand and gravel in base-course layers of paved roads.

Scaling to year 2020

To be consistent with the accounting of materials for the year 2020, the "present day" global stock of asphalt embedded in road pavement was adjusted to 2020 based on the growth from the estimated global asphalt stock (62.296 Gt) to the value given by Elhacham, et al. (2020) (64.677 Gt). The scaling was also applied to the estimates of global aggregates and concrete stock in roads presented previously.

D. PASSENGER CARS AND COMMERCIAL VEHICLES

Number of registered vehicles

The International Organization of Motor Vehicle Manufacturers (OICA[5]) groups 37 national trade associations, with 20 of them representing major automobile manufacturing countries all over the world. OICA publicly shares data on numbers of registered in-use passenger cars and commercial vehicles from 2005 to 2015 for 141 countries (OICA, 2021). The downloaded file had only one missing entry: the 2005 number of commercial vehicles in Kuwait. The missing value was estimated by a linear regression based on stocks from other years. The two main categories of in-use vehicles defined by OICA (2021) and Vehicle Technologies Office (2013) were :

- *Passenger cars* : carriages designed to seat no more than nine person, driver included, so covering taxis, pickup trucks, microcars, etc.
- *Commercial vehicles* : include light commercial vehicles (LCV), heavy trucks, as well as buses and coaches when reported.
    - *LCV* : used to transport goods and/or transporting at least 10 people or more, examples can be full-size pickup and box trucks, city delivery vans, and large walk-ins.
    - *Heavy-duty vehicles* : referring to truck tractors, which are the vehicles pulling a trailer through a pivot point, but also straight trucks (ex.: garbage and dump trucks, concrete mixers, furniture trucks, etc.), and city transit buses.

[5] Organisation International des Constructeurs Automobiles

Not only were unregistered vehicles not included, but a few manufacturers were not included in the number of in-use vehicles disclosed by OICA. So, in-use numbers are likely to underestimate the true fleet size.

Fleet composition

Passenger cars were further divided into large and small categories, which was based on the IEA time-series on new SUV[6] registrations at a global scale (IEA, 2021) and averaged between 2010 and 2021. Thus, it was determined that 30.21% of the passenger car fleet in each country would be considered as "large" vehicles and the rest would be characterized as typical mid-size/small cars. To further support this assumption, a global leader in providing data on vehicles reported that 35.5% of top selling cars during the first half of 2012 were pickups and SUVs (Experian Information Solutions, 2012). However, large vehicles can make 45 to 49% of the passenger car market in the USA and Europe respectively (Munoz, 2018; ACEA Auto, 2021) to 24% in India (Gupta and Shekhar, 2010).

The share of heavy-duty vehicles within the commercial fleet was not specified. It was estimated by assuming it was the same proportion as the average production number of heavy-duty vehicles within the commercial fleet production between 2016 and 2020. This meant 18.6% of the registered commercial vehicles in each country were considered as heavy-duty vehicles, and the rest as LCV. Number of truck tractors within the heavy-duty vehicle fleet were also necessary, so that the number of trailers in circulation could be estimated. Based on a national transport statistics of registered trucks in the USA by the Department of Transportation, 20.9% of heavy-duty vehicles were assumed to be truck tractors (U.S. Department of Transportation, 2021). This value was applied to the heavy-duty vehicle fleet in each country. Finally, the in-use ratio of trailers to truck tractors was assumed to be about 1.4-to-1 in Europe (Sharpe and Rodriguez, 2018; Meszler et al., 2018; Hill et al., 2011) and 3-to-1 in North America (Sharpe, 2014). Without additional information, the average of 1.5-to-1 was applied to the rest of the world.

Material composition by vehicle type

Total curb weights, without fuel, and material composition of different representative vehicles were needed to evaluate material stocks in the automotive fleet. In terms of mass of any given vehicle, more than 80% of it is composed of steel, cast iron, plastic composites, aluminium, rubber, glass, and copper. It was assumed that 54.1% of rubber was synthetic rubber made of plastic, based on the 2010-2020 average fraction of synthetic rubber amongst world consumption of rubber (International Rubber Study Group, 2021).

[6] Sport Utility Vehicle (SUV)

A standard small/mid-size passenger car and SUV were defined in the GREET 2.7 model, which is a product developed for the U.S. Department of Energy where vehicle characterizations were based on various sources, such as tear-down data, automotive models, personal communications, and literature reviews (Burnham, Wang, and Wu, 2006; Burnham, 2012). A typical pickup truck was presented in Kelly, et al. (2015), who specifically investigated pickup trucks in a module to be integrated in the GREET model. To avoid further distinction in the large car category between pickups and SUVs, characteristics from both types were averaged. The standard characteristics for the LCV category were taken from Dai, et al. (2016) who published a life-cycle analysis of U.S. light-duty vehicles. Average characteristics for heavy-duty vehicles were taken from a life-cycle inventory study by Wolff, et al. (2020) and material requirements for truck trailers were averaged over data from Galos and Sutcliffe (2020), Allen County Government (2022), and Prucz, et al. (2006). Fig. S4 presents the resulting material composition for a small/mid-size car, large car, LCV, heavy-duty vehicle, and truck trailer. All vehicle were assumed to be internal combustion engine vehicles.

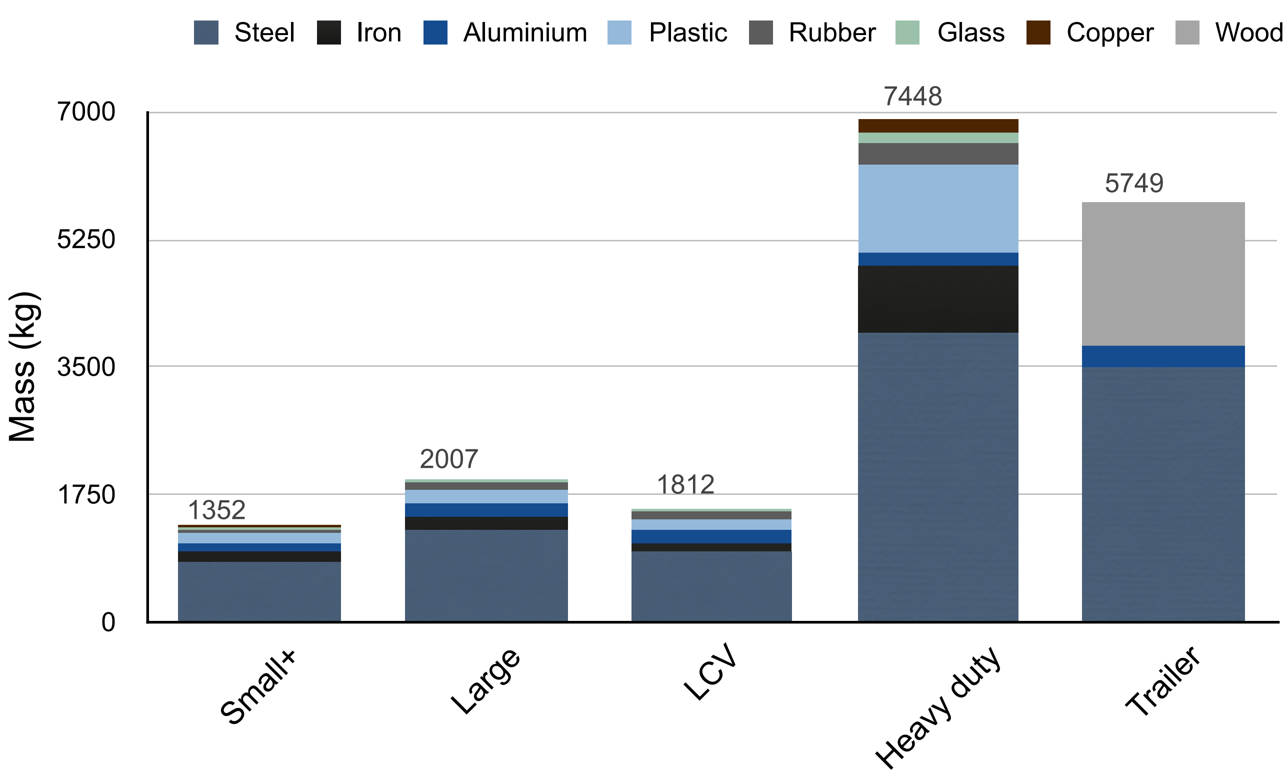


Fig. S4. Material composition in terms of mass (kg) of a typical small/mid-size and large passenger car, light commercial vehicle (LCV), heavy duty truck, and truck trailer. Total estimated curb weight (kg) of representative vehicles are specified on top of the bars. (Burnham, 2012; Kelly, et al., 2015; Dai, et al., 2016; Wolff, et al., 2020; Galos and Sutcliffe, 2020; Allen Country Government, 2022)

Scaling to year 2020

The latest data on vehicles numbers was for the year 2015. To scale the resulting material stocks embedded in passenger and commercial vehicles to 2020, the proportion of each material compared to the 2015 global stocks were kept the same for the year 2020. For example, 12.98% of global aluminium was estimated to be in passenger cars for the year 2015, so 12.98% of global aluminium stock in 2020 was allocated to passenger cars.

E. RAILWAYS

Three sources for length of railways around the world were used. First, United Nations Economic Commission for Europe (UNECE) reports total railway length (km) for 53 countries, irrespective of the number of parallels tracks (UNECE, 2021). It did not include lines operated for touristic purpose during a season, or lines that serve mines or other agricultural or industrial undertakings which are not open to public traffic. In some instances, the organization mentioned the length of "double tracks or more" in a given network. Second, the CIA World Factbook published the total railway length for 136 countries in recent years (no historical data) (CIA, 2021a). Total route was also irrespective of the number of parallels tracks, but would include non-public lines as opposed to UNECE. Third, World Bank shared the data of the International Union of Railways (UIC), thus providing total length of railway routes for 120 countries, again without consideration for the number of parallel tracks (World Bank, 2021). However, World Bank data did not seem to have been updated or contained caveats, because when examining UIC data portal[7], some numbers did not match. For example, the Argentinian network was estimated by World Bank at 17 866 km in 2018 while on UIC portal, it was reported at 20 465 km for the same year. Discrepancies between the three datasources (Fig. S5) have individually been investigated and values adjusted when necessary (see next section for details).

One value of railway length per country, from either UNECE, CIA, World Bank, or else, was determined according to these principles :

- If only one source of information : value directly used, but checked for possible inconsistency (ex : large railway network in a small isolated country). This method was notably applied to the United Arab Emirates where there was only one estimate in 2019 from World Bank. The value was compared to official numbers disclosed by the UAE Government portal (2022) and was found similar.

[7] Union International des Chemins de fer — UIC data portal : https://uic-stats.uic.org/select/ (visited 17 January 2022)

- If two or three sources available, with no significant gap : arithmetic mean between the data points, only if the difference between them was less than 10% (ex: for Armenia, UNECE reported 703 km in 2017 and World Bank, 686 for the same year).

- If two or three sources available, with significant gap (but not in Fig. S5) : alternative sources were used to determine which value was better representative of the reality (ex: Mali — CIA value was retained because the source behind the information was the U.S. National Geospatial Intelligence Agency (NGA, 2018) that provided a geospatial map of Malian rail network).

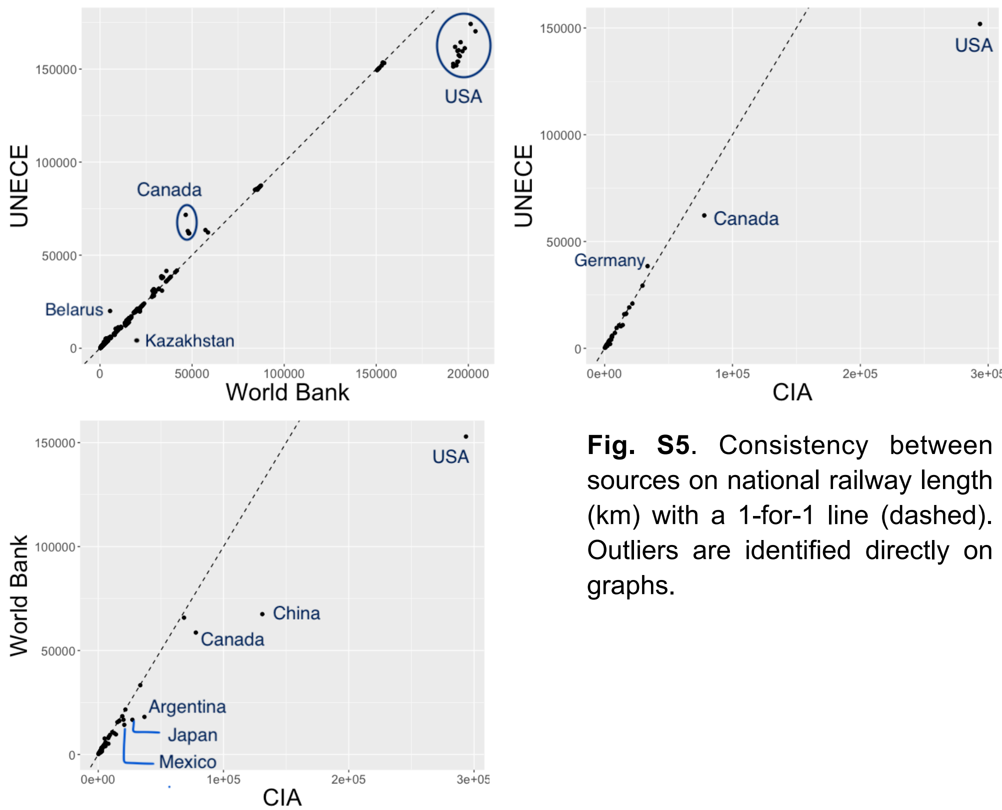


Fig. S5. Consistency between sources on national railway length (km) with a 1-for-1 line (dashed). Outliers are identified directly on graphs.

Length of double tracks (or more) were only reported in 40 countries by UNECE (2021) and none of them was classified as a low-income country. It was also assumed there would be a maximum of two parallels tracks in a network. Out of the 132 countries considered, 92 got attributed a double track ratio, based on a linear regression with the most parsimonious model (eq. S3, adjusted $R^2 = 0.5106$), although if classified in the low-income group, the value 0 was assumed. There were unusually high values from the regression that had to be manually adjusted. Lebanon was attributed the average value of double track ratio of its income group. Hong Kong was given the highest value found in the dataset (0.818) and Bangladesh was assumed to have the same ratio as India.

$$R = 0.00125P_{density} + 0.156 \quad \text{(S3)}$$

$P_{density}$: population density (people per km^2)

R : ratio of double tracks within a country's network

Outliers investigated

USA. From the Association of American Railroads (AAR), and corroborated by Federal Railroad Administration of the U.S. Department of Transportation[8], freight rail network in 2020 was about 219 917 km across the country (AAR, 2021). The data from AAR was used as the most recent length of railway network in the United States.

Canada. Statistics Canada reported there was 64 878km of total railway in operation at the end of 2019 (Statistics Canada, 2021). In 2018, they reported a total network of 63 050 km, which is very close to what UNECE has disclosed (62 959 km). Here again, the latest estimate from Statistics Canada was used instead of the CIA, World Bank, or UNECE data.

Belarus. There was total agreement between World Bank and UNECE data (identical numbers), except for year 2011. It is believed a mistake slipped into UNECE dataset since the railway length oscillated around 5000 km and suddenly was reported to be 20 000 km in 2011 before going back to 5462 km in 2012. This unusual value was discarded and the analysis proceeded with the latest information from 2019.

Kazakhstan. UNECE and World Bank provided similar railway length except for the year 2010. In fact, there was a missing number in UNECE dataset. The value in the original dataset was changed from 407 km to 9407 km[9]. In a book by Europa Publications (2004), total in use rail tracks for 2000 was 13 615 km, while for the same year, UNECE estimated a network of 13 208 km and World Bank, 13 545 km. After the correction, the maximum difference between values from the three data sources was less than 3%, so the arithmetic mean between all of them was taken .

China. For the Chinese railway network, World Bank numbers were much lower than the CIA and what could be found in China Statistical Yearbook published by the Chinese government. In 2018, the Chinese government published the length of railways in operation (131 651 km) (National Bureau of Statistics of China, 2022), while the CIA estimated for the same year, a

[8] Federal Railroad Administration. https://railroads.dot.gov/rail-network-development/freight-rail-overview (visited 2 February 2021)

[9] Length of single track for year 2007 = 9403, 2010 = 407, 2011 = 9419. Therefore, the 2010 statistic was replaced by 9407.

network of 131 000 km (CIA, 2021a). The latest data from the Chinese government was selected to improve the precision of final estimates.

Argentina. World Bank reported 18 097 km of railways compared to 36 917 km reported by the CIA for the year 2014. Without finding an explicit number for the length of the network, Eurostat Statistical Book of 2014 provided a histogram where one could read that the Argentinian network covered approximately 30 000 km in 2007 (Eurostat, 2014). Thus, World Bank data were disregarded and the CIA information was kept.

Japan. World Bank data abruptly changed between 2012 and 2016, declining from 20 087 km to 15 108 km, while the CIA numbers didn't fluctuate much (Fig. S5). From the Japan Railway Technical Service and a presentation by Tamura (2012), Senior-Deputy Director-General of the Ministry of Land, Infrastructure, Transport, and Tourism, Japan railways was 20 071 km long in 2003. Since the 2015 CIA value was consistent with Tamura number, CIA data were used instead of numbers from World Bank.

Mexico. Similar to the case for Argentina, World Bank reported a much lower network's length than the CIA for year 2017. According to the International Trade Administration (2021) of the United States, Mexico's railways were 26 914 km long; the year was not specified but last update was recorded in September 2021. This information was similar to what the CIA reported in 2017. To better depict the reality of today, the network length provided by the International Trade Administration (2021) was used.

Germany. The 15% difference between UNECE and CIA data was worth investigating since Germany has one of the most extensive railway system in the world. The time series of UNECE seemed to be most representative of present day as similar numbers were found in the German railway report by the governmental agency BNetzA (2019). Therefore, UNECE was the privileged source of information.

Material requirements

Tracks are generally made of hot-rolled steel. There are different material intensities (kg/m) depending on the rail type as weight is an important factor in axle loads and speed limits. Light rails are usually used for local metropolitan transport, but the data in this report are mainly focused on long-distance networks, hence heavy rail tracks. Popular heavy rails weights are 40, 50, 52, 60, 65, 70, 75 kg of steel per meter for one rail bar, thus giving an average of 58.85 kg/m (AGICO[10], 2017; Indian Railways Institute, 2019). For instance, Russia typically uses 65 or 75 kg/m rails (Huang, 2013) while in India, they are usually made with 52 or 60 kg/m tracks (Indian

[10] AGICO is a worldwide Chinese company specialized in manufacturing and supplying railway products.

Railways Institute, 2019). Since railways need two tracks to be functional, one kilometre of functional railway would require about 117.7 tonnes of steel. Wood, steel, or concrete used as railway sleepers, as well as gravel used as ballast were not considered in this study.

F. ROLLING STOCK

The number of registered locomotives, railcars, and coaches were taken from a report from the UIC (UIC, 2021) and their data portal (UIC, 2022), covering 66 countries around the world. The numbers of wagons were only disclosed in the 2021 report (UIC, 2021). "Railcars" grouped railcars and multiple units together. It was assumed the data reflected the size of the rolling stock fleet for the year 2020.

While the data were from the same source, different values were sometimes reported. The final numbers of registered rolling stock vehicles were determined according to the following method. Locomotives in a country, as well as railcars, were estimated by taking the arithmetic mean between the geometric mean and arithmetic mean of the two values (same method described in section B on roads and based on Bar-On, et al., 2018). For coaches, the maximum value was retained. Important discrepancies in the UIC data were found for Canada and Japan. After individual investigation, the Canadian number of locomotives from the UIC data portal was retained instead of the average (UIC, 2022) and number of wagons was changed to the value disclosed by the Railway Association of Canada (2015). Japan's number of locomotives, railcars, wagons, and coaches were also changed to the values reported by the Japan Association of Rolling Stock Industries (2021).

Mass and material content in different types of rolling stock were compiled from three independent peer-reviewed studies and average values were taken (Table S6).

Table S6. Assumptions on mass and percentage of four materials in different types of rolling stock.

Rolling stock	Mass (tonnes)	Steel (%)	Aluminium (%)	Plastic (%)	Glass (%)
Wagon	80 [1, 3]	85.5 [1, 3]	14.5 [1, 3]	0	0
Locomotive	60 [2, 3]	85.5 [1, 3]	14.5 [1, 3]	0	0
Railcar	60 [2, 3]	60.6 [2, 3]	31.4 [2, 3]	0.02 [2, 3]	0.01 [2, 3]
Coach	51 [2, 3]	60.6 [2, 3]	31.4 [2, 3]	0.02 [2, 3]	0.01 [2, 3]

Percentage may not sum to 100% because other in-use materials were not included in this paper.
Sources :
[1] Harvey, 2022
[2] Delogu, et al., 2017
[3] Kaewunruen, et al., 2019

G. MERCHANT FLEET AND SHIPPING CONTAINERS

Per country gross tonnage for five ship categories from 2011 to 2020 were downloaded on the UNCTAD[11] (2020) website. Vessels considered were of 1000 gross tons and above, thus composed of bulk carriers (42%), oil tankers (29%), container ships (13%), general cargo (4%), and other types[12] (12%). Military vessels, yachts, waterway vessels, fishing vessels, offshore platforms and barges were excluded (UNCTAD, 2021). Steel mass per gross tonnage for the five ship categories considered were reported in the supplementary information of Kong, et al. (2022). No other material embedded in the merchant fleet could be assessed due to lack of information.

From a market analysis report, Container Service International (CSI) gave an overview of the world container fleet in 2012 by type (CSI, 2012). As of 2022, more than 25 million containers, in twenty-foot equivalent units (TEU), were in circulation according to Alphaliner, a private platform providing up-to-date data for liner market services (Alphaliner, 2022). Tare weights for each container type were taken from a technical report by DSV Global Transport and Logistics, a prominent worldwide supplier in this sector (DSV, 2022). Information collected and used to determine the steel stock embedded in containers are summarized in Table S7.

Table S7. Information on global container fleet.

Container type [1]	**Composition of the fleet in TEU (%)** [1]	**Number of units (10^6)** [2]	**tare weight (kg)** [3]
20' dry van	16	4.92	2 300
40' dry van	19	2.87	3 750
40' high cube container	49	7.79	3 940
others	16	4.92	2 300

[1] from CSI, 2012
[2] based on total number of containers in twenty-foot-equivalent (TEU) from Alphaliner, 2022
[3] from DSV, 2022

H. COMMERCIAL AIRCRAFT

Number of registered commercial aircraft operated by all registered air carriers within a country were found on the CIA website (CIA, 2021d). Average material composition of an aircraft was determined by taking the geometric mean of material intensities for five types of commercial

[11] United Nations Conference on Trade and Development (UNCTAD)

[12] Other types can be offshore supply, gas carriers, chemical tankers, ferries, and passenger ships.

aircraft as reported in Jemiolo (2015). It was assumed the results were representative of the year 2020.

I. MILITARY EQUIPMENT

From a highly detailed report from the International Institute for Strategic Studies (IISS, 2022), military equipment was grouped into ten categories and manually summed to determine the number of units in each category for 14 countries : Canada, the United States of America, the Russian Federation, China, India, Pakistan, Japan, North and South Korea, Saudi Arabia, the United Kingdom, France, Germany, and Brazil. The ten categories of equipment were satellites, armoured vehicles, artillery, submarines, ships, aircrafts, helicopters, drones, radar centres, and missiles. The mass of 6 to 21 different models in each category from either the U.S, the Russian, or the Chinese army were compiled and the geometric mean was taken as the representative mass of an item in that category. For submarines and ships, displacement in tonnes were most commonly found instead of the mass although there were a few instances where both were disclosed. The average ratio of weight to displacement was computed and used as a multiplier to estimate the mass of different ships and submarines before taking the geometric mean of their mass. It was assumed 63% of the displacement was equivalent to the mass of the submarine or ship. Average masses for the ten categories of military equipment are grouped in Table S8.

Table S8. Average mass for ten categories of military equipment

Category	Average mass (kg)
Satellite	1 501
Armoured vehicle	19 796
Artillery	2 327
Drone	334
Aircraft	13 885
Helicopter	6 729
Submarine	4 036 860
Ship	1 673 049
Radar centre	249 594
Missile	4 166

Scaling to global stock of military equipment

Military expenditure for 158 countries was taken from SIPRI[13] data portal (SIPRI, 2022). The fourteen countries investigated spent about 80% of the global military expenditure in 2020. It was assumed the total mass of military equipment could be approximated by scaling the mass determined for the fourteen countries based on their share of military expenditure. The resulting mass of global military equipment differed by less than 1% from the mass in this sector estimated by Harvey (2022).

Due to the secrecy behind military items, material intensities of various equipment could not be retrieved. However, if the total mass of military equipment worldwide was made of steel, which would be a large overestimation, it would represent less than 0.1% of global steel stock, thus showcasing the insignificant stock accumulation in the military sector.

J. MANUFACTURING AND CONSTRUCTION MACHINERY

To estimate the material stocks embedded in this category, it was assumed that 15 to 16% of global in-use steel was used for mechanical equipment, which includes heavy-duty off road machinery, bulldozers, rolling mills, automotive machinery, and hand tools amongst many other things (World Steel Association, 2020).

The average composition of a machine with the main function of lifting and moving heavy loads was given in a comparative life cycle analysis on heavy-duty machinery. Data from the study is transcribed in Table S9. The mass of the machine was averaged at 18 053 kg (Kwak, et al., 2012).

Table S9. Average material composition and mass of a standard heavy-duty off-road machinery from Kwak, et al. (2012).

	Iron/Steel	Aluminium	Copper	Rubber	Plastic	Flat glass	Fiber glass
Mass (%)	88.9	1.17	0.11	6.73	0.66	0.81	0.08

Without the possibility to represent the diversity of industrial machinery in existence, it was assumed the steel stock determined with World Steel Association information was compositionally well-represented by the heavy machinery defined by Kwak, et al. (2012). Therefore, combined with Table S9 information, the order of magnitude of the other material stocks embedded in this category could be estimated. Here again, it was assumed 54.1% of rubber was synthetic and made of plastic products (see section C). The resulting value for the aluminium stock (72.287 Mt) was compared with data from Cullen and Allwood (2013),

[13] Stockholm International Peach Research Institute (SIPRI)

reporting that 9.05% of global aluminium production was directed towards the mechanical equipment category. Assuming a lifetime of 12 years (Kwak, et al., 2012) and a steady-state equilibrium, the Cullen and Allwood (2013) production rate would imply an aluminium stock of 48.87 Mt, 30% less than the steel-based estimate. The arithmetic mean was taken.

K. AGRICULTURAL MACHINERY

FAOSTAT reported in-use numbers of four-wheel (4W) agricultural tractors, two-wheel (2W) pedestrian tractors, combine harvesters-threshers, ploughs, milking machines, and other agricultural machinery[14] from 1999 to 2009 for 134 countries (FAOSTAT, 2018). Because of their numerical dominance and widespread reporting, only 4W and 2W tractors, as well as combines, were taken into consideration here. After removing outliers within the initial dataset (i.e. more than 20% change over a year in 4W tractor stock), data for 124 countries were analyzed, which altogether represented more than 80% of Earth's population and food produced.

Average horsepower of 4W tractors was determined by comparing 203 products sold by John Deere and Caterpillar. Average horsepower of 2W was based on a study by Ademiluyi, et al. (2007) and average horsepower of combines was estimated with 46 products sold by major companies worldwide. Then, the mass of two to three models with a similar horsepower for each machine was recorded. Final average values are reported in Table S10.

Table S10. Assumptions on horsepower and mass of two-wheel tractors, four-wheel tractors, and combine harvesters-threshers.

Machine	Horsepower (hp)	Mass (kg)	Sources
two-wheel tractors	10	280	Ademiluyi, et al. (2007)
four-wheel tractors	214	11 982	average of 203 products from John Deere and Caterpillar
combines	263	12 946	average of 45 products from most popular brands

Steel was the only material that could be estimated in the agricultural machinery. Lee, et al. (2000) conducted a life cycle assessment for tractors and stated that 85% of their mass was made of steel. With the lack of information and peer-review studies on combine harvesters-threshers, the same proportion of steel within their mass was applied. For 2W tractors, it was assumed 50% of their mass would be steel, based on the structure of various model sold online.

[14] Threshing machines, root or tuber harvesters, balers, seeders and similar items, manure and fertilizer spreaders

Steel stock calculated was representative of the year 2009, which contributed at that time to 0.21% of global steel stock. The same proportion of steel stock in this sector for year 2020 was kept.

L. PIPELINES

Reliable energy data at global scale was found on the website of the non-profit organization Global Energy Monitor (2021). Transmission pipeline lengths for gas and oil were accessible, but the following pipelines were not accounted for : length under 100 km, distribution and gathering pipelines, as well as small pipelines with a capacity below a minimum threshold for each fossil fuel type. The CIA World Factbook also reported length of transmission pipelines, including when possible distribution pipelines, circa year 2014 (CIA, 2021c). Datasets were combined and final lengths were estimated with the arithmetic mean between the geometric mean and arithmetic mean of two values (Bar-On, et al., 2018).

It was assumed the standard pipeline would have the average dimensions of X70 and X80 pipelines, which are the most commonly used as high-pressure transmission pipelines. The outer diameter was set at 89 cm, the thickness of the pipeline at 1.9 cm (Bai and Bai, 2014), and an average density of steel equivalent to 7 900 kg/m^3 was used to calculate the steel mass per km.

M. ELECTRICITY NETWORK

Based on an inventory of global electricity infrastructure, a stock-driven bottom-up assessment quantified concrete, steel, copper, and aluminium in power plants, grids, and transformers (Kalt, et al., 2021). Results were for the year 2017 and estimates for year 2020 were determined by scaling the proportion of materials in 2017 global stocks to the stocks size in 2020 (eq.1 of main text)

N. DOMESTIC APPLIANCES

World Steel Association (2020) estimated 2% of global steel was allocated in domestic appliances. Other materials embedded in this category were not considered due to poorly constrained information on material intensities and number of units globally.

O. FOOD AND BEVERAGE PACKAGING

Results from Cullen and Allwood (2013) and global statistics from Government of Canada (2022) on end-uses of global aluminium production specified 15 ± 6% was used for food and beverage packaging (ex: foil, drink and food cans) in 2007 and in 2020. Assuming a two year lifetime and a steady-state condition, aluminium stock in this category could be estimated.

Global plastic stock and flow investigated by Geyer, et al. (2017) showed that 44.8% of global plastic production, averaged over the period 2002-2014, was directed to packaging. Moreover, from a business report in the plastic industry, 33-35% of plastic packaging is directed to the food and beverage industry (Plastemart, 2021; Nemat, et al., 2019). Without considering plastic recycling, new plastic production was estimated at 422 Mt in 2020 (Table S1), similar to estimates from Plastic Europe[15]. By assuming the share of plastic in this sector were static in time and that plastic packaging had a lifetime of one year (Geyer, et al., 2017), global in-use plastic stock in food and beverage packaging was determined for the year 2020. In-use plastic for other packaging could also be derived with the above information, considering a lifetime of 2 years.

P. TABLEWARE

In the Supplementary Information of Westbroek, et al. (2021), it was specified that about 4% of global glass production was used for tableware (such as drinking glasses, pitchers, and more). It was assumed tableware had a lifetime of four years based on Krausmann, et al. (2018) and that this sector was close to steady-state on this time scale. Other materials embedded in this class could not be estimated due to lack of information.

Q. CONSUMER ELECTRONICS

As reported in Wang, et al. (2021) and Geyer, et al. (2017), 3.8% of global plastic production was directed towards consumer electronics for the 2002-2014 period. It was assumed the lifetime was 8 years (Geyer, et al., 2017) and that the percentage of plastic in this sector stayed the same in 2020. Again, no other material was accounted for within this class.

R. MEDICAL EQUIPMENT

The average global plastic stock dedicated to medical equipment (3%) was the mean of global plastic share directed in this field between Germany, China, and Austria (Wang, et al., 2021). Other materials embedded in this class could not be estimated due to lack of information.

S. FURNITURES

[15] visited 5 July 2022 https://plasticseurope.org/wp-content/uploads/2021/12/Plastics-the-Facts-2021-web-final.pdf

On a global scale, it was evaluated by Geyer, et al. (2017) that 12% of global plastic production was allocated to furnitures and household products, equivalent to a plastic flow of 50.6 Mt per year. From a detailed study on lifetime of various everyday products (Box, 1983), it was assumed furnitures would be replaced after 8 year, with a standard deviation of 7 years.

T. TEXTILES

It was assumed the average person owns 80 ± 40 kg of textiles, which includes towels, bed sheets, and clothes. Given the lack of data, there was no attempt to resolve discrepancies between income groups and the value was scaled to population in each country. According to a report from Textiles Exchange (2021), synthetic fibres (i.e. plastic fibres) made 60-65% of global textile production in 2020.

U. UNCERTAINTY ASSESSMENT

Data availability and quality was highly irregular, complicated by varying definitions and uneven spatial coverage across sources. The methodology is generally omitted in international databases and business leader reports. To translate the reliability of the constructed database presented in this paper, each source was attributed a score based on five quality indicators : reliability, completeness, temporal correlation, geographical correlation, and other technical correlation. The ordinal scoring was then translated into normally distributed standard deviations. This framework of uncertainty assessment was developed by Laner, et al. (2015) and based on a Pedigree matrix. *Reliability* relates to the methodology and data compilation documented by the source. *Completeness* is about the composition of the data and if all relevant mass flows are included with possible over- or underestimation. *Temporal* and *geographical correlations* indicate deviations in time and space from the date of interest, while *other correlation* takes other discrepancies into account, such as conversion issues and speculative interactions.

The source-quality uncertainty scoring was translated from an ordinal to a rational scale using the following equations (eq. S4-S5) and total coefficient of variation (CV_{tot}) was calculated with eq. S6, all provided in Plank, et al. (2022b). Exponential functions were chosen as exponential increase in uncertainties was more likely than a linear behaviour. Functions were fit so that resulting CV_{tot} would not exceed 33.3% in the case that all data quality indicators were attributed the worst score. More details on the reasoning behind fitting methods and translation of scoring into continuous CV can be found in section 10 of Plank, et al. (2022b) and in Laner, et al. (2015).

$$CV_R = 0.00167 * e^{1.105(x-1)} \tag{S4}$$

$$CV_{C,G,T,O} = 0.00167 * e^{1.105x} \tag{S5}$$

$$CV_{tot} = \sqrt{CV_R^2 + CV_C^2 + CV_G^2 + CV_T^2 + CV_O^2} \quad \text{(S6)}$$

A list of baseline scoring and resulting coefficient of variation for all main data sources used in the final database is provided in Table S11. CV_{tot} for each material stock was computed by taking into account the CV of each source contributing to the material stock. The error range for each material stock shown in Fig. 2 is reported in Table S12.

Table S11. Baseline scoring (1-4) of data quality indicators for all initial sources used to construct the database (based on Laner, et al., 2015 and Plank, et al., 2022b). R-reliability, C-completeness, T-temporal correlation, G-geographical correlation, O-other correlation

Item	Data source	Data quality score					Final coefficient of variation (%)
		R	C	T	G	O	
Agricultural machinery	FAOSTAT	1	1	4	1	1	13.9
Commercial aircrafts	CIA	3	2	2	1	1	2.7
Consumer electronics	Geyer, et al. (2017); Wang, et al. (2021)	1	2	3	4	1	14.7
Domestic appliances	World Steel	4	2	1	4	2	14.8
Electricity network	Kalt, et al. (2021)	1	2	2	1	2	2.7
Food and beverage packaging	Cullen and Allwood (2013); Westbroek, et al. (2021); Geyer, et al. (2017) ; Government of Canada (2022)	2	2	2	4	1	14.1
Furnitures	Geyer, et al. (2017)	1	2	3	4	1	14.7
Manufacturing and construction machinery	World Steel; Kwak, et al. (2012); Geyer, et al. (2017)	3	3	1	4	3	15.4
Mechanical equipment	World Steel	4	2	1	4	2	14.8
Medical equipment	Wang, et al. (2021)	1	2	1	4	1	14.0
Merchant fleet	UNCTAD	1	2	1	1	1	1.8
Military equipment	IISS	1	1	2	1	2	2.3
Other packaging	Cullen and Allwood (2013); Westbroek, et al. (2021); Geyer, et al. (2017) ; Government of Canada (2022)	1	2	2	4	1	14.1
Pipelines	GFIT	2	3	2	1	1	5.6
Pipelines	CIA	3	2	2	1	1	
Railtracks	UNECE	1	2	2	1	1	4.0
Railtracks	CIA	3	2	2	1	1	
Railtracks	World Bank	1	1	2	1	1	
Residential buildings	Marinova, et al. (2020)	3	2	1	4	2	14.1
Road length	CIA	3	1	4	1	1	14.2
Road length	Meijer, et al. (2018)	1	2	2	1	2	
Rolling stock	UIC	1	3	2	1	1	4.9
Service-sector buildings	Deetman, et al. (2020)	3	2	1	4	2	14.1
Shipping containers	Alphaliner	4	2	2	4	1	14.8
Tableware	Westbroek, et al. (2021)	1	2	3	4	1	14.7
Textiles	Expert judgment	4	4	1	1	3	15.3
Vehicles	OICA	1	2	3	3	1	6.7

Table S12. Resulting total coefficient of variation for each material. Values correspond to error bars in Fig. 2 of the main text.

Material	**CV_{tot} (%)**
Aggregates	24.5
Aluminium	30.3
Asphalt	14.2
Concrete	24.7
Copper	26.2
Glass	33.5
Iron/Steel	37.4
Plastic	39.7
Wood/Paper	21.1

V. ADDITIONAL RESULTS

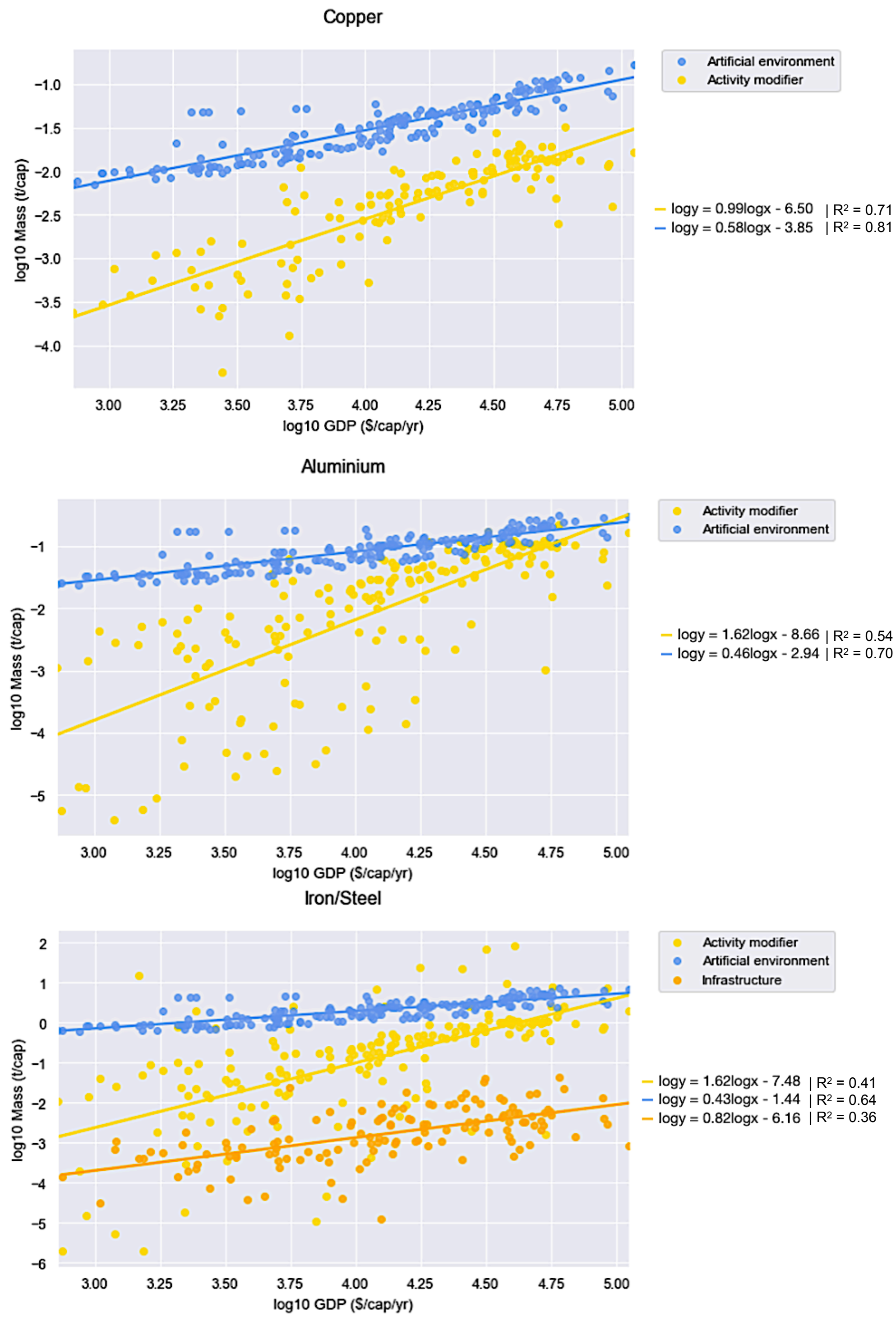


Fig. S6. Correlation between per capita mass of copper, aluminium, and iron/steel embedded in sub-categories of anthropogenic mass and per capita GDP, for all countries in 2020. Regression equations are specified on the right.

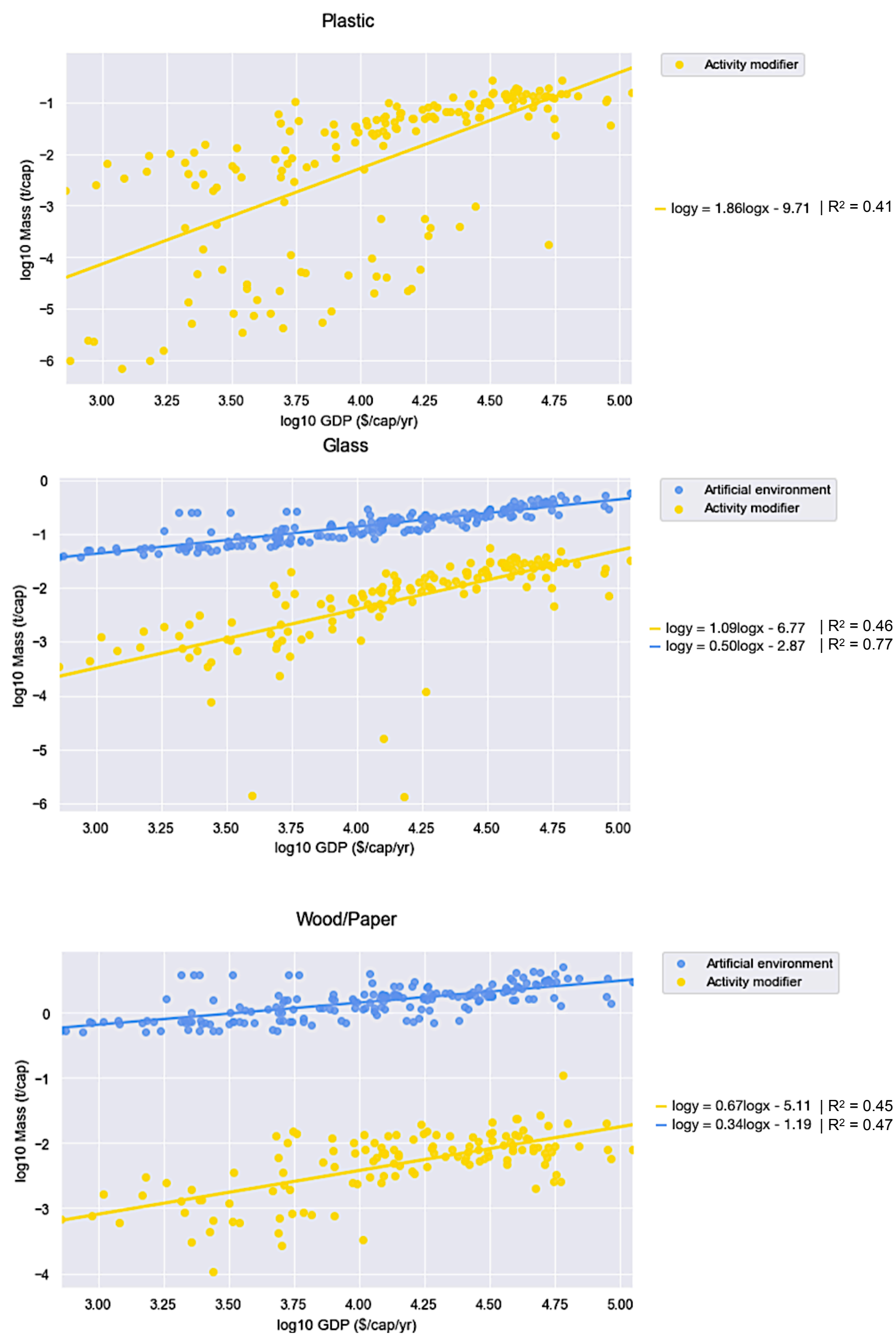


Fig. S7. Correlation between per capita mass of plastic, glass, and wood/paper embedded in sub-categories of anthropogenic mass and per capita GDP, for all countries in 2020. Regression equations are specified on the right.

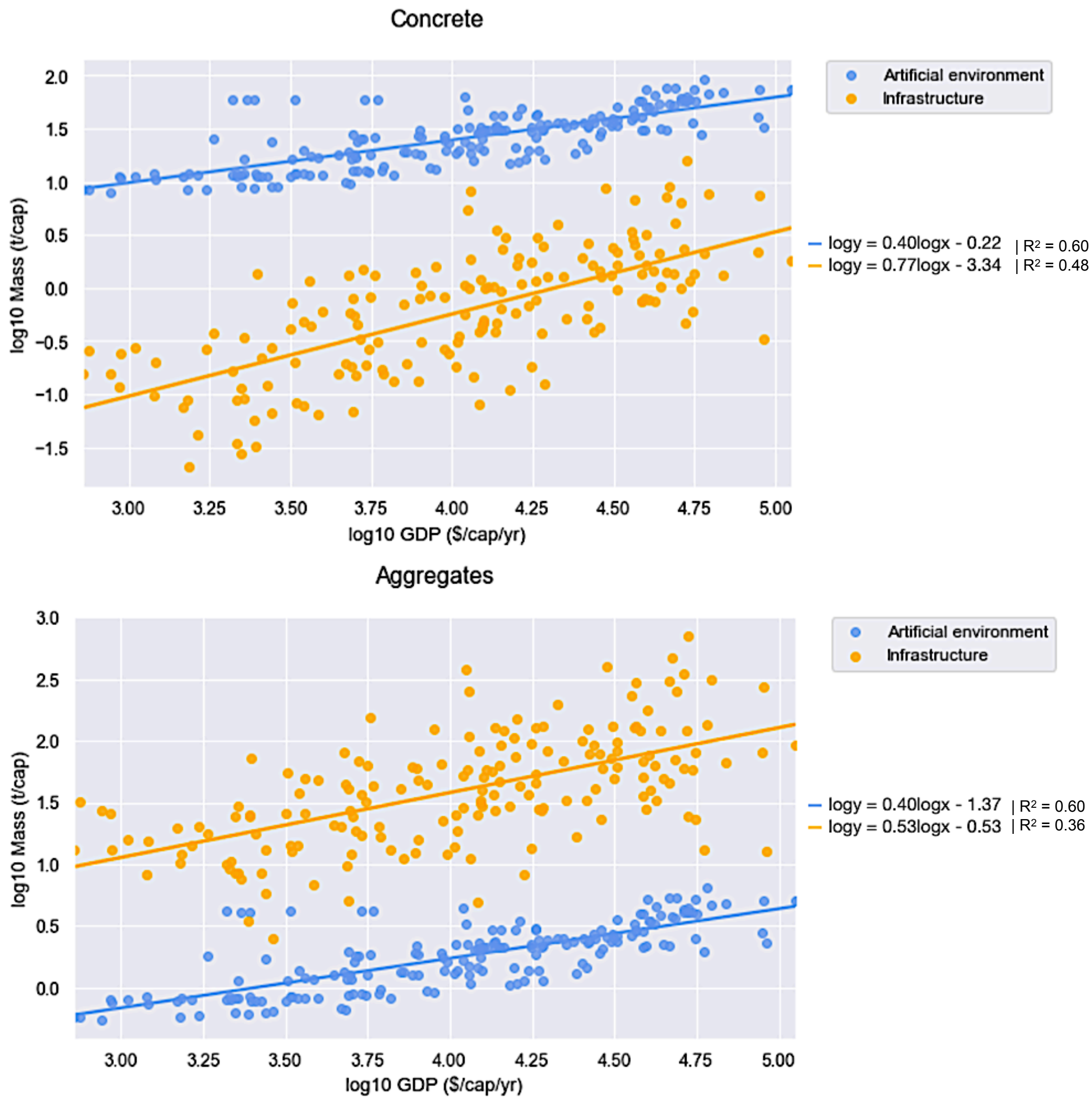


Fig. S8. Correlation between per capita mass of concrete and aggregates in sub-categories of anthropogenic mass and per capita GDP, for all countries in 2020. Regression equations are specified on the right.

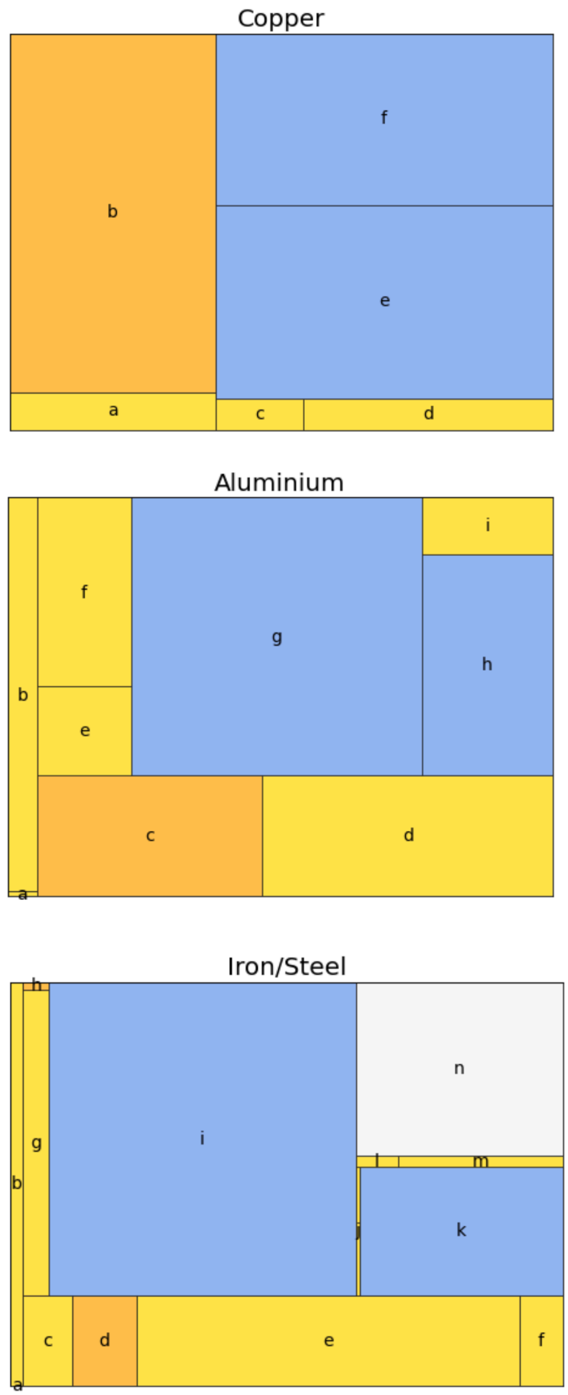
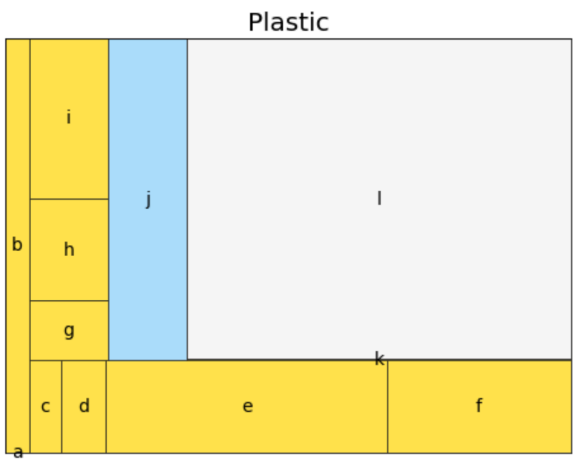


Fig. S9. End-use composition of copper, aluminium, and iron/steel stock in 2020. Legend is different for each plot. Sub-categories of items are highlighted with the same color coding as Fig.S6-S8. Blue : artificial environment, Orange : infrastructure, Yellow : activity modifier

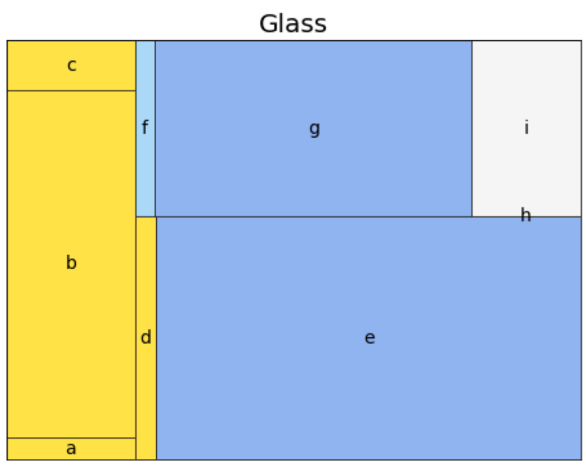
a : commercial vehicles
b : electricity network
c : manufacturing and construction machinery
d : passenger cars
e : residential buildings
f : service-sector buildings

a : commercial aircraft
b : commercial vehicles
c : electricity network
d : food and beverage packaging
e : manufacturing and construction machinery
f : passenger cars
g : residential buildings
h : service-sector buildings
i : rolling stock

a : commercial aircraft
b : commercial vehicles
c : domestic appliances
d: electricity network
e : manufacturing and construction machinery
f : merchant fleet
g: passenger cars
h : pipelines
i : residential buildings
j : shipping containers
k : service-sector buildings
l : agricultural machinery
m : rolling stock
n : unaccounted mass



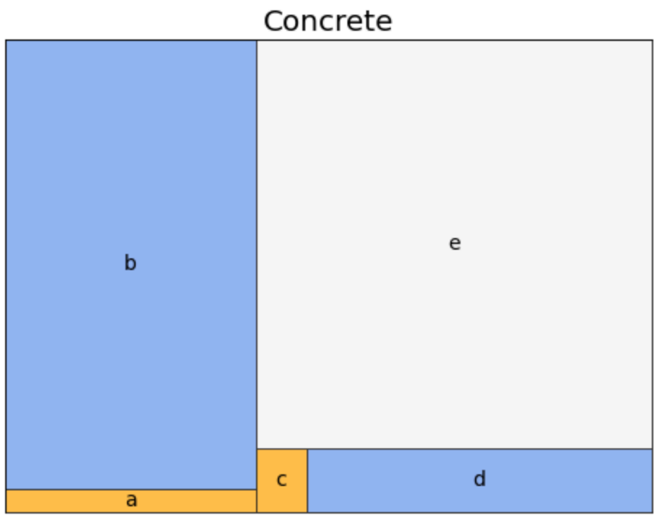
a : commercial aircraft
b : commercial vehicles
c : consumer electronics
d: food and beverage packaging
e : furnitures
f : manufacturing and construction machinery
g: medical equipment
h : other packaging
i : passenger cars
j : textiles
k : rolling stock
l : unaccounted mass



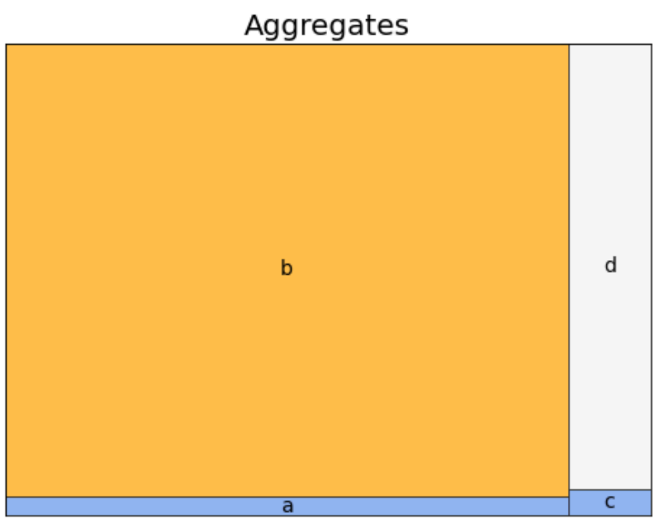
a : commercial vehicles
b : food and beverage packaging
c : manufacturing and construction machinery
d : passenger cars
e : residential buildings
f : tableware
g : service-sector buildings
h : rolling stock
i : unaccounted mass

a : commercial vehicles
b : residential buildings
c : service-sector buildings
d : unaccounted mass

Fig. S10. End-use composition of plastic, glass, and wood/paper stock in 2020. Legend is different for each plot. Sub-categories of items are highlighted with the same color coding as Fig.S6-S8



a : electricity network
b : residential buildings
c : roads
d : service-sector buildings
e : unaccounted mass



a : residential buildings
b : roads
c : service-sector buildings
d : unaccounted mass

Fig. S11. End-use composition of concrete and aggregates stock in 2020. Legend is different for each plot. Sub-categories of items are highlighted with the same color coding as Fig.S6-S8

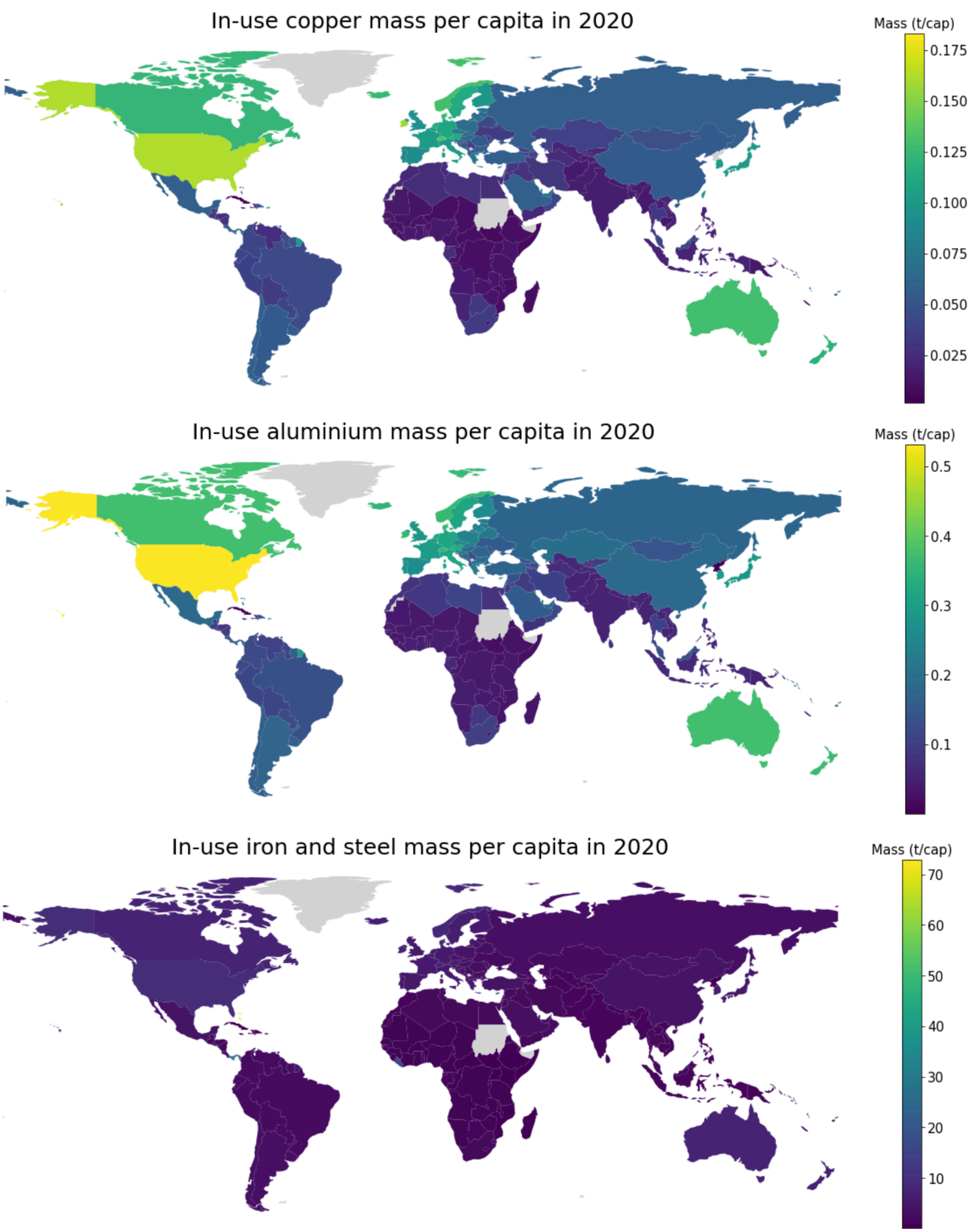


Fig. S12. In-use mass of copper, aluminium and iron/steel per capita in 2020. Scale of axis is different for each material.

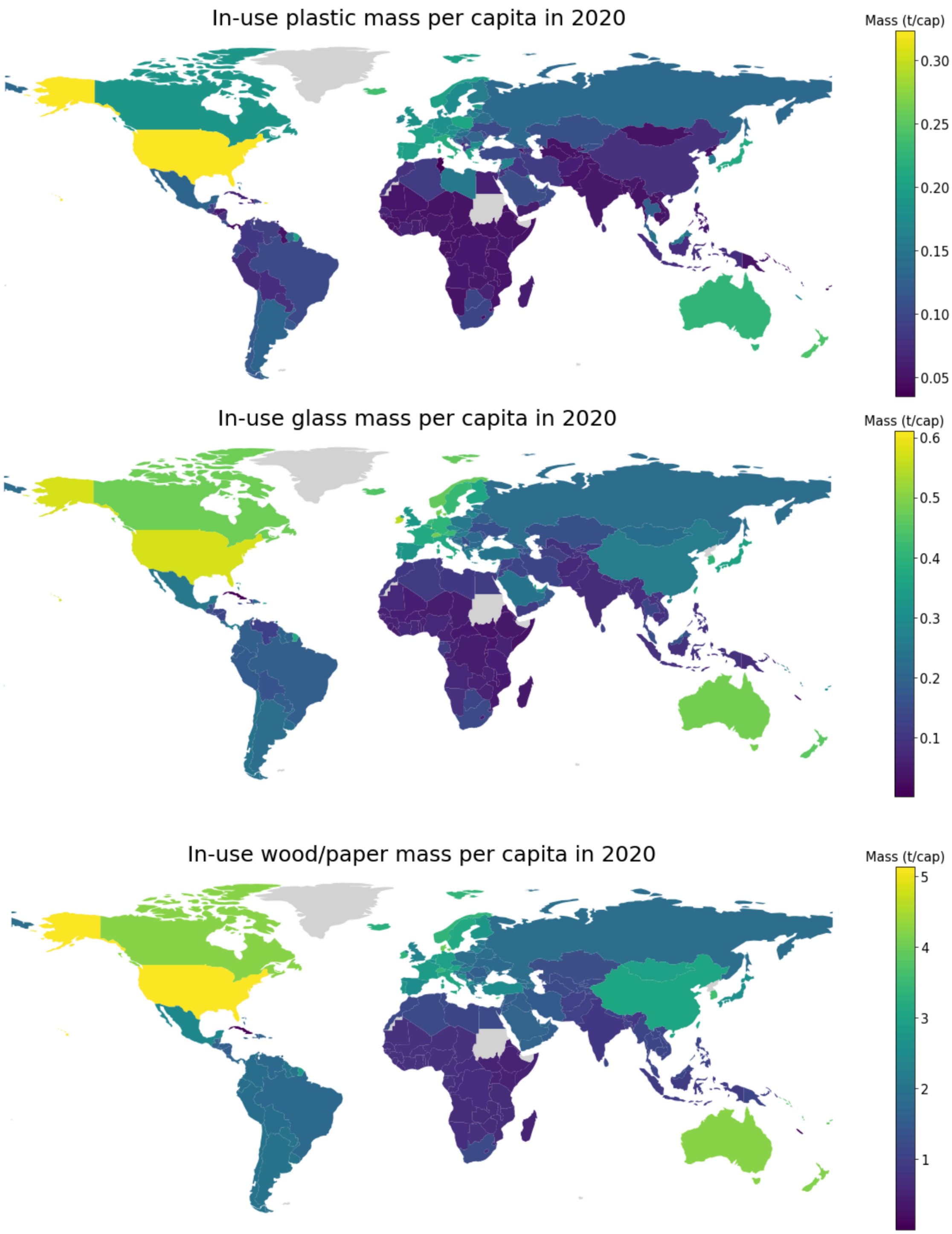


Fig. S13. In-use mass of plastic, glass and wood/paper per capita in 2020. Scale of axis is different for each material.

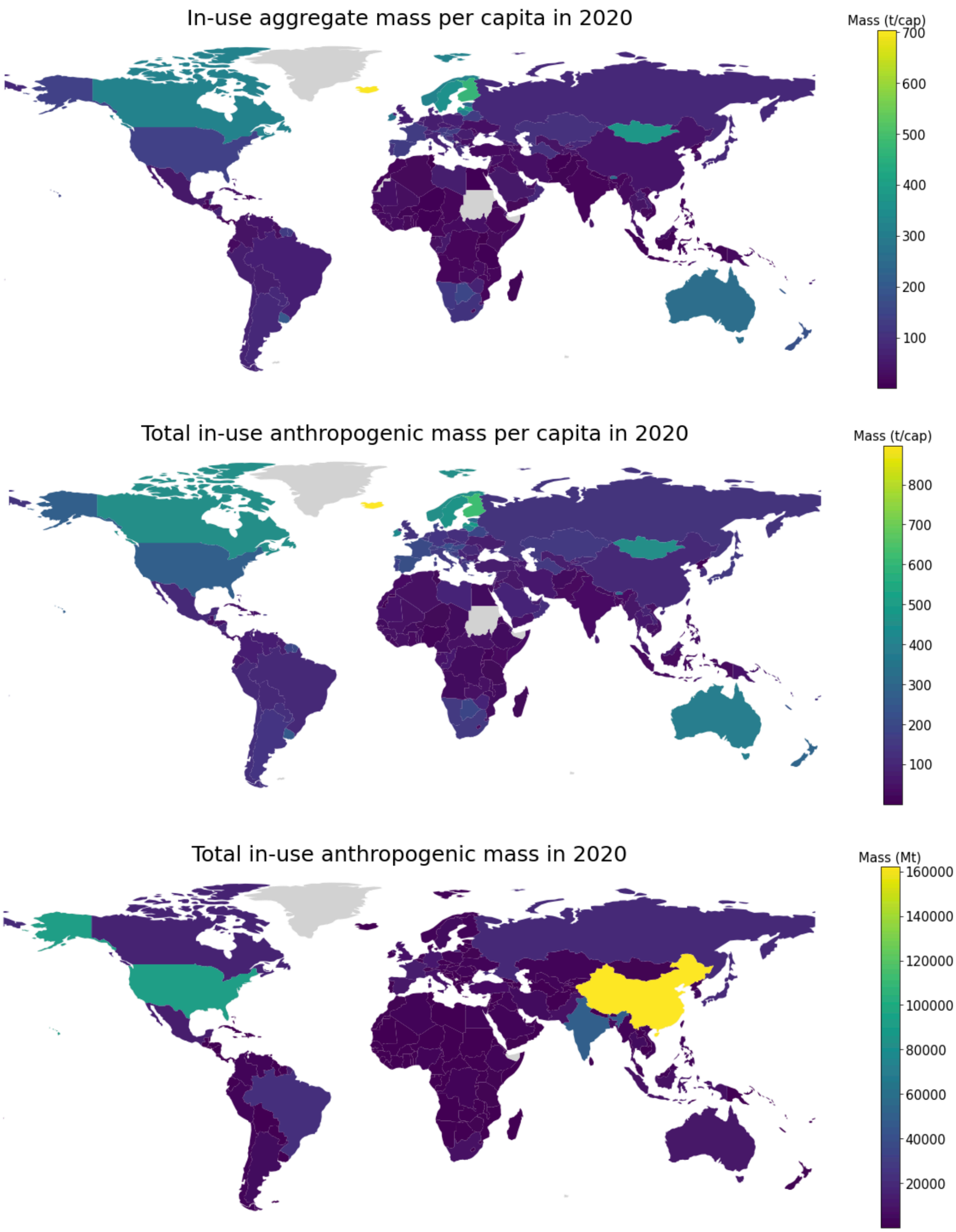


Fig.S14. In-use mass of aggregates per capita and total anthropogenic mass, in per capita and in absolute terms for year 2020. Scale of axis is different for each material.

REFERENCES

AAR — Association of American Railroads (2021) “Freight railroads in United States”. Fact sheet, visited 7 January 2022. https://www.aar.org/wp-content/uploads/2021/02/AAR-United-States-Fact-Sheet.pdf

ACEA Auto (2021) “New passenger cars by segment in the EU”, visited 7 March 2022. https://www.acea.auto/figure/new-passenger-cars-by-segment-in-eu/

Ademiluyi, Y. S. et al. (2007) “Performance Assessment of Two- Wheel Tractor on a Loamy Sand Soil of Ilorin”, Nigerian Journal of Technology, 26(1), pp. 59–66.

AGICO (2017) “Chinese Steel Rails Overview”, visited 13 December 2021. http://www.railway-fasteners.com/news/steel-rails-overview.html

Allen County Government (2022) “A Guide to Truck Trailers”, visited 5 March 2022. https://www.allencounty.us/homeland/images/lepc/docs/TruckTrailerGuide.pdf

Alphaliner (2022) “Alphaliner Top 100”, visited 7 March 2022. https://alphaliner.axsmarine.com/PublicTop100/

APAI — Asphalt Paving Association of Iowa (2016) “ Chapter 4. Thickness Design”, Asphalt Paving Design, pp. 4.1–4.7

Asphalt Institute and EuroBitume (2015) “The Bitumen Report — a global perspective”. 3rd edition. USA. pp.6. available for download : https://www.eurobitume.eu/public_downloads/General/The%20Bitumen%20Industry%203rd%20edition.pdf

Alzubaidi, H. (1999) “Operation and maintenance of gravel roads. A literature study”, Swedish National Road and Transport Research Institute, Linkopïng. Table 5-4

Bai, Q. and Bai, Y. (2014) “Use of High-Strength Pipeline Steels”, Subsea Pipeline Design, Analysis, and Installation, pp. 675–694. doi: 10.1016/b978-0-12-386888-6.00031-6.

Bar-On, Y. M., Phillips, R. and Milo, R. (2018) “The biomass distribution on Earth”, Proceedings of the National Academy of Sciences of the United States of America, 115(25), pp. 6506–6511. doi: 10.1073/pnas.1711842115.

BNetzA — Bundesnetzagentur (2019) “Railway market analysis Germany 2019”, Bonn, pp.84-85. available for download : https://www.bundesnetzagentur.de/SharedDocs/Downloads/EN/BNetzA/PressSection/ReportsPublications/2019/RailwayMarketAnalysis2019.pdf?__blob=publicationFile&v=1

Box, J. M. F. (1983) “Extending product lifetime: Prospects and opportunities”, European Journal of Marketing, 17(4), pp. 34–49. doi: 10.1108/EUM0000000004830.

Burnham, A. (2012) “Updated Vehicle Specifications in the GREET Vehicle-Cycle Model”, (July), pp. 1–40.

Burnham, A., Wang, M. and Wu, Y. (2006) “Development and Applications of GREET 2.7 — The Transportation Vehicle-Cycle Model”. pp.13-52.

CIA — Central Intelligence Agency (2021a) “The World Factbook — Railways”. Electronic dataset, visited 2 December 2021. https://www.cia.gov/the-world-factbook/field/railways/

CIA — Central Intelligence Agency (2021b) “The World Factbook — Roadways”. Electronic dataset, visited 9 November 2021. https://www.cia.gov/the-world-factbook/field/roadways/

CIA — Central Intelligence Agency (2021c) “The World Factbook — Pipelines”. Electronic dataset, visited 27 November 2021. https://www.cia.gov/the-world-factbook/field/pipelines/

CIA — Central Intelligence Agency (2021d) “The World Factbook — National Air Transport System”. Electronic dataset, visited 27 November 2021. https://www.cia.gov/the-world-factbook/field/national-air-transport-system/

CEIC (2022) “China residential area per capita” compiled from China’s National Bureau of Statistics, visited 8 March 2022. https://www.ceicdata.com/en/china/residential-area-per-capita

CSI — Container Service International (2012) “World Container Fleet Overview”, summary of two market analysis and research reports. https://www.csiu.co/resources-and-links/world-container-fleet

Cullen, J. M. and Allwood, J. M. (2013) “Mapping the global flow of aluminum: From liquid aluminum to end-use goods”, Environmental Science and Technology, 47(7), pp. 3057–3064. doi: 10.1021/es304256s.

Dai, Q., Kelly, J., and Elgowainy, A. (2016) “Vehicle materials: material composition of US light-duty vehicles”, Argonne National Laboratory for U.S. Department of Energy, University of Chicago, pp. 1–4.

Daioglou, V., van Ruijven, B. J. and van Vuuren, D. P. (2012) “Model projections for household energy use in developing countries”, Energy, 37(1), pp. 601–615. doi: 10.1016/j.energy.2011.10.044.

Davis, A. Y. et al. (2010a) “The environmental and economic costs of sprawling parking lots in the United States”, Land Use Policy, 27(2), pp. 255–261. doi: 10.1016/j.landusepol.2009.03.002.

Davis, A. Y. et al. (2010b) “Estimating parking lot footprints in the Upper Great Lakes Region of the USA”, Landscape and Urban Planning, 96(2), pp. 68–77. doi: 10.1016/j.landurbplan.2010.02.004.

Deetman, S. et al. (2020) “Modelling global material stocks and flows for residential and service sector buildings towards 2050”, Journal of Cleaner Production, 245, p. 118658. doi: 10.1016/j.jclepro.2019.118658.

Delogu, M. et al. (2017) “End-of-Life in the railway sector: Analysis of recyclability and recoverability for different vehicle case studies”, Waste Management, 60, pp. 439–450. doi: 10.1016/j.wasman.2016.09.034.Elhacham, E. et al. (2020) “Global human-made mass exceeds all living biomass”, Nature, 588(7838), pp. 442–444. doi: 10.1038/s41586-020-3010-5.

DSV (2022) “Dry container”, visited 7 March 2022. https://www.dsv.com/en/our-solutions/modes-of-transport/sea-freight/shipping-container-dimensions/dry-container

Elhacham, E. et al. (2020) “Global human-made mass exceeds all living biomass”, Nature, 588(7838), pp. 442–444. doi: 10.1038/s41586-020-3010-5.

ENTRANZE Project (2008). “Average floor area per capita”, visited 29 March 2021. https://entranze.enerdata.net/average-floor-area-per-capita.html

European Asphalt Pavement Association (2021) “Asphalt applications”, visited 24 November 2021. https://eapa.org/asphalt-applications/

Europa Publications (2004) “The Europe World Year Book 2004 volume II — Countries : Kazakhstan-Zimbabwe”, Editor : Joanne Maher, 45th edition. London, Routledge. pp.2430

Eurostat (2014) Figure 10.2 “The EU in the world 2014 — A statistical portrait”, Editor : Fabienne Montaigne and Helene Strandell. Belgium, European Union. pp.123

Experian Information Solutions (2012) “Experian Automotive: Midrange Cars are Top-Selling Segment; Toyota Camry Top Vehicle”, visited 7 March 2022. https://www.experian.com/blogs/news/2012/09/11/top-selling-cars/

FAOSTAT — Food and Agricultural Organization of the United Nations Statistical portal (2018) “Machinery”, data file downloaded on 25 May 2021 http://www.fao.org/faostat/en/#data/RM

Federal State Statistics Service (2022) “Living Standard — Housing”, visited 8 March 2022. https://eng.rosstat.gov.ru/living

Galos, J. and Sutcliffe, M. (2020) “Material Selection and Structural Optimization for Lightweight Truck Trailer Design”, SAE International Journal of Commercial Vehicles, 12(4), pp. 281–297. doi: 10.4271/02-12-04-0022.

Geyer, R., Jambeck, J. R. and Law, K. L. (2017) "Production, use, and fate of all plastics ever made", Science Advances, 3(7), pp. 25–29. doi: 10.1126/sciadv.1700782.Global Energy Monitor (2021) "Global Fossil Infrastructure Tracker", electronic dataset, downloaded 7 December 2021. https://globalenergymonitor.org/projects/global-fossil-infrastructure-tracker/summary-tables/

Government of Canada (2022) "Aluminium Facts", visited 6 June 2022. https://www.nrcan.gc.ca/our-natural-resources/minerals-mining/minerals-metals-facts/aluminum-facts/20510#L1

Gupta, N. and Shekhar, V. (2010) "The Indian Mid-Segment Passenger Car Industry", The IUP Journal of Business Strategy, VII(3), pp. 60–73.

Hall, K. et al. (2007) "Long-life concrete pavements in Europe and Canada", Federal Highway Administration from the US Department of Transportation, Washington DC. pp.13-23

Harder, J. (2018) "Glass recycling – Current market trends", visited 10 July 2022. https://www.recovery-worldwide.com/en/artikel/glass-recycling-current-market-trends_3248774.html

Harvey, L. D. D. (2022) "Reconciling global iron and steel mass flow datasets, with an update to 2011-2015 and an assessment of uncertainty in global end-of-life scrap flow", Resources, Conservation and Recycling, 182(March), p. 106281. doi: 10.1016/j.resconrec.2022.106281.

Harvey, L. D. D. et al. (2014) "Construction of a global disaggregated dataset of building energy use and floor area in 2010", Energy and Buildings, 76, pp. 488–496. doi: 10.1016/j.enbuild.2014.03.011.

Hill, N., et al. (2011). "Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles— Lot 1: Strategy". Ricardo-AEA. https://ec.europa.eu/clima/sites/clima/files/transport/vehicles/docs/ec_hdv_ghg_strategy_en.pdf

Hoxha, E. et al. (2021) "Life cycle assessment of roads: Exploring research trends and harmonization challenges", Science of the Total Environment, 759, pp. 143506. doi: 10.1016/j.scitotenv.2020.143506.

Huang, N. (2013) "Infrastructure" in "Living with a fair share ecological footprint", editors : Robert and Brenda Vale, 1st edition, publisher : Routledge, London, UK. pp.120. doi : 10.4324/9780203126448

IEA (2012) "Energy Technology Perspectives 2012", International Energy Agency, Paris. https://www.iea.org/reports/energy-technology-perspectives-2012

IEA (2020) "Energy Technology Perspectives 2020", International Energy Agency, Paris. pp.159;230. https://www.iea.org/reports/energy-technology-perspectives-2020

IEA (2021) "Global SUV sales set another record in 2021, setting back efforts to reduce emissions" International Energy Agency, Paris, visited 7 March 2022. https://www.iea.org/commentaries/global-suv-sales-set-another-record-in-2021-setting-back-efforts-to-reduce-emissions

Indian Railways Institute (2019) "Rail steels and stresses", Institute of Civil Engineering, visited during December 2021.https://www.iricen.gov.in/iricen/books_jquery/railsteel.pdf

IISS — International Institute for Strategic Studies (2022). "The Military Balance 2022. The annual assessment of global military capabilities and defence economics", editor : James Hackett, publisher : Routledge, London, UK.

International Road Federation (2021) "World Road Statistics (WRS) edition of 2021", visited 4 November 2021. https://worldroadstatistics.org/wrs-data/data/

International Rubber Study Group (2021) "Consumption of natural and synthetic rubber worldwide", visited 7 June 2022. https://www.statista.com/statistics/275399/world-consumption-of-natural-and-synthetic-caoutchouc/

International Trade Administration (2021) “Country Commercial Guide — Mexico : Transport infrastructure equipment and services”, Department of Commerce, USA, visited 12 January 2022. https://www.trade.gov/country-commercial-guides/mexico-transportation-infrastructure-equipment-and-services

Isaac, M. and van Vuuren, D. P. (2009) “Modeling global residential sector energy demand for heating and air conditioning in the context of climate change”, Energy Policy, 37(2), pp. 507–521. doi: 10.1016/j.enpol.2008.09.051.

Japan Association of Rolling Stock Industries (2021) “Number of operating rail cars”, visited 26 March 2022. https://www.tetsushako.or.jp/english/english02.html

Jemiolo, W. (2015) “Life cycle assessment of current and future passenger air transport in Switzerland”, February-December 2015.

Kachhawa, S., Singh, M. and Kumar, S. (2019) “Decoding India’s residential building stock characteristics to enable effective energy efficiency policies and programs”, Eceee Summer Study Proceedings, 2019-June, pp. 1289–1294.

Kaewunruen, S., Rungskunroch, P. and Jennings, D. V. (2019) “A through-life evaluation of end-of-life rolling stocks considering asset recycling, energy recovering, and financial benefit”, Journal of Cleaner Production, 212, pp. 1008–1024. doi: 10.1016/j.jclepro.2018.11.271.

Kalt, G. et al. (2021) “Material stocks in global electricity infrastructures – An empirical analysis of the power sector’s stock-flow-service nexus”, Resources, Conservation and Recycling, 173, p. 105723. doi: 10.1016/j.resconrec.2021.105723.

Kelly, J, Dai, Q., and Elgowainy, E. (2015) “Addition of new conventional and lightweight vehicle models in the GREET model”, Argonne National Laboratory for U.S. Department of Energy, University of Chicago, pp. 1–14.

Kollaros, G. and Athanasopoulou, A. (2017) “Influence of drainage on flexible road pavement design”, Research on Engineering Structures and Materials, pp. 38–46. doi: 10.17515/resm2016.76ma0726.

Kong, X. et al. (2022) “Steel stocks and flows of global merchant fleets as material base of international trade from 1980 to 2050”, Global Environmental Change, 73(February), p. 102493. doi: 10.1016/j.gloenvcha.2022.102493.

Krausmann, F. et al. (2018) “From resource extraction to outflows of wastes and emissions: The socioeconomic metabolism of the global economy, 1900–2015”, Global Environmental Change, 52(April), pp. 131–140. doi: 10.1016/j.gloenvcha.2018.07.003.

Kwak, M. et al. (2012) “Comparative life cycle assessment of complex heavy-duty off-road equipment”, Proceedings of the ASME Design Engineering Technical Conference, 5, pp. 425–433. doi: 10.1115/DETC2012-70547.

Laner, D. et al. (2015) “A Novel Approach to Characterize Data Uncertainty in Material Flow Analysis and its Application to Plastics Flows in Austria”, Journal of Industrial Ecology, 20(5), pp. 1050–1063. doi: 10.1111/jiec.12326.

Lee, J. et al. (2000) “Life cycle assessment of tractors”, International Journal of Life Cycle Assessment, 5(4), pp. 205–208. doi: 10.1007/BF02979361.

Liu, J. et al. (2020) “Material flows and in-use stocks of durable goods in Chinese urban household sector”, Resources, Conservation and Recycling, 158(February), p. 104758. doi: 10.1016/j.resconrec.2020.104758.

Machinchik, T., Freas, B. from Guidehouse Insights (2018) “Global Building Stock Database”. The most recent version of the report is described here : https://guidehouseinsights.com/reports/global-building-stock-database

Marinova, S. et al. (2020) “Global construction materials database and stock analysis of residential buildings between 1970-2050”, Journal of Cleaner Production, 247, p. 119146. doi: 10.1016/j.jclepro.2019.119146.

Meijer, J. R. et al. (2018) "Global patterns of current and future road infrastructure", Environmental Research Letters, 13(6). doi: 10.1088/1748-9326/aabd42.

Miatto, A., Fishman, T., Tanikawa, H., Schandl, H. (2016) "Global Patterns and Trends for Non-Metallic Minerals Used for Construction", J. Ind. Ecol. 21, pp. 924–937. doi: 10.1111/jiec.12471

Meszler, D., Delgado, O., Rodríguez, F., and Muncrief, R. (2018). "EU HDVs: Cost Effectiveness of Fuel Efficiency Technologies for Long-Haul Tractor-Trailers in the 2025–2030 Timeframe", International Council on Clean Transportation. www.theicct.org/publications/cost-effectiveness-of-fuel-efficiency-tech-tractor-trailers

Moura, M. C. P., Smith, S. J. and Belzer, D. B. (2015) "120 years of U.S. Residential housing stock and floor space", PLoS ONE, 10(8), pp. 1–18. doi: 10.1371/journal.pone.0134135.

Munoz, F. (2018) "More SUVs, more trucks and less cars : the shift continues in the USA" JATO Dynamics, visited 7 March 2022. https://www.jato.com/more-suvs-more-trucks-and-less-cars-the-shift-continues-in-the-usa/

National Bureau of Statistics of China (2022) "China Statistical Yearbook 2019", Table 16-3 and Table 16-4, visited 11 January 2022. http://www.stats.gov.cn/tjsj/ndsj/2019/indexeh.htm

Natural Resources Canada (2020) "Residential Housing Stock and Floor Space", visited 28 June 2022. https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=HB&sector=res&juris=00&rn=11&page=3

Nemat, B. et al. (2019) "The role of food packaging design in consumer recycling behavior-a literature review", Sustainability (Switzerland), 11(16), pp. 1–23. doi: 10.3390/su11164350.NGA — National Geospatial Intelligence Agency of the United States (2018). GIS map "Mali transportation lines", viewed 17 December 2021. https://www.arcgis.com/home/item.html?id=381e79791c314974832b735db75b5b0c

OICA — International Organization of Motor Vehicle Manufacturers (2021). Electronic datasets, all viewed and downloaded during November and December 2021.
"Vehicles in-use" https://www.oica.net/category/vehicles-in-use/
"Production Statistics" from 2010 to 2020 https://www.oica.net/production-statistics/

Pavement Interactive (2021). "Bulk specific gravity", by the Pavement Tools Consortium (a partnership between states' Department of Transport, the Federal Highway Administration and the University of Washington), visited December 18, 2021. https://pavementinteractive.org/reference-desk/testing/asphalt-tests/bulk-specific-gravity/

Plank, B. et al. (2022a) "From resource extraction to manufacturing and construction: flows of stock-building materials in 177 countries from 1900 to 2016", Resources, Conservation and Recycling, 179(September 2021). doi: 10.1016/j.resconrec.2021.106122.

Plank, B. et al. (2022b) "Compilation of an economy-wide material flow database for 14 stock-building materials in 177 countries from 1900 to 2016", MethodsX, 9, p. 101654. doi: 10.1016/j.mex.2022.101654.

Plastemart (2021) "Food packaging accounts for almost 35% of the global packaging market", visited 1 July 2022. http://www.plastemart.com/plastic-technical-articles/food-packaging-accounts-for-almost-35-of-the-global-packaging-market/2337

Prucz, J. C. et al. (2006) "FreedomCAR and Vehicle Technology Office Innovative Structural and Joining Concepts for Lightweight Design of Heavy Vehicle Systems". Report for US Department of Energy. West Virginia University.

Railway Association of Canada (2015) "Rail Trends 2016", visited 25 March 2022. https://www.railcan.ca/wp-content/uploads/2017/03/Rail_Trends_2016.pdf

Sharpe, B. (2014). "Integrating Trailers into HDV Regulation: Benefit-Cost Analysis". International Council on Clean Transportation. www.theicct.org/publications/integrating-trailers-hdv-regulation-benefit-cost-analysis

Sharpe, B. and Rodríguez, F. (2018) "Market analysis of heavy-duty commercial trailers in Europe", International Council on Clean Transportation, (September), pp.34.

SIPRI — Stockholm International Peace Research Institute (2022) Electronic dataset, downloaded 6 June 2022. https://milex.sipri.org/sipri

Statistics Canada (2021). Table 23-10-0052-01 "Railway industry length of track operated at the end of the year by area, by company", Electronic dataset, visited 7 January 2022. doi : 10.25318/2310005201-eng.

Tamura, A. (2012) "An overview of Japan's high-speed railway : Shinkansen", Ministry of Land, Infrastructure, Transport, and Tourism, visited 11 January 2022. https://www.jttri.or.jp/docs/120113_tamura_pres.pdf

Textile Exchange (2021) "Preferred fibre and materials market report 2021", visited 28 June 2022. https://textileexchange.org/preferred-fiber-and-materials-market-report/

Tielmann, M. R. D. and Böhm, S. (2016) "Laying of all Asphalt Courses in One Step", Transportation Research Procedia, 14, pp. 3562–3571. doi: 10.1016/j.trpro.2016.05.330.

U.S. Department of Transportation (2021) "Number of U.S. truck registrations by type", visited 20 December 2021, Bureau of Transportation Statistics, Federal Highway Administration, Washington DC. https://www.bts.gov/browse-statistical-products-and-data/national-transportation-statistics/number-us-truck

U.S. Energy Information Administration (2021) "Annual Energy Outlook 2021 : Table 22. Commercial sector energy consumption, floorspace, equipment, efficiency, and distributed generation", visited 28 March 2021. EIA webpage

UIC — Union International des Chemins de Fer (2021) "Railway Statistics Synopsis", downloaded 20 March 2022, https://uic-stats.uic.org/resources/help_resource/?id=4 (only the 2022 report is available)

UIC — Union International des Chemins de Fer (2022) Electronic dataset, visited 22 March 2022. https://uic-stats.uic.org

UNCTAD — United Nation Conference on Trade and Development (2021) "Merchant fl Electronic dataset, downloaded 16 March 2022. https://unctadstat.unctad.org/wds/ReportFolders/reportFolders.aspx

UNCTAD — United Nation Conference on Trade and Development (2021) "Chapter 2. Maritime transport and infrastructure" in Review of Maritime Transport of 2021. https://unctad.org/webflyer/review-maritime-transport-2021

UNECE — United Nations Economic Commission of Europe (2021) Electronic dataset, downloaded 16 November 2021. https://w3.unece.org/PXWeb2015/pxweb/en/STAT/STAT__40-TRTRANS__11-TRINFRA/ZZZ_en_TRRailInfra1_r.px/

United Arab Emirates Government Portal (2022) "Railways — Etihad Rail", visited 13 April 2022. https://u.ae/en/information-and-services/transportation/railways

USGS — United States Geological Survey (2021) "Copper", Mineral Commodities Survey. https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-copper.pdf

Vehicle Technologies Office (2013) "Workshop report : trucks and heavy-duty vehicles technical requirements and gaps for lightweight and propulsion materials", Energy Efficiency & Renewable Energy, U.S. Department of Energy. p.iii

Wang, C. et al. (2021) "Critical review of global plastics stock and flow data", Journal of Industrial Ecology, 25(5), pp. 1300–1317. doi: 10.1111/jiec.13125.

Westbroek, C. D. et al. (2021) "Global material flow analysis of glass: From raw materials to end of life", Journal of Industrial Ecology, 25(2), pp. 333–343. doi: 10.1111/jiec.13112.Wolff, S. et al. (2020) "Scalable life-cycle inventory for heavy-duty vehicle production" Supplementary data 1, Sustainability (Switzerland), 12(13). doi: 10.3390/su12135396.

Whitelegg, J. (1994) “Transport and land take”, report for the CPRE (Campaign to Protect Rural England), Eco Logica Ltd. White Cross, Lancaster. pp.10. https://www.eco-logica.co.uk/pdf/CPRELandTake.pdf.

World Bank (2021). “Rail lines (total route-km)”, electronic dataset, downloaded 16 November 2021. https://data.worldbank.org/indicator/IS.RRS.TOTL.KM?view=map&year=2018

World Steel Association (2020) “2020 World Steel in figures”, Belgium. pp.1-16. https://aceroplatea.es/docs/WorldSteelinFigures2020.pdf