Delineating the Technosphere: Definition, categorization and characteristics

Eric Galbraith[1,2], Abdullah-Al Faisal[1], Tanya Matitia[1], William Fajzel[1], Ian Hatton[1], Helmut Haberl[3], Fridolin Krausmann[3], and Dominik Wiedenhofer[3]

[1]Earth and Planetary Sciences, McGill University, Montreal, Canada
[1]Institut de Ciencia i Tecnologia Ambientals (ICTA-UAB), Universitat Autonoma de Barcelona, Cerdanyola del Valles, Spain
[3]Institute of Social Ecology, BOKU University, Vienna, Austria

Correspondence: Eric Galbraith (eric.galbraith@mcgill.ca)

Abstract. The global assemblage of human-created buildings, infrastructure, machinery and other artifacts has been called the 'technosphere', and plays a major role in the present-day dynamics of the Earth system. The technosphere enables the rapid extraction of natural resources and the combustion of fossil fuels, impacting biodiversity and causing climate change while producing copious waste materials. At the same time, the technosphere supports the provision of food, shelter, transportation and long-distance communication, and is the main component of material wealth. Despite its importance, Earth system science has been slow to explicitly incorporate the technosphere as an integrated part of its conceptual and quantitative frameworks. Here we propose a refined definition of the technosphere, intended to assist in developing functional integration with other Earth system spheres as well as social sciences, and suggest a categorization system based on how the end-uses support and catalyze human activities. Given the formal definition and resolved categorization, we delineate basic attributes of the technosphere, including its mass distribution among components and across the Earth surface, as well as its first-order temporal dynamics. In particular, of the roughly 1 trillion ton technosphere mass, we estimate that one half is comprised of buildings and one third transportation infrastructure, both of which we globally map at one-degree resolution. Movable entities, mostly composed of vehicles, vessels and machinery, account for less than 2% of the total technosphere mass, yet are comparable to the biomass of all animals on Earth. We show that reconstructions of the technosphere since 1900 are consistent with an autocatalytic process, resulting in exponential growth with long-run increase of $>3\%\ y^{-1}$, equivalent to a 20-year doubling time. Building a stronger quantitative understanding of the technosphere can help to better integrate it within Earth system science, while bridging natural and social sciences to support physically-plausible pathways towards sustainability and human wellbeing.

1 Introduction

More than 8 billion humans live on Earth, embedded within a massive network of roads, buildings, vehicles, machinery, computers and other artifacts that spans the globe. The entirety of these human creations, arrayed across the surface of our planet as well as orbiting above it, has been referred to as the 'technosphere' (Haff, 2023). Humans create the technosphere to provide diverse end uses such as transport, comfortable living spaces and communication, as well as for social reasons (Pauliuk and Müller, 2014; Schaffartzik et al., 2021). We are also entirely dependent on it to keep us alive - no more than a few million humans could be provided with food, drinking water, or shelter without it (Daily and Ehrlich, 1992; Fischer-Kowalski and Weisz, 1999; Smil, 2004).

The use of the term technosphere has been justified by the fact that these human creations can be considered a large and complex functional aggregate, like other spheres of the Earth system (Table 1). Like the atmosphere, in which convection at one location can be strongly linked to precipitation at a distant location a week later, components of the technosphere are involved in many globally-interconnected internal processes. For example, the functions of mining machinery are strongly linked to transportation networks, metal processing facilities and manufacturing plants. Like the biosphere, the technosphere supports its own growth over time by increasing the rate at which materials can be extracted, processed, transported, and transformed to final products (Herrmann-Pillath, 2018). In addition, it represents a significant and rapidly changing component of the Earth surface. Depending on how it is defined, the technosphere has been estimated to be of comparable scale to the biosphere, both in terms of its mass and the fluxes it enables. For example, the mass of human creations has likely exceeded the dry mass of all living organisms (roughly 1100 Gt dry mass) (Elhacham et al., 2020), the rate of primary energy conversion within the technosphere (roughly 20 TW) is roughly half that of terrestrial above-ground net primary production (Haberl et al., 2007) and continues to increase (Smil, 1991; Lenton et al., 2016), and the rate of mass dislocation at the Earth surface by machines (roughly 320 Gt y^{-1}) appears to exceed all natural geomorphological processes by an order of magnitude (Cooper et al., 2018). There seems little doubt that, at this point, the technosphere can be considered a major component of the Earth system.

The technosphere is also central to two prominent themes of discussion in the realm of Earth system science and sustainability: planetary boundaries (Steffen et al., 2015) and the wellbeing of humans (Stiglitz et al., 2009; Raworth, 2018). The vast scale and complexity of the technosphere make its nature difficult to grasp, and like the proverbial fish who is unaware of the water she swims in, we can be remarkably oblivious to the role of technosphere dynamics in both of these Earth system themes. By trying to make sense of the whole technosphere, at the planetary scale and in connection with human lives, we can better comprehend how and why it comes into existence, as well as its functional role in driving global change.

Yet despite its importance, the technosphere remains absent from most conceptions of Earth system science (Herrmann-Pillath, 2018). The term is inconsistently defined, lacks a system of categorization, and its basic attributes have not been holistically assessed, including its mass distribution and temporal dynamics. Industrial ecology and ecological economics have made great strides in estimating the fluxes of material and energy through the global technosphere, under the names industrial metabolism or socioeconomic metabolism research (Graedel et al., 2015; Weisz et al., 2015; Pauliuk and Hertwich, 2015; Haberl et al., 2019; Lanau et al., 2019; Fu et al., 2022). However, so far there have been few efforts to integrate this work with the Earth system science perspectives. In short, the understanding of what the technosphere is, as an Earth system component, remains remarkably poorly resolved.

This paper aims to improve the resolution of the technosphere by providing an interdisciplinary foundation for linking its material basis with its functionality, and by presenting a compilation of data that gives some insights on its geographical and dynamical characteristics. The paper is structured as follows. Section 2 reviews existing definitions of the technosphere and proposes a refinement. Section 3 presents a technosphere categorization scheme, which is aligned with the ways in which technosphere entities interact with human activities. Section 4 assesses the composition of the technosphere in terms of the

Sphere	Description
Lithosphere	The rigid planetary crust, composed of a continuous spheroid of rock.
Pedosphere	The mixture of non-living debris that lies on top of the lithosphere, including the inorganic and organic components of soils and marine sediments.
Atmosphere	The layer of gas that envelopes the Earth, including suspended solutes and particles.
Hydrosphere	Liquid and solid phases of water comprising the ocean, lakes and rivers, groundwater, permafrost, snowpack and glaciers, including solutes and entrained particles.
Biosphere	All living organisms, from unicellular bacteria to whales, including humans and domesticated animals.
Technosphere	All non-food matter extracted from other spheres of the Earth system and transformed to novel states that achieve end-uses intended by humans.

Table 1. Conceptualizing the spheres of the Earth system, including the technosphere, defined according to the constituent matter. See Huggett, (2024) for a discussion of the spheres.

activity-based categorization, and provides maps of its first-order distribution across the Earth surface. Section 5 discusses basic empirical features of the temporal dynamics of the technosphere, and Section 6 concludes the paper.

2 Defining the boundaries of the technosphere

The term ‘technosphere’ has been attributed to science writer Wil Lepkowski, who was apparently the first to use it in a 1960 article (Otter, 2022). It was subsequently used by systems engineer John Milsum (Milsum, 1968) and, the following year, by biologist Julian Huxley in a reflection on the first moon landing (Huxley and Nicholson, 1969). More recently, geologist Peter Haff effectively promoted the term to encapsulate the global proliferation of human technology at the heart of the concept of the Anthropocene (Haff, 2014, 2023). Haff described the technosphere as including "everything that enables rapid extraction from the Earth of large quantities of free energy, long-distance, nearly instantaneous communication, rapid long-distance energy and mass transport, high-intensity industrial and manufacturing operations, and a myriad additional ‘artificial’ or ‘non-natural’ processes without which modern civilization could not exist". His use of ‘technosphere’ was chosen rather than ‘anthroposphere’ to suggest a detached view of an emerging geological process that has partly entrained humans, rather than one that has humans exclusively at the centre. Zalasiewicz (2017) used a slightly modified version of this definition, specifying the part of the technosphere which is currently in use. The in-use portion of the technosphere is also distinguished by Johansson (2013), and is generally equivalent to commonly used terms in industrial ecology, including ‘in-use stocks’ (Pauliuk and Hertwich, 2015), ‘material stocks’ (Haberl et al., 2019), ‘manufactured capital’ (Weisz et al., 2015) and ‘technomass’ (Inostroza, 2014), as well as ‘artefacts’ in the early socio-ecological literature drawing on ecological anthropology (Fischer-Kowalski and Weisz, 1999). Throughout the years, the technosphere has been defined in many different ways, sometimes including human-disturbed soils, or even ideas.

Although there can be no 'correct' definition of the technosphere, we propose here a refinement which is compatible with the standard Earth system spheres conceptualization (Table 1). We follow the Earth system science convention of defining a sphere in terms of the properties of the matter of which it is comprised (i.e. state variables), rather than in terms of processes (i.e. fluxes). In other words, to use the terminology common among industrial ecologists and economists, a sphere is defined as an assemblage of stocks, not according to flows. For example, the atmosphere is defined as the envelope of gas that surrounds our planet, including tiny particles suspended within it. There are many processes that occur within the atmosphere, such as convection, precipitation and cloud formation, but these are not what define the atmosphere. Similarly, the biosphere is defined as the stock of living organic matter, rather than the processes and flows that carry on the business of life.

Even with a deliberate focus on stocks, the boundaries of the technosphere are inherently blurry. To varying extents, this bluriness applies to all spheres of the Earth system. For example, one could ask whether bubbles of air mixed into the surface ocean by waves belong to the atmosphere or the hydrosphere, or if they oscillate back and forth as they are injected and subsequently outgas. As such, the sphere framework is not obviously suited to precise categorizations, at least not without a long list of instructions on how to treat edge cases. Nonetheless, the spheres have proven helpful for sketching, in broad strokes, the components of our planetary system in an intuitive way, helping to think more clearly about processes that extend up to the global scale.

To these ends, the technosphere is here defined as: *all non-food matter extracted from other spheres of the Earth system and transformed to novel entities that can provide end-uses to humans*. We highlight four important distinctions inherent in this definition.

First, we limit the components of the technosphere to nonliving creations, i.e. not including organisms composed of cells with active ribosomes. As such we do not include living humans or any other life form within the technosphere, but instead consider all living organisms as components of the biosphere (where the biosphere is the sum of all organisms). This provides long-term continuity with Earth history, since humans were clearly a part of the biosphere in the ancient past, as were the ancestors of our domestic animals, and there was no point at which we 'left' the biosphere. Our food continues to be derived almost entirely from the living organisms that comprise the biosphere, with whom we also share viruses and bacteria. Thus, the definition here considers broiler chickens, grapefruit, oil palms, corn and genetically-modified sheep as part of the biosphere, while pacemakers and prosthetic limbs are considered part of the technosphere. Also, we do not include modifications of the pedosphere or lithosphere as part of the technosphere, thus excluding the soils of croplands and rubble of mines, all of which would remain classified in the pedosphere. This definition avoids conflating the technosphere with the meaning of 'artificial', a conflation which easily occurs with the term 'anthroposphere' (Pauliuk and Hertwich, 2015) and which promulgates a false dichotomy between natural and artificial worlds. Because of these exclusions, the technosphere definition proposed here implies a much smaller mass than that estimated using the definition proposed by Zalasiewicz (2017), which was dominated by human-disrupted soils and sediments.

Second, because the technosphere refers exclusively to non-living physical matter, it does not include human activities or immaterial social constructs like institutions, corporations, or social norms. In physical terms, social processes are couched in the neural structures of humans, coordinated by symbolic information exchange, and neurons are located within the biosphere

(Galbraith, 2021). This is not to say that the technosphere is independent from social dynamics. Rather, social processes and the technosphere are strongly coupled, in the same way that the growth of plankton in a culture depends on the nutrient content of the water in which they grow, or the dynamics of the ocean and atmosphere are tied through the exchange of energy. In addition to providing a more unambiguous definition, this separation of human society from the technosphere preserves the independence of human agency, which was identified by Donges (2017) as a conceptual problem with the technosphere of Haff (2014).

Third, we draw a boundary where the state of an entity deteriorates so as to be unfit to serve an intended end-use. An object that undergoes repair remains in the technosphere, while an object that is discarded or irreparably damaged does not. As such, this boundary can be subject to social characteristics that determine the willingness or ability to maintain or repurpose items. The out-of-use boundary can be seen as analogous to the definition of the biosphere as comprised exclusively of living organisms – when an organism dies, it ceases to be part of the biosphere. And, just as heterotrophic consumption can recycle organic matter within the biosphere, material recycling can transform defunct technosphere components into new in-use entities (see recycling flux in Figure 1), while a medieval fortress that was abandoned after losing its original functionality can be repaired and returned to the in-use technosphere as a museum.

Fourth, this definition of the technosphere does not include mass that would be called ‘waste’. Although waste is clearly important for humans, sustainable development, and the Earth system, a precise definition that works on long timescales is difficult to construct. Most of what would be considered technosphere waste is gradually transformed or mixed across the Earth system on timescales from hours to millennia, making it difficult to define a boundary at which it would ever stop being waste. This differentiates the technosphere definition proposed herein from the anthroposphere concept, which would include all waste ever produced by humanity (Pauliuk and Hertwich, 2015). Furthermore, biological analogs of technosphere waste are not typically considered part of the biosphere in Earth system science. For example, exhaled CO_2 is part of the atmosphere, while dissolved organic molecules in seawater are part of the hydrosphere, and the carbonate shells of foraminifera accumulated in sediments are part of the pedosphere. Placing the boundary in this way captures the fact that abandoned components of the technosphere are inexorably re-incorporated into the other spheres, rather than remaining apart. A discarded soda can interacts with its surroundings as part of the pedosphere, microplastics in the ocean are consumed by plankton as part of the hydrosphere, and polychlorinated biphenyls incorporated into living organisms are part of the biosphere. Although external to the technosphere, persistently identifiable wastes can be termed ‘technofossils’, as suggested by Zalasiewicz (2014). Thus, the flux of matter through the technosphere has introduced many novel chemicals and structures that are now distributed throughout the other spheres of the Earth system, and have fundamentally changed our planet, just as the flux of oxygen from the biosphere changed the redox state of the atmosphere billions of years ago (Lenton et al., 2016).

As illustrated in Figure 1, we distinguish the in-use portion of the technosphere from substances that have been extracted or produced from the other Earth system spheres, but remain in an intermediate state as materials or components. We also separate substances that are chemically transformed, in a single use, to an unusable state, and refer to these as technosphere metabolites, by analogy with the molecules that are transformed within organisms to provide metabolic energy and fuel growth. The technosphere metabolites include fuels (fossil fuels, firewood, bio-ethanol, uranium ore), industrial chemicals (reagents,

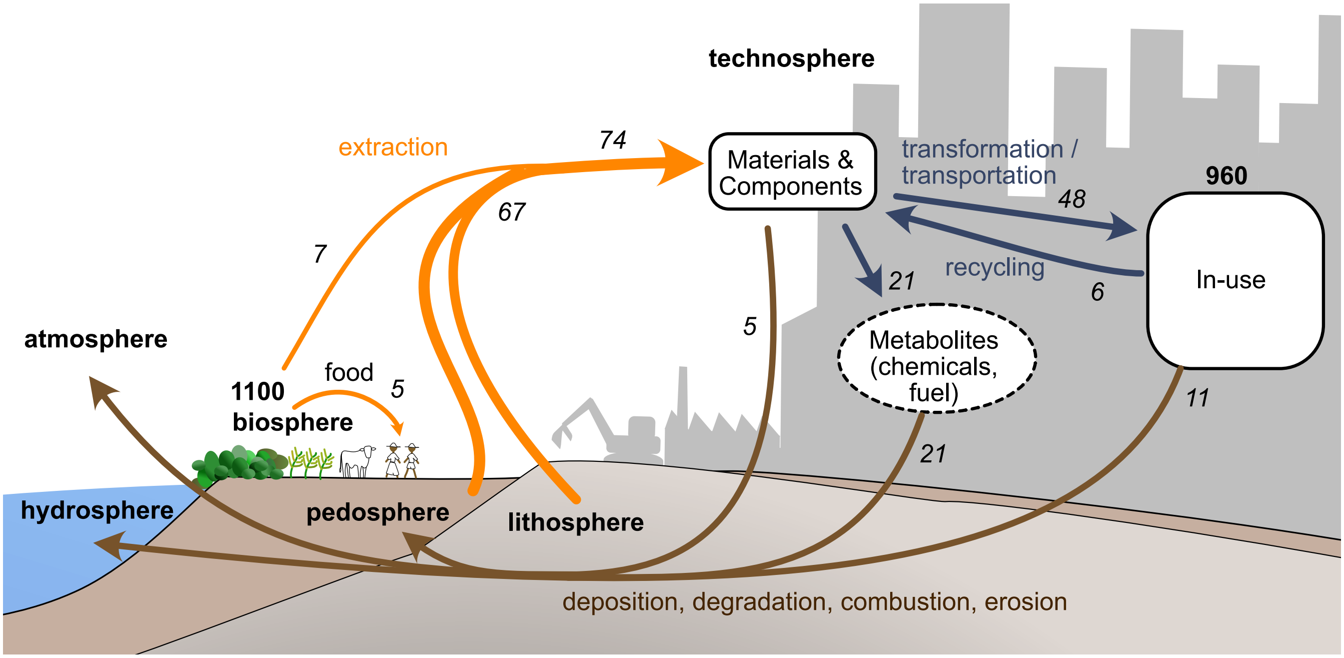

Figure 1. Schematic of the Earth system including the technosphere. Italicized numbers show fluxes in $Gt\,y^{-1}$ and bold number shows the in-use mass in Gt, as estimated by Krausmann et al. (2018) for the year 2015. The dry mass of the biosphere as estimated by Elhacham et al. (2020) and dry mass of food flux estimated by Alexander et al. (2017) are also shown.

fertilizers and pesticides) and pharmaceuticals. Food – the organic matter produced by organismal growth and consumed by living humans – is not considered part of the technosphere.

We also note that this definition of the technosphere is equivalent to the concept of in-use material stocks of socio-ecological metabolism research (Fischer-Kowalski and Weisz, 1999; Haberl et al., 2019) while excluding human bodies and domesticated animals (since the Earth system framework places all of these within the biosphere). This provides a consistency with economy-wide Material Flow Accounting (ew-MFA, see below) which is helpful for estimating fluxes (Krausmann et al., 2017a; UNEP, 2023).

3 Categorizing the technosphere

A systematic and holistic categorization of the technosphere can provide a global scale perspective, making it easier to comprehend what the whole technosphere is, as well as contextualizing the parts within it. It can also help to build an understanding of the functional behaviour of the technosphere, and how it relates to outcomes for human wellbeing.

However, developing such a categorization is not an easy task, nor can it be seen to have a unique solution. The technosphere is extremely diverse in composition, function, and in the interactive roles it plays within human societies. It also evolves over time, often in coordination with social changes, so that designing a categorization that is robust on long timescales is challenging. Nonetheless, even imperfect classifications can provide useful frameworks within which to better understand a system, just as the Linnean classification of species (Linnaeus, 1758) continues to prove a useful framework for the biosphere, despite the fact that it cannot ever capture the underlying reality of phylogeny (Benton, 2000).

3.1 Existing categorizations

Extensive classification systems of human creations do already exist, largely developed by economists and business entities to organize commerce and develop trade statistics. For example, the central product classification (CPC), developed by the United Nations (United Nations Statistical Division, 2004) provides an exhaustive and exclusive categorization of goods and services – the outputs of economic activity. The CPC consists of more than 4000 classes, nested within a 5-level hierarchical classification. However, these categories are designed to apply to economic data, rather than a physical systems understanding of technosphere function within the human-Earth system. As a result, many classes are specific to materials or manufacturing sectors, or include intermediate components, and these are frequently mixed together. For example, one category includes "Medical appliances, precision and optical instruments, watches and clocks", which aggregate a wide range of end uses based on the technical nature of manufacturing.

A more Earth-system relevant set of categorizations has been used within the framework of economy-wide Material Flow Accounting (ew-MFA), which has been developed for the purpose of monitoring the biophysical basis of society and informing sustainable resource use policies (Krausmann et al., 2017a; UNEP, 2023). The ew-MFA framework is widely used to provide policy-relevant indicators in the Sustainable Development Goals and for national resource policies, consistently accounting for all fluxes and in-use stocks in physical units. This accounting draws on data using the CPC classifications and other socio-economic statistical data sources such as the Food and Agriculture Organization, International Energy Agency and United States Geological Survey. Annual raw material extraction and physical trade between economies are reported, as well as the material footprint, i.e. all upstream material use along supply chains whose products are ultimately destined for consumption elsewhere (Wiedmann et al., 2015; Lenzen et al., 2022; UNEP). Work within this framework has primarily categorized fluxes and in-use stocks by their material properties, or focused on specific end uses within a subset of the technosphere (Chen and Graedel, 2015; Lanau et al., 2019; Streeck et al., 2023). Recent developments in ew-MFA have provided the first fully mass-balanced accounts of the global socio-metabolic system including raw material extraction and in-use material stocks, as well as all waste and emissions (Krausmann et al., 2017b, 2018; Wiedenhofer et al., 2019). Economy-wide, fully mass-balanced accounts across all bulk materials, which can be linked to their main end-uses, have become available even more recently (Wiedenhofer et al., accepted) and which we will return to below as a key component of our data compilation.

3.2 Alignment with activity end-uses

Our end-use categorization system should rest on a consistent conceptual underpinning that can help to reveal functional aspects of the technosphere. One might imagine starting directly from the measurable physical changes in the world caused by the use or operation of a technosphere entity. For example, some entities can be used to generate heat, or pump heat from one place to another. However, if we want to link to the motivations that cause an entity to be produced, this approach would be very indirect. For example, one might generate heat in a smelter to produce nickel, in a kettle to make tea, or in the boiler of a steamship to power transportation – the immediate physical outcome is similar, but the outcomes that motivate the heat production are very different. One useful and tractable alternative, that lends itself to connections both to physical changes and human motivations, is to align the categorization with human time use, which we can describe in terms of activities (Gershuny and Sullivan, 2019; Galbraith et al., 2022).

We therefore choose to focus on physically-oriented end-use outcomes that are aligned with activities. Human-centred, end-use outcomes are essential aspects of the technosphere, since they are are what motivate its creation - every component of the technosphere can be associated with at least one type of intended end use. Many end-uses can be mechanistically linked through activities to physical, material impacts on the Earth system, including energy transformations, mass transport, biosphere modification, and chemical processes. Other end uses change our surroundings, altering the context in which we spend our time. Thus, an activity-aligned end-use perspective connects naturally to both human and Earth system outcomes.

To facilitate quantitative connections with existing records of human activities, we align the end uses with the Motivating Outcome-Oriented General Activity Lexicon (MOOGAL) (Galbraith et al., 2022; Fajzel et al., 2023). The MOOGAL was created to provide an exhaustive and exclusive categorization of human activities based on the outcomes that motivate the undertaking of the activities. Outcome orientations were identified in existing lexicons from economic, anthropological and sociological literature, and harmonized using physically-based descriptions (Galbraith et al., 2022). MOOGAL activities were chosen to clearly identify processes that alter the Earth system in material terms. The alignment with activities provides the benefit of clearly associating the technosphere with the human activities with which they are engaged, at least for the components for which this relationship is clear.

3.3 Proposed end-use categories

Table S1 provides an overview of the proposed Motivating End-Use Technosphere Entity Categorization, or MEUTEC for short. The MEUTEC is intended to provide an exhaustive and exclusive set of categories for the in-use technosphere, i.e. extracted materials that have been transformed into the state intended for use, and persist in a usable state. The MEUTEC is shown alongside the MOOGAL human activity classification in Figure 2. Shaded polygons indicate connections between activities and technosphere categories, including how activities motivate the creation or maintenance of technosphere categories, as well as the ways in which technosphere entities alter the outcomes of activities. For example, the MEUTEC categories ‘Material extraction’ and ‘Material processing’ include entities that exist to support the ‘Material provisioning’ MOOGAL category, and whose use enable the provision of materials at greater rates, and in different forms, for a given investment of activity. Note that some categories have direct correspondences (e.g. Food growth and collection) while others do not align directly, but have multiple interactions.

3.4 Catalytic properties

Many technosphere entities operate in direct support of human activities, in a way that materially alters the outcomes of the activities. For example, the ability to catch fish is enhanced by the use of a fishing boat and fishing gear, while a highway

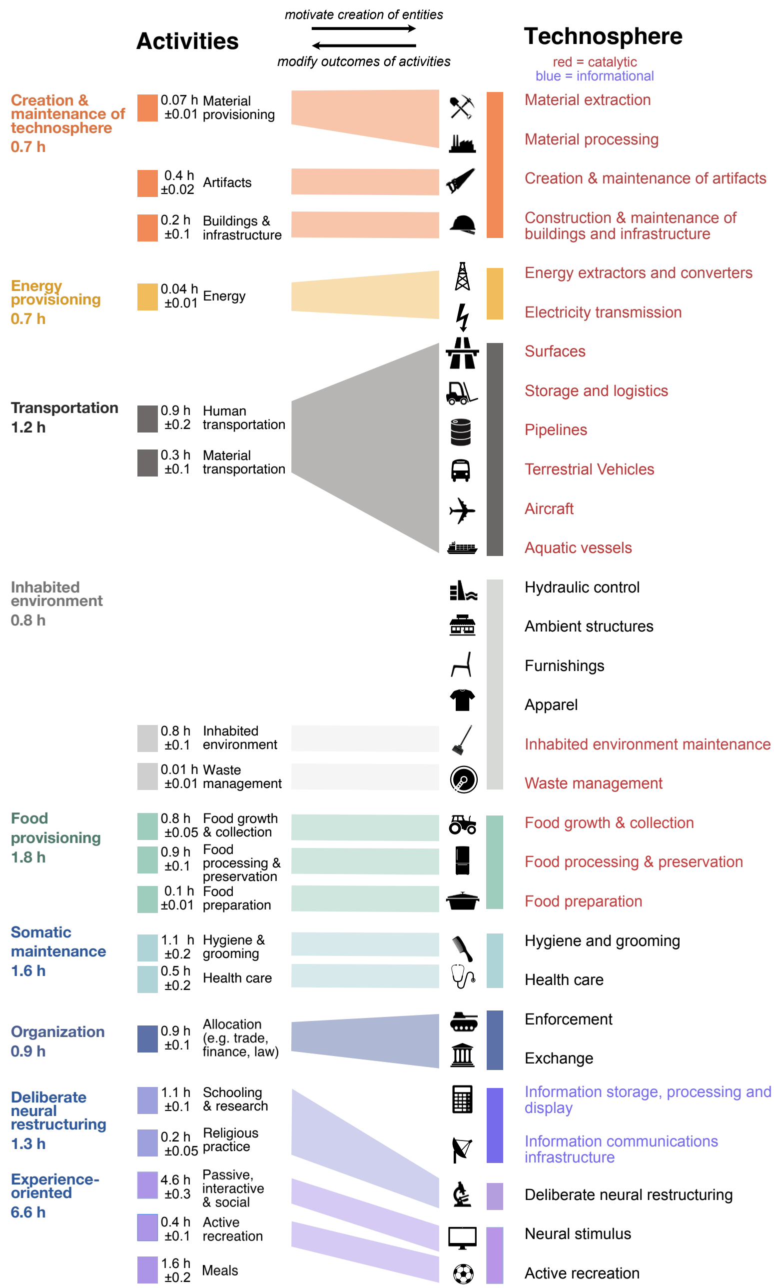

Figure 2. Connecting human activities with the technosphere. Strong associations between categories are shown by shaded polygon connections. Technosphere categories that do not have clear associations to individual activities are found in the Inhabited environment and information-related categories. Each activity is accompanied by the average amount of time (in hours) devoted per day to the activity by the global human population (Fajzel et al., 2023).

increases the rate at which people and goods can be transported. In contrast, other things are produced just to change the context in which humans live - the buildings that serve as our ambient environments, for example.

If the activity-modifying entities accelerate the outcomes of the activity, for a given human time expenditure, we call them *catalytic* entities. Here we use the term catalysis in the chemical sense, since - like enzymes - these entities accelerate the creation of products without themselves being consumed. The idea of catalytic entities can be quantitatively expressed in the following differential equation,

$$\frac{dx}{dt} = A_x N T_x \epsilon_x \tag{1}$$

Here, x is an output (e.g. in units of kg) produced at some rate over time t (e.g. days) by the allocation of time to activity A_x (e.g. hours per day) within a population of N persons, T_x is the mass of technosphere entities that play a catalytic role in the production of x (e.g. kg), and ϵ_x captures all other factors involved in determining the overall efficiency of production (e.g. kg per person-hour per day per kg of T_x). Thus, an increase in the available technosphere entities T_x will tend to accelerate the production of x (increasing dx/dt) for a given amount of human time, though it is well-known in economics that this is not a linear relationship due to changes in ϵ_x (e.g. Cobb and Douglas (1928)) and there is frequently a saturating relationship.

Catalytic processes can be complex, with a given entity playing a catalytic role in the production of multiple outputs. However, in the aim of making sense of the technosphere, we qualitatively identify groups of entities that clearly play catalytic roles. These are listed in red in Table S1 and Figure 2.

3.5 Difficult entities to categorize

We also highlight a broad array of entities that are particularly difficult to categorize, yet intensely relevant to the functioning of the global human system. These could perhaps be called *neural interaction* entities. These are found near the bottom of Figure 2 and include devices, artifacts and infrastructure created to provide neural stimulus, rather than supporting physical changes in the state of human environments, bodies, or the Earth system. Their existence allows us to externalize thought processes, share insights and observations across space and time, organize complex behaviour, and generate a wealth of enjoyable sensory experiences. These features are hugely important for society and collective cognitive processes.

Many of these entities store, process, generate or display symbolic information – physical patterns that may be written words and numbers, or digital (electrical impulses representing strings of zeros and ones). Together these are referred to as Information and Communication Technologies by Creutzig et al. (2022) and indicated in blue font in Figure 2. Information and Communication Technologies play essential roles in human societies, by providing high quality communication (Boyd, 2018) and enabling complex logical operations and computation. Information can be stored in many forms, including as engravings on stelae, words on paper, or magnetic fields in solid-state electronics. Long-distance transmission is enabled by radio antennae, fiber optic cables, and communications satellites.

Also among the difficult-to-categorize entities used for neural stimulus are many that do not utilize symbolic information, such as dice games, musical instruments, and photographs. These were all invented before the digital age, but all can now be replicated or simulated with computers, and transmitted across the internet. This may reflect the underlying importance of information-rich patterns to the forms of neural stimulus that we find both useful and pleasurable.

Because of the wide range of activities we engage in with things such as printed matter, computers, and smartphones, it is challenging to associate them directly with particular activities. As a result, the connections indicated for Organization, Deliberate Neural Restructuring and Experience-Oriented activities, as well as the Informational MEUTEC categories, should be seen as provisional, and we hope that they can be improved in future work.

3.6 Assigning entities to categories

We categorize at the scale of functional entities. Most of the objects/entities of the technosphere are assembled from multiple components, what Oswalt (1976) calls technounits. For the purpose of categorization, we generally consider technosphere entities at the scale at which the motivating end use is fulfilled, which one could regard philosophically as holons. (A holon, *sensu* Koestler 1970, is recognizable as a distinct and functional unit, yet it is composed of multiple parts, while itself being part of a larger assemblage.) An *entity* is here considered as a coherent spatially-organized and persistent object that provides a recognizable end use (i.e. a service) without requiring additional components to do so, although it may require an input of metabolites and/or energy. Thus, a building is an entity, including all integral plumbing, wiring, paint, and exterior cladding, while a chair inside the building is a separate entity (since it would provide the same end use if placed outdoors, though its occupant might get rained on). In addition, the assignment of entities to categories applies the following principles:

- The relevant end-use is the physical outcome which motivated the production of the entity or its ongoing maintenance. For example, the creation of a television is motivated by the desire to provide experiences to viewers, rather than a desire to convert electrical energy to electromagnetic radiation for its own sake.

- Because any interaction with an entity will change the context of human experience, the experience is not used as the basis of categorization unless it is the only motivating outcome. For example, a car can provide a pleasant context for sitting and listening to music at a comfortable temperature, but it is the physical outcome of transporting humans and goods that is used for categorizing the car.

- The social, cultural, or economic significance of an entity is not considered, unless there is no other end-use. Instead the classification is according to the ostensible, physically-grounded end use. For example, a block of apartments would be categorized as residential buildings, regardless of whether their construction was motivated by an actual need for housing or by capital investment strategies.

- A single category can include both fixed, immovable creations (i.e. elements of the built environment) as well as movable entities, where they both contribute to the same type of outcome. For example, the end use 'material processing' can include machinery as well as constructed refining facilities.

- The material of which an entity is comprised does not influence its classification. A jacket is classified in the same way, whether the material is derived of petroleum (nylon), plants (cotton), or animals (leather). Electronics are considered a particular collection of materials, rather than an end use.
- Components are not considered as entities. For example, a screw is a component, which could become part of an end-use entity by being incorporated in a residential building, or in furniture. Similarly, engines are not classified as entities, but included within the vehicle they power.
- Because entities are classified by end-use, superficially similar entities can fall into different categories. For example, a hunting knife would be categorized in food growth and collection, while a kitchen knife would fall into food preparation. The motivating outcome is determined by the ostensible reason for investment of human activity and/or energy in its creation/maintenance.
- To reduce ambiguity, we define priorities for some categories (Table S1).

3.7 Application to existing lists of entities

We compare the MEUTEC categories to other lists of human creations to demonstrate their applicability across cultures.

First we apply the categorization to lists compiled by ethnographers for two hunter-gatherer societies, as reported by Kelly (2013). The Ju/'huan live in the sub-tropical Kalahari Desert, while the Nuvugmiut live at Point Barrow on Alaska's northern coast. As shown in Table 2, the 20 entities of the Ju/'hoansi technology and 36 entities of the Nuvugmiut technology are all readily associated with one of the level 2 MEUTEC categories. Food provisioning is the most common level 1 category for both societies, according to the way the ethnographers described item types. Within the Nuvugmiut technology, both the Creation & Maintenance of Technosphere and the Transportation entities are more common than they are in the Ju/'hoansi technology, consistent with a greater reliance on the technosphere to persist in the cold environment and to undertake long-distance travel over snow, ice and water. Notably, four level 1 categories – Somatic Maintenance, Organization, Deliberate Neural Restructuring and Experience-oriented – are absent in both societies. It is possible that some artifacts that would have fallen in these categories (such as combs and dice games) were not recorded by the ethnographers. However, the absence of these categories is also consistent with their development as a hallmark of larger societies in which labour specialization is more prominent (Graeber and Wengrow, 2021).

We also applied the MEUTEC categorization to the Central Product Classification (United Nations Statistical Division, 2004), mentioned above, after removing services, raw materials, components and metabolites. This resulted in 389 classes of finished, traded goods, which were associated with MEUTEC categories as listed in Table S2. Unlike with the hunter-gatherers, every MEUTEC category had representative goods in the CPC, from a minimum of 2 (Electricity transmission) to a maximum of 45 (Apparel). Some classes were difficult to uniquely categorize, particularly those related to information and neural stimulus, but these represented a minority.

The fact that the MEUTEC can be used with these two very different types of technosphere entities is encouraging for its potential application to long timescales, both for historical changes and future projections. Nonetheless, the fact that prominent

Level 1	Level 2	Ju/'huan	Nuvugmiut
Creation & maintenance of technosphere	Creation of artifacts	adze	mauls, adzes, chisels, saws, awls, whetstones, scrapers
Energy provisioning	Energy extraction and converters	fire-making equipment	bow drills
Transportation	Storage and logistics	carrying bags, ostrich egg canteens	wooden pails, storage boxes
	Terrestrial vehicles	-	sledges
	Aquatic vessels	-	kayaks, umiaks
Inhabited environment	Ambient structures	hut	house
	Furnishings	-	soapstone lamps
	Apparel	clothing, bead ornaments	clothing, goggles, mittens
Food provisioning	Food growth & collection	bow, arrows, quiver, spear, throwing stick, springhare pole, carrying net	fishhooks, sinkers, fishing line, leisters, fishing nets, bows, arrows, quiver, atlatl, bola, snares, harpoons
	Food processing & preservation	nut-cracking stones	-
	Food preparation	knife, bowls, spoons, mortar and pestle	wooden bowls, knives, dippers, spoons, ladles
Somatic maintenance	-	-	-
Organization	-	-	-
Deliberate neural restructuring	-	-	-
Experience-oriented	-	-	-

Table 2. Categorization of hunter-gatherer material cultures. Ethnographic lists of entities were taken from Kelly (2013). Each entity was associated with a MEUTEC Level 2 category (unused Level 2 categories are not shown).

categories in modern industrialized society were apparently minor or absent among hunter gatherers is a good reminder that new categories may be required in the future. For example, general-purpose robots capable of doing most human tasks would not easily fit into any existing categories.

4 Basic attributes of the technosphere

Given the formal definition and categorization adopted above, we now characterize basic features of the technosphere. We first provide an overview of how the mass of the technosphere is partitioned among the MEUTEC categories and across the planet surface, circa year 2019. The overall mass of technosphere components is not necessarily the most relevant variable for Earth system interactions – for example, the extraction and processing of some elements, such as gold, can have large environmental impacts even for small masses, and a jet airplane can combust fossil fuel extremely rapidly for its size. In addition, the services provided by entities do not necessarily increase in a simple way with mass, for example transportation can become less efficient due to increased traffic congestion caused by a greater mass of vehicles and roadways. However, mass is a very straightforward starting point with which to understand the physical scale of the technosphere's main components.

4.1 Distribution of mass among MEUTEC categories

Despite their omnipresence in human lives, there has been relatively little prior work to assess the total masses of most technosphere components. Global studies of in-use material stocks have only been available for a little over a decade (Rauch, 2009; Müller et al., 2013; Glöser et al., 2013) and uncertainties frequently exceed a factor of 3, even for large aggregated categories (Lanau et al., 2019). In particular, the mass of materials in specialized buildings and heavy machinery is very poorly documented, and the masses of large public infrastructures such as dams and sewer systems are not typically available. Even for residential buildings, substantial disagreement exists in the literature. As a result, the estimates provided here should be seen as preliminary, and we hope that they will become better constrained through future work.

With those caveats in mind, we combine estimates from Wiedenhofer et al. (accepted), which are derived from the dynamic Material Inputs Stocks and Outputs version 2 (MISO2) model, with inventory-based estimates from Matitia (2022) and multiple other sources to quantify a subset of technosphere components. The methodology for combining estimates is described in Appendix A. Within each MEUTEC category, we differentiate buildings, total fixed stock and non-fixed (i.e. movable) stocks. Table A1 lists the estimated mass of each category, as a best guess, together with a representative uncertainty provided as a multiplicative range. For example, if the estimated value is 2 Gt and the uncertainty range is 3-fold, the actual value is thought very likely to lie between 0.67 and 6 Gt. The results are shown graphically in figure 3 for the total technosphere mass (including all of the built environment) and for movable objects on their own.

Despite the large uncertainties, it is quite clear that the largest two components of the technosphere, by mass, are the non-movable elements of the Inhabited Environment and the Transportation system. Transportation is dominated by surfaces (37% of total, comprised of roads, railroads, bridges and tunnels), and also includes associated logistical infrastructure. The inhabited environment is comprised mostly of residential and service buildings (36 % of total mass), though dams and water infrastructure are also significant.

The movable parts of the technosphere account for only about 1.6 % of the total mass, $\approx$ 17 Gt. This is comparable to the total wet biomass of all animals on Earth ($\approx$ 20 Gt), or significantly more than the dry biomass of all animals ($\approx$ 4 Gt) (Bar-On et al., 2018). Terrestrial vehicles have the largest estimated mass of any movable category (3 Gt), though the within uncertainty range the terrestrial vehicle mass overlaps with the machinery and devices included in the technosphere manufacturing and construction categories ($\approx$2 Gt each). The mass estimates for Furnishings and Information storage, processing and display are somewhat smaller still ($\approx$1 Gt each), but again the uncertainties are very large and they overlap with a number of slightly smaller categories. Aircraft account for a remarkably small mass of $\approx$2 Mt.

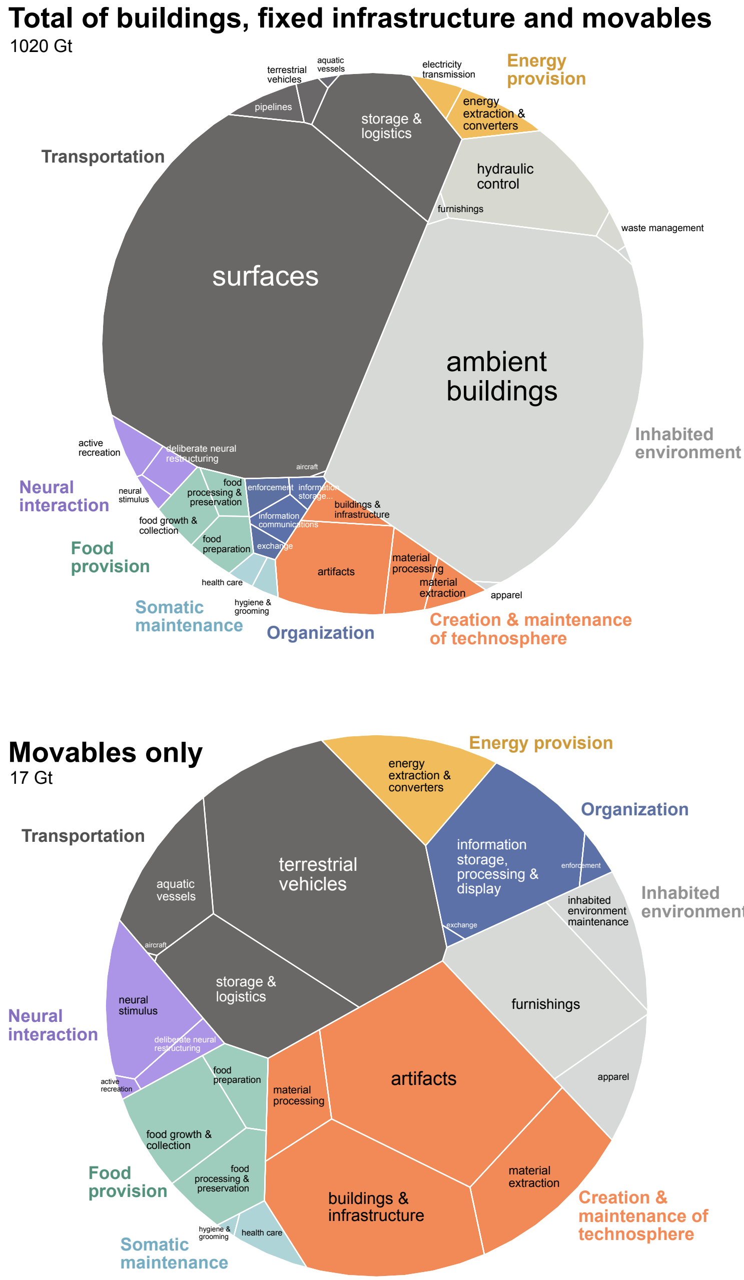

Figure 3. Approximate distribution of mass among the technosphere end-use categories. The area of each coloured region is proportional to the estimated mass. The top circle includes all fixed buildings and infrastructure as well as movable entities, while the lower circle shows only movable entities. The estimates include both inventory-based and material-inflow approaches over a range of years from 2015-2022, and the sums are therefore not representative of any single year. The estimated uncertainties for most categories exceed a factor of 3-fold due to lack of observational constraints. See Appendix A for estimation methodology.

4.2 Mapping the technosphere

We also provide an estimate of the overall spatial distribution of the two parts of the technosphere that comprise most of the mass: buildings, and the transportation system (Figure 4). Together these account for an estimated nine tenths of the technosphere. As detailed in Appendix B, the spatial distributions of these components are estimated from a combination of satellite observations and down-scaling of national data using surrogate local variables. The transportation system includes roads, railways, bridges and tunnels, passenger and commercial vehicles, rolling stock, commercial passenger aircraft, oil and gas pipelines, and the merchant fleet.

Although the total global masses of buildings and the transportation system are similar ($\approx$ 550 Gt and $\approx$ 350 Gt, respectively), they are distributed differently between world regions. The estimated transportation system mass is large relative to the building mass in Oceania and North America, and small compared to the building mass in Asia. As evident on the maps, the transportation system is particularly concentrated in central Europe, eastern North America, and eastern Asia.

It is important to avoid equating the geographic distribution of technosphere mass with direct Earth system impact. Technosphere-dense urban centres draw resources from the rural hinterland through processes that can cause dramatic changes (Brenner, 2014), even though the mass of technosphere in rural areas is relatively low. Nonetheless, the spatial distribution shown in Figure 4 provides a first-order picture of where the technosphere is most heavily concentrated, as a result of historical economic and social processes.

5 Dynamics of the technosphere

The technosphere is an extremely dynamic component of the Earth system, undergoing rapid internal transformations as well as driving large-scale changes in the rest of the Earth system such as climate change and habitat destruction. The technosphere is a newcomer to the Earth system – arguably, the earliest components of the technosphere were stone and wooden tools, more than 2 million years ago (Otter, 2022), though these early hominin creations did not have the complex functional interconnections and quantitative significance that justify the term ‘sphere’ today. At that time, the global human population was likely only a few hundred thousand individuals, and the subsequent human population growth - over four orders of magnitude - has occurred symbiotically with the growth of the technosphere.

The total technosphere has grown particularly rapidly over the period for which ew-MFA estimates are available, which extends back to 1900 (Krausmann et al., 2017b; Wiedenhofer et al., 2019) as shown in Figure 5. The increase of technosphere mass since 1900 is well approximated by an exponential with a slope of $3.6\%\, y^{-1}$, equivalent to a doubling time of about 20 years. The details of the technosphere growth rates must be interpreted with caution, given the inherent uncertainties in the reconstructed masses based on ew-MFA. The material flows of major components are modeled from sparse data, and in-use lifetime assumptions are relatively simple. With those caveats in mind, it is notable that the exponential fit is particularly good since 1970, the period during which the data is likely to be most reliable compared to earlier time periods.

This rapid exponential growth can be attributed, at least in part, to the autocatalytic properties of the technosphere. *Autocatalysis* occurs when the products of a process increase the rate of the same process that produced them, thereby accelerating

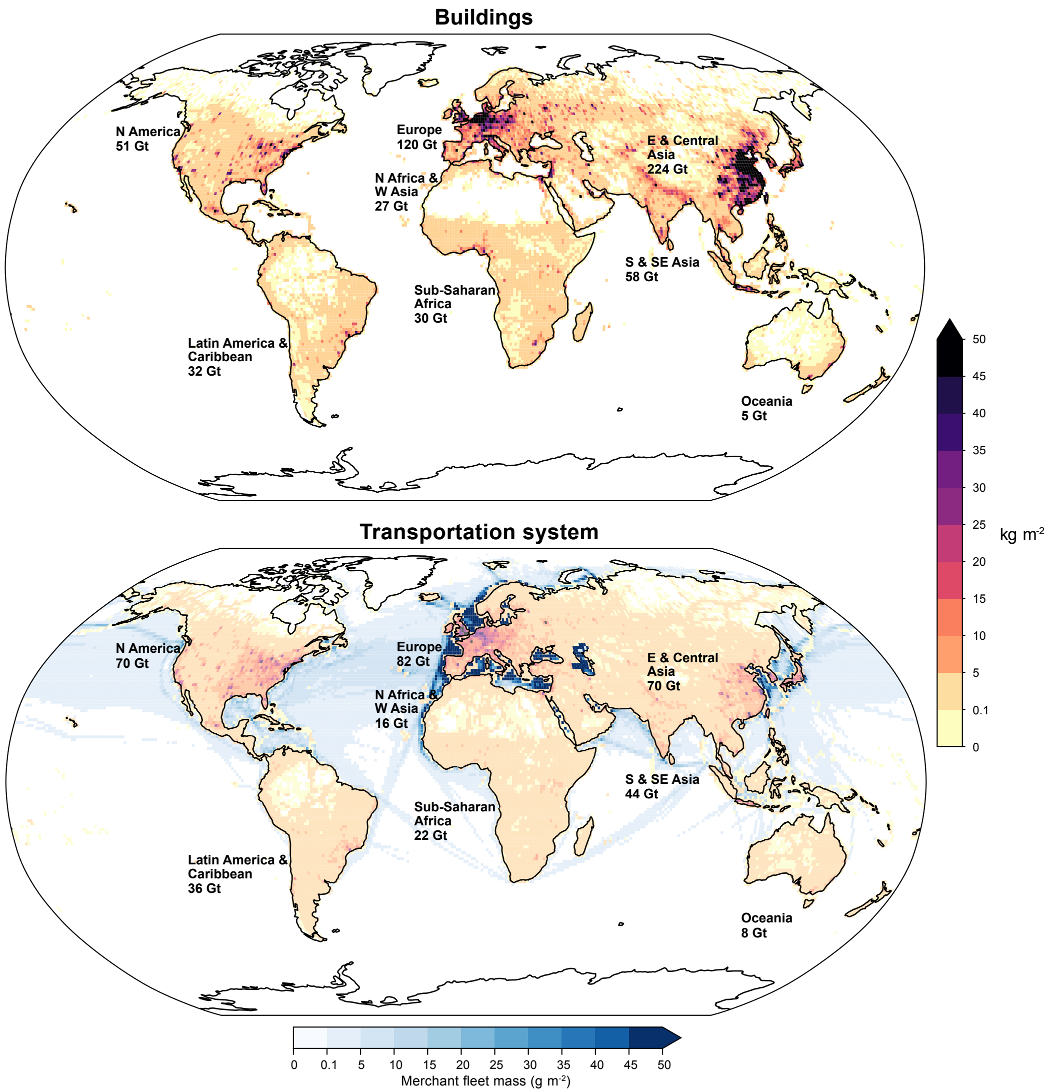

Figure 4. Spatial distribution of the two largest components of the technosphere by mass, at 1-degree resolution. Buildings (top) are taken from Haberl et al. (accepted). Transportation system data (bottom) were compiled and distributed as described in Appendix B. The masses of ships used for marine transport are shown on a separate colour scale (bottom), whereas the same colour scale is used for all terrestrial masses of both panels (right hand side). Note that the palest yellow colour shows very low values, less than 0.1 $kg\,m^{-2}$, and a lower threshold of 0.001 $kg\,m^{-2}$ was used, below which the area is white.

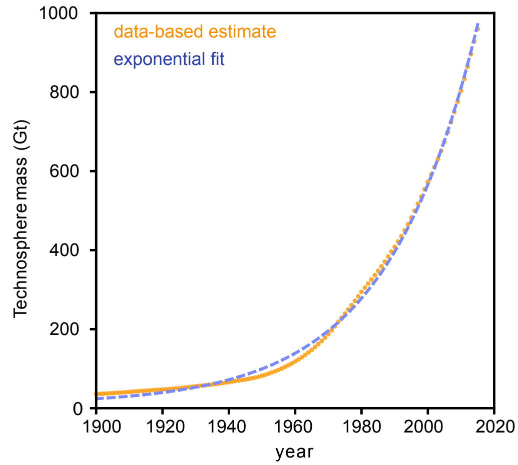

Figure 5. Growth of technosphere since 1900. Dots show estimated technosphere mass from Krausmann et al. 2018 with humans and domesticated animals removed. The blue line shows an exponential fit with growth coefficient $c = 0.036$, equivalent to a doubling time of roughly 20 years.

growth as the mass increases. The production of much of the technosphere, such as extractive and processing machinery and transportation infrastructure, clearly catalyze the activities of technosphere creation and maintenance, as discussed above. As a result, they can directly accelerate the overall growth.

The autocatalytic nature of the technosphere sets it apart from the analogous creations of non-human organisms. Other organisms do modify their abiotic environments, including deliberate niche construction by animals. For example, birds build nests, beavers build dams and termites construct mounds. But although these modifications benefit their constructors, they do not catalyze their own further growth in the same way: a termite mound does not directly contribute to the construction of further termite mounds other than by helping to ensure the survival of termites. As such, the masses of these other constructions are bound tightly to the masses of their creators. The technosphere, in contrast, has grown at a far higher rate than the human population, with the ratio of technosphere mass: human mass increasing by roughly a factor of 8 over the past century (from 18 t person^{-1} to 140 t person^{-1}).

The autocatalytic growth of the technosphere at a given point in time can be described by a simple equation,

$$\frac{dT}{dt} = cT \tag{2}$$

where the rate of change of the technosphere mass (T, in g) is a linear function of itself. The coefficient c (in s^{-1}) captures the degree to which a given increment of technosphere growth accelerates its continued growth. The value of c would be expected to vary with many factors, including technological efficiency, societal organization, the labour pool and worker skill, resource availability, etc. The autocatalytic property does not, on its own, predict how the technosphere will grow in future, since c can go up or down depending on a multiplicity of social processes. However, if c is constant over time, the autocatalytic relationship produces exponential growth of T.

The relatively good exponential fit of the technosphere growth since 1900 suggests that c has indeed been relatively stable for much of this time period. This does not imply that it is an inherent feature of the technosphere: autocatalysis does not imply autonomy of the technosphere, and c can unquestionably vary. Prior works have identified changes in technosphere mass fluxes over the 20th century that were coincident with prominent historical events, reflecting impacts of human social dynamics on the value of c (Krausmann et al., 2009; Wiedenhofer et al., 2013; Görg et al., 2020; Elhacham et al., 2020; Fischer-Kowalski et al., 2023). The value of c could potentially decrease or increase in future, dependent on changes in human activities coordinated by societal forces, as well as planetary feedbacks such as tipping points (Dietz et al., 2021; Wiedenhofer et al., accepted). If it were to drop to zero, the total mass would be stabilized, while if it were to become negative, there would be a decrease of technosphere mass.

In addition, although we do not have detailed information on the size of the technosphere prior to the 20th century, we can be confident that the exponential growth of 3% was not typical of long-term growth of the technosphere. For one thing, extrapolating this rate of growth backwards would imply that the technosphere had a mass of 1 t around year 1330 AD. Obviously this is incorrect, as the single great pyramid of Giza, constructed in 2600 BC, was - on its own - roughly 6 Mt. Even if the great pyramid were the only component of the technosphere in existence at that time, the average long-run rate of growth would have had to be on the order of 0.1% per year in order to arrive at the present-day mass. The present global net growth rate of the in-use technosphere (110 Mt d^{-1}) - which amounts to roughly 20 great pyramids per day - obviously results from an acceleration that is anomalous in human history. There are many societal innovations that could have contributed to the historical rise of the autocatalytic growth rate, but it seems likely that, among these, the greatly increased availability of technical energy due to the development of fossil fuels (Fischer-Kowalski and Haberl, 2007), now augmented with renewable electricity, was an essential element.

6 Conclusions

The technosphere definition proposed here is intended to provide a clear and relatively unambiguous definition, in the hopes of better integrating the physical underpinnings of human societies within Earth system science. Socio-ecological research provides a rich body of observations that can serve as a starting point for this integration (Haberl et al., 2019). Unlike most prior categorizations of the technosphere, which were based on material types, the MEUTEC introduced here is based on the end-uses that motivate the creation of technosphere components, in alignment with human activities. The MEUTEC remains an imperfect categorization that could be improved through future work, and would benefit from comparison with alternative categorizations that capture other important features of the technosphere. Nonetheless, by grounding the categories on physically-oriented activity end uses, we hope that the MEUTEC can help to bridge the core features of economies and societies with Earth system processes.

As shown by the global data compilation, the mass of the technosphere is dominated by buildings used to provide a comfortable ambient context for humans, and by infrastructure and vehicles used to make the relocation of humans and materials faster and more convenient. The compilation shows that many categories are poorly constrained by data, a problem that is particularly pronounced for industrial buildings and fixed infrastructure (other than roads). Material Flow Accounting analyses have also shown that the technosphere is composed almost entirely of geological materials: aggregate, brick, concrete, asphalt, plastic, glass and iron account for the vast majority (Krausmann et al., 2018). It is therefore predominantly a modification of lithospheric components. However, the technosphere has major impacts on the biosphere, accelerating the modification of the land surface and extraction of organic matter from the biosphere, and on the atmosphere, through the combustion of billions of tons of fossil fuels each year.

Our maps of the technosphere show the degree to which it is unevenly distributed over the Earth surface. The transportation system is particularly concentrated in Europe, eastern North America, and east Asia. Our appraisal of technosphere dynamics shows that the technosphere must have grown slowly over the Holocene, with average rates on the order of 0.1% y^{-1}. This contrasts strongly with the past century, when growth rates exceeded 3% y^{-1}. Although many factors could have contributed to this rapid growth, it appears likely that the strong autocatalytic character of the technosphere was implicated, linking it to other autocatalytic processes about which much has been learned. Importantly, autocatalysis does not imply autonomy – human engagement is necessary for the creation and maintenance of the technosphere, and it follows that its future trajectory can be modified by societal processes. Thus, autocatalysis can allow for many future scenarios, including the possibility of decreasing material throughput while providing high well-being to humans.

There remains much to be done to improve the understanding of the technosphere. For example, we have highlighted large uncertainties in the quantification of the fixed technosphere, primarily regarding industrial buildings and public infrastructure, which could potentially be greatly improved using remote sensing and machine learning. Further work could also elaborate details of the material composition and energy use of different technosphere components and link chemical elements within the technosphere with their Earth system sources and sinks, to build a unified understanding of how they contribute to global biogeochemical (or, perhaps, 'technogeochemical') cycles. There are many ways that the data compilation here could be used as a starting point for modeling aspects of the technosphere, potentially exploring links to time allocation, power dynamics or well-being implications. Coupled human-Earth system models incorporating a dynamical, fully integrated technosphere can help improve the understanding of physical constraints on system dynamics, supplementing Integrated Assessment Models to provide a complementary perspective on pathways towards long-term sustainability, as well as identifying potential tipping points. The trillion-ton technosphere is a major component of the Earth system, and its evolution over the next century is likely to determine the future of climate – and life – for millennia to come.

Data availability. Global mass estimates derived from prior works are summarized in Table S4. The gridded data used for Figure 4 will be provided as part of the Surface Earth System Analysis and Modeling Environment (SESAME) dataset Faisal et al. (submitted) and as an electronic supplement on Zenodo.

Appendix A: Estimation of technosphere composition by category

Constructing an estimate of the global technosphere composition by end-use remains highly challenging. Some categories are reasonably well-constrained by observations, but others are, at present, strongly limited by data availability. Our goal here is to provide an overview of the existing estimates as a starting point for future work, and to use them to provide current best estimates for all categories, which are necessarily highly uncertain. The available estimates are not all for the same year, but are generally for the period 2015-2021 unless otherwise noted. The sum of all individually-estimated categories, arrived at through a combination of bottom-up and top-down approaches, is 1.03 Tt, equivalent to the total for year 2017 extrapolating from the Krausmann et al. (2018) material flow analysis.

Because buildings comprise a large part of the total mass and contribute to many MEUTEC categories, we discuss them first before proceeding to the other categories.

A1 Buildings

We draw on three sources for global building mass.

Haberl et al. (accepted) provide an estimate of building mass drawing on satellite observations of building volume (Esch et al., 2022) to which they apply geographically-variable material intensities (i.e. masses of material per building volume). The total estimated stocks for year 2019 are 547 Gt (+/- 25%), of which 474 Gt are associated with residential use, 33 Gt with non-residential use, and 41 Gt associated with either residential or non-residential use. It should be noted that the identification of residential vs. non-residential buildings is methodologically challenging and should be seen as approximate.

Deetman et al. (2020) estimated building stocks based on a regression model of reported floor areas, interpolated across regions, and simulated over time with a dynamic stock model. Their model differentiates residential from service buildings, but explicitly left out industrial and agricultural buildings, given the lack of statistical data on floor space.

Wiedenhofer et al. (accepted) use the MISO2 model to provide economy-wide, country-level estimates of material stocks across 13 end-uses. Two of these are buildings, divided between residential and non-residential, and suggest a total of 524 Gt in year 2021. Unfortunately, as for other estimates, the industrial, agricultural and other specialized non-residential building masses are unconstrained.

We take Deetman's estimate for dominantly ambient environment service buildings (offices, retail and shops, hotels and restaurants) of 15 Gt, and assume the remaining 33 Gt of service buildings are more specialized to specific activities (e.g. schools, hospitals, public transportation, assembly buildings). Adding this ambient service building total to the residential building arrive at a total ambient building stock of 364 Gt, to which we attribute a factor of 1.5-fold uncertainty.

We aim for overall consistency between estimates by assuming the difference between the ambient building stock and the MISO2 total is accounted for by specialized non-ambient buildings, totalling 160 Gt, of which 33 Gt is non-industrial and non-agricultural. This suggests 127 Gt of industrial and agricultural buildings, roughly 1/4 of the total building stock. This is a highly uncertain value, and could be wrong by at least a factor of 2, which we hope can be addressed in future work. We then make a weakly-informed estimate of how this industrial building mass is distributed across the MEUTEC categories, to which we assign a 3-fold uncertainty range.

A2 Other categories

Because MISO2 provides a consistent, mass-balanced estimate that includes the entire technosphere, we use it as an overarching framework by relating the 11 non-building categories of MISO2 to the MEUTEC categories. The largest uncertainty arises from the category 'Civil engineering except roads', due to its large mass (242 Gt) and diverse contents. For each of the 11 MISO2 categories, the total was partitioned among the MEUTEC categories as described in the notes. Uncertainties tend to be large, with estimated ranges of 3 to 10. These MISO2 estimates were supplemented additionally as follows.

For transportation surfaces, we supplemented the MISO2 estimate with the global estimate of 314 Gt in year 2021 from Wiedenhofer et al. (2024) of all roads and railway infrastructure, including tunnels and bridges, constructed with archetypal material intensities applied to Open Street Maps data. We also used the similar estimate of 377 Gt provided by Matitia (2022) which also included CIA World Factbook road length estimates and applied slightly different material intensities. Averaging the three estimates suggests a mass of 375 Gt.

The energy provision category includes fossil fuel infrastructure as well as electricity production and distribution infrastructure. The masses of electrical transmission grids, distribution grids and transformers were taken as the median estimates of Kalt et al. (2021) for year 2017, totalling 1.7 Gt for electricity transmission with an uncertainty of roughly 50%. The energy extraction and conversion includes the power plant estimate of Kalt et al. of 8.4 Gt, including concrete in hydroelectric dams, and 0.7 Gt of fossil fuel extraction and refining infrastructure, of which 0.1 Gt is offshore oil platforms (Matitia, 2022). These estimates have significant uncertainty (range factor 4). The mass of pipelines was taken from Le Boulzec et al. (2022) as 3 Gt, which compares well to the independent estimate of Matitia (2022) of 1.8 Gt (uncertainty range factor 3).

We used bottom-up estimates from Matitia (2022) for agricultural tractors, passenger and commercial vehicles, rolling stock, the global merchant fleet, aircraft, military vehicles and weapons (see below for further details). The agricultural tractors and vehicles were interpolated to missing countries using a random forest model with GDP, total population, crop production, harvested area, percentage of urban population, year, and income class as predictors for machinery mass. We also used Matitia (2022) estimates for textiles, and the plastic components of furniture, electronics and health equipment as lower bounds on the corresponding categories.

Appendix B: Estimating spatial distributions

The spatial distribution of some technosphere components can be observed directly, such as roads (Wiedenhofer et al., 2024). However, most technosphere mass estimates are only available on a jurisdictional basis, with a single value per country. To develop a harmonized, spatially-gridded raster dataset from jurisdiction-level data, our strategy is to employ the widely used dasymetric mapping downscaling method (Mennis, 2003; Faisal et al., submitted). The dasymetric method allocates data from jurisdictions to 1-degree grid-cells by using appropriate variables (referred to as surrogate variables). The jurisdictional data

Level 1	Level 2	Movable	Total	Uncertainty
Creation & maintenance of technosphere	Material extraction	0.4	6.8	5
	Material processing	0.8	14	5
	Creation of artifacts	2	40	3
	Construction of buildings and infrastructure	2	8	3
Energy provisioning	Energy extraction and converters	0.7	9	5
	Electricity transmission	-	3	5
Transportation	Surfaces	-	380	2
	Storage and logistics	1	57	3
	Pipelines	-	3	3
	Terrestrial vehicles	3	4	2
	Aircraft	0.002	0.002	3
	Aquatic vessels	0.6	0.6	2
Inhabited environment	Ambient structures	-	360	2
	Furnishings	1	1	3
	Apparel	0.4	0.4	5
	Inhabited environment maintenance	0.4	0.4	3
	Hydraulic control	-	60	5
	Waste management	-	3	5
Food provisioning	Food growth & collection	0.6	7	5
	Food processing & preservation	0.4	7	5
	Food preparation	0.3	10	3
Somatic maintenance	Hygiene & grooming	0.02	3	10
	Health care	0.2	3	5
Organization	Information storage, processing & display	1	4	5
	Information communications infrastructure	-	13	5
	Exchange	0.02	3	10
	Enforcement	0.06	3	10
Neural interaction	Deliberate neural restructuring	0.2	7	3
	Neural stimulus	0.6	2	3
	Active recreation	0.03	2	3

Table A1. Technosphere mass by category. All masses are given in Gt (10^{15} g), for a movable 'non-fixed' portion, as well as for the total (including buildings and immovable infrastructure). The uncertainty range is multiplicative factor. See Appendix for methodological details.

is distributed throughout the jurisdictional domain in proportion to the surrogate variable distribution. Thus, estimating the distribution for each category of technosphere mass requires an estimate of the value per country, and a surrogate variable to use for dasymetric redistribution.

B1 Aircraft

Commercial aircraft data were sourced from the Central Intelligence Agency (CIA) factbook. The average material composition of an aircraft was determined by taking the geometric mean of material intensities for five types of commercial aircraft as reported in Jemiolo (2015). The country level airplane mass data was proportionally distributed on airport counts per grid cell. The airport locations were obtained from http://ourairports.com. The ratio of plane capacities among these airport types is difficult to quantify, as it can vary greatly depending on a variety of factors such as the size and layout of the airport, the type and size of the aircraft it serves, and its operating procedures. We make a rough estimate based on general characteristics of these airport types, such that Seaplane Base : Small Airport : Medium Airport : Large Airport = 1 : 5 : 30 : 100.

B2 Building material stock

The total building stock is taken from Haberl et al. (accepted) and regridded to 1-degree resolution. Note that the mapped data are shown as previously published in Figure 4, which gives a slightly higher total (550 Gt) than the multi-source estimate shown in Supplementary Table 4 (520 Gt).

B3 Merchant fleet

Country level merchant fleet data were obtained from United Nation Conference on Trade and Development (UNCTAD). Matitia (2022) utilized UNCTAD data to analyze per-country gross tonnage for five ship categories from 2011 to 2020, focusing on vessels with a gross tonnage of 11,000 tons and above. Steel mass per gross tonnage for these vessels was sourced from Kong et al. (2022). Because operational merchant ships are rarely in their home port, and are usually in transit, we dasymetrically mapped the global fleet mass using global shipping traffic density data.

B4 Oil and gas pipelines

The spatial distributions of pipelines were collected from Sabbatino (2018). The oil and gas pipelines were converted from line to grids based on sum of pipeline length per pixel.

B5 Roads and railways

The distribution of road and railway masses is taken from Wiedenhofer et al. 2024 and regridded to 1-degree resolution.

B6 Rolling stock

The data for the number of registered locomotives, railcars, wagons, and train coaches were collected from a report of Union International des Chemins de Fer (UIC) and their data portal. The mass and material content of various rolling stock types were averaged from previously-published estiamtes (Delogu et al., 2017; Harvey, 2022; Kaewunruen and Rungskunroch, 2019). The country level rolling stock data was distributed proportionally to the railway densities, where the density data was collected from Global railways (WFP SDI-T - Logistics Database) at https://data.humdata.org/dataset/global-railways.

B7 Terrestrial vehicles

The International Organization of Motor Vehicle Manufacturers (OICA) provided the information of registered passenger cars and commercial vehicles worldwide from 2005 to 2015. Passenger cars were categorized into large and small groups, with approximately 30.21% classified as "large" based on global new SUV registrations. Commercial vehicles encompass light commercial vehicles (LCVs), heavy trucks, buses, and coaches. It was assumed that the ratio of trailers to truck tractors is 1.5:1 globally, with estimates of 1.4:1 in Europe and 3:1 in North America (Matitia, 2022). We employed three distinct random forest models for passenger vehicles, commercial vehicles, and trailers. These models aimed to estimate the number of vehicles per capita for countries and years where such data were missing. Predictor variables included GDP per capita, total road length, urban population percentage, and the year of analysis. All three models demonstrated a high level of accuracy, with test r^2 values exceeding 0.94, indicating robust predictive performance for vehicles across the specified categories. The country-level vehicle mass was distributed assuming that 5% of vehicles remained on the road, and thus distributed based on road density (Meijer et al., 2018) while the remaining 95% of vehicle data was distributed based on population density (Bondarenko, 2018).

Author contributions. EDG: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review and editing, Visualization. AF: Investigation, Data curation, Writing - review and editing. TM: Methodology, Investigation, Data curation. WF: Methodology, Writing - review and editing. IH: Visualization, Writing - review and editing. HH: Writing - review and editing. FK: Data curation, Writing - review and editing. DW: Methodology, Data curation, Writing - review and editing.

Competing interests. The authors declare no competing interests.

Acknowledgements. We thank Ben Goldstein and Maxwell Kaye for insightful discussions, and Ron Milo for thoughtful feedback on the draft. This project was supported by the Canada Research Chairs Program fund number CRC-2020-00108 and the Natural Science and Engineering Research Council (NSERC) Discovery Grant RGPIN-2020-04889. HH and DW gratefuly acknowledge funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme MAT_STOCKS, grant agreement No 741950.

References

Alexander, P., Brown, C., Arneth, A., Finnigan, J., Moran, D., and Rounsevell, M. D.: Losses, Inefficiencies and Waste in the Global Food System, Agricultural systems, 153, 190–200, 2017.

Bar-On, Y. M., Phillips, R., and Milo, R.: The Biomass Distribution on Earth, Proceedings of the National Academy of Sciences, 115, 6506–6511, 2018.

Benton, M. J.: Stems, Nodes, Crown Clades, and Rank-Free Lists: Is Linnaeus Dead?, Biological Reviews, 75, 633–648, 2000.

Bondarenko, M.: Global 1km Population, 2018.

Boyd, R.: A Different Kind of Animal: How Culture Transformed Our Species, Princeton University Press, 2018.

Brenner, N.: Implosions/Explosions: Towards a Study of Planetary Urbanism, Jovis, Berlin, 2014.

Chen, W.-Q. and Graedel, TE.: In-Use Product Stocks Link Manufactured Capital to Natural Capital, Proceedings of the national academy of sciences, 112, 6265–6270, 2015.

Cobb, C. W. and Douglas, P. H.: A Theory of Production, The American Economic Review, 18, 139–165, 1928.

Cooper, A. H., Brown, T. J., Price, S. J., Ford, J. R., and Waters, C. N.: Humans Are the Most Significant Global Geomorphological Driving Force of the 21st Century, The Anthropocene Review, 5, 222–229, 2018.

Creutzig, F., Acemoglu, D., Bai, X., Edwards, P. N., Hintz, M. J., Kaack, L. H., Kilkis, S., Kunkel, S., Luers, A., and Milojevic-Dupont, N.: Digitalization and the Anthropocene, Annual review of environment and resources, 47, 479–509, 2022.

Daily, G. C. and Ehrlich, P. R.: Population, Sustainability, and Earth's Carrying Capacity, BioScience, 42, 761–771, 1992.

Deetman, S., Marinova, S., van der Voet, E., van Vuuren, D. P., Edelenbosch, O., and Heijungs, R.: Modelling Global Material Stocks and Flows for Residential and Service Sector Buildings towards 2050, Journal of Cleaner Production, 245, 118 658, 2020.

Delogu, M., Del Pero, F., Berzi, L., Pierini, M., and Bonaffini, D.: End-of-Life in the Railway Sector: Analysis of Recyclability and Recoverability for Different Vehicle Case Studies, Waste management, 60, 439–450, 2017.

Dietz, S., Rising, J., Stoerk, T., and Wagner, G.: Economic Impacts of Tipping Points in the Climate System, Proceedings of the National Academy of Sciences, 118, e2103081 118, 2021.

Donges, J. F., Lucht, W., Müller-Hansen, F., and Steffen, W.: The Technosphere in Earth System Analysis: A Coevolutionary Perspective, The Anthropocene Review, 4, 23–33, 2017.

Elhacham, E., Ben-Uri, L., Grozovski, J., Bar-On, Y. M., and Milo, R.: Global Human-Made Mass Exceeds All Living Biomass, Nature, 588, 442–444, 2020.

Esch, T., Brzoska, E., Dech, S., Leutner, B., Palacios-Lopez, D., Metz-Marconcini, A., Marconcini, M., Roth, A., and Zeidler, J.: World Settlement Footprint 3D-A First Three-Dimensional Survey of the Global Building Stock, Remote sensing of environment, 270, 112 877, 2022.

Faisal, A.-A., Kaye, M., Ahmed, M., and Galbraith, E.: The SESAME Human-Earth Atlas: Integration of Human and Earth System Data, Scientific Data, submitted.

Fajzel, W., Galbraith, E. D., Barrington-Leigh, C., Charmes, J., Frie, E., Hatton, I., Le Mézo, P., Milo, R., Minor, K., and Wan, X.: The Global Human Day, Proceedings of the National Academy of Sciences, 120, e2219564 120, 2023.

Fischer-Kowalski, M. and Haberl, H.: Socioecological Transitions and Global Change: Trajectories of Social Metabolism and Land Use, Edward Elgar Publishing, 2007.

Fischer-Kowalski, M. and Weisz, H.: Society as Hybrid between Material and Symbolic Realms: Toward a Theoretical Framework of Society-Nature Interaction, Advances in human ecology, 8, 215–252, 1999.

Fischer-Kowalski, M., Krausmann, F., Pichler, P. P., Schaeffer, R. K., and Stadler, S.: Great Transformations: Social Revolutions Erupted during Energy Transitions around the World, 1500–2013, Energy Research & Social Science, 105, 103 280, https://doi.org/10.1016/j.erss.2023.103280, 2023.

Fu, C., Zhang, Y., Deng, T., and Daigo, I.: The Evolution of Material Stock Research: From Exploring to Rising to Hot Studies, Journal of Industrial Ecology, 26, 462–476, 2022.

Galbraith, E., Fajzel, W., Xu, S., Xia, V., Frie, E., Barrington-Leigh, C., and Reyes-García, V.: Interdisciplinary Applications of Human Time Use with Generalized Lexicons, PloS one, 17, e0270 583, 2022.

Galbraith, E. D.: Earth System Economics: A Biophysical Approach to the Human Component of the Earth System, Earth System Dynamics, 12, 671–687, 2021.

Gershuny, J. and Sullivan, O.: What We Really Do All Day: Insights from the Centre for Time Use Research, Penguin UK, London, 2019.

Glöser, S., Soulier, M., and Tercero Espinoza, L. A.: Dynamic Analysis of Global Copper Flows. Global Stocks, Postconsumer Material Flows, Recycling Indicators, and Uncertainty Evaluation, Environmental science & technology, 47, 6564–6572, 2013.

Görg, C., Plank, C., Wiedenhofer, D., Mayer, A., Pichler, M., Schaffartzik, A., and Krausmann, F.: Scrutinizing the Great Acceleration: The Anthropocene and Its Analytic Challenges for Social-Ecological Transformations, The Anthropocene Review, 7, 42–61, https://doi.org/10.1177/2053019619895034, 2020.

Graeber, D. and Wengrow, D.: The Dawn of Everything: A New History of Humanity, Penguin UK, 2021.

Graedel, T. E., Harper, E. M., Nassar, N. T., and Reck, B. K.: On the Materials Basis of Modern Society, Proceedings of the National Academy of Sciences, 112, 6295–6300, 2015.

Haberl, H., Erb, K. H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W., and Fischer-Kowalski, M.: Quantifying and Mapping the Human Appropriation of Net Primary Production in Earth's Terrestrial Ecosystems, Proceedings of the National Academy of Sciences, 104, 12 942–12 947, 2007.

Haberl, H., Wiedenhofer, D., Pauliuk, S., Krausmann, F., Müller, D. B., and Fischer-Kowalski, M.: Contributions of Sociometabolic Research to Sustainability Science, Nature Sustainability, 2, 173–184, 2019.

Haberl, H., Baumgart, A., Zeidler, J., Schug, F., Palacios-Lopez, D., Fishman, T., Peled, Y., Cai, B., Virág, D., Hostert, P., Wiedenhofer, D., and Esch, T.: Weighing the Global Built Environment: High Resolution Mapping and Quantification of Material Stocks in Buildings, Journal of Industrial Ecology, accepted.

Haff, P.: Technology as a Geological Phenomenon: Implications for Human Well-Being, Geological Society, London, Special Publications, 395, 301–309, 2014.

Haff, P. K.: Technosphere, in: Handbook of the Anthropocene: Humans between Heritage and Future, pp. 537–541, Springer, 2023.

Harvey, L. D.: 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, 106 281, 2022.

Herrmann-Pillath, C.: The Case for a New Discipline: Technosphere Science, Ecological Economics, 149, 212–225, 2018.

Huggett, R.: Earth's Spheres: Conceptual and Definitional Debates, Progress in Physical Geography: Earth and Environment, p. 03091333241275465, 2024.

Huxley, J. and Nicholson, M.: Man's Deteriorating Environment, Times, p. 8, 1969.

Inostroza, L.: Measuring Urban Ecosystem Functions through 'Technomass'—A Novel Indicator to Assess Urban Metabolism, Ecological Indicators, 42, 10–19, 2014.

Jemiolo, W.: Life Cycle Assessment of Current Aned Future Passenger Air Transport in Switzerland, Ph.D. thesis, Universitetet i Nordland, 2015.

Johansson, N., Krook, J., Eklund, M., and Berglund, B.: An Integrated Review of Concepts and Initiatives for Mining the Technosphere: Towards a New Taxonomy, Journal of Cleaner Production, 55, 35–44, 2013.

Kaewunruen, S. and Rungskunroch, P.: A Through-Life Evaluation of End-of-Life Rolling Stocks Considering Asset Recycling, Energy Recovering, and Financial Benefit, Journal of cleaner production, 212, 1008–1024, 2019.

Kalt, G., Thunshirn, P., Wiedenhofer, D., Krausmann, F., Haas, W., and Haberl, H.: Material Stocks in Global Electricity Infrastructures–an Empirical Analysis of the Power Sector's Stock-Flow-Service Nexus, Resources, Conservation and Recycling, 173, 105 723, 2021.

Kelly, R. L.: The Lifeways of Hunter-Gatherers: The Foraging Spectrum, Cambridge University Press, 2013.

Koestler, A.: Beyond Atomism and Holism—the Concept of the Holon, Perspectives in Biology and Medicine, 13, 131–154, 1970.

Kong, X., Feng, K., Wang, P., Wan, Z., Lin, L., Zhang, N., and Li, J.: Steel Stocks and Flows of Global Merchant Fleets as Material Base of International Trade from 1980 to 2050, Global Environmental Change, 73, 102 493, 2022.

Krausmann, F., Gingrich, S., Eisenmenger, N., Erb, K.-H., Haberl, H., and Fischer-Kowalski, M.: Growth in Global Materials Use, GDP and Population during the 20th Century, Ecological economics, 68, 2696–2705, 2009.

Krausmann, F., Schandl, H., Eisenmenger, N., Giljum, S., and Jackson, T.: Material Flow Accounting: Measuring Global Material Use for Sustainable Development, Annual Review of Environment and Resources, 42, 647–675, 2017a.

Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., Fishman, T., Miatto, A., Schandl, H., and Haberl, H.: Global Socioeconomic Material Stocks Rise 23-Fold over the 20th Century and Require Half of Annual Resource Use, Proceedings of the National Academy of Sciences, 114, 1880–1885, 2017b.

Krausmann, F., Lauk, C., Haas, W., and Wiedenhofer, D.: From Resource Extraction to Outflows of Wastes and Emissions: The Socioeconomic Metabolism of the Global Economy, 1900–2015, Global Environmental Change, 52, 131–140, 2018.

Lanau, M., Liu, G., Kral, U., Wiedenhofer, D., Keijzer, E., Yu, C., and Ehlert, C.: Taking Stock of Built Environment Stock Studies: Progress and Prospects, Environmental Science & Technology, 53, 8499–8515, https://doi.org/10.1021/acs.est.8b06652, 2019.

Le Boulzec, H., Delannoy, L., Andrieu, B., Verzier, F., Vidal, O., and Mathy, S.: Dynamic Modeling of Global Fossil Fuel Infrastructure and Materials Needs: Overcoming a Lack of Available Data, Applied Energy, 326, 119 871, https://doi.org/10.1016/j.apenergy.2022.119871, 2022.

Lenton, T. M., Pichler, P.-P., and Weisz, H.: Revolutions in Energy Input and Material Cycling in Earth History and Human History, Earth System Dynamics, 7, 353–370, 2016.

Lenzen, M., Geschke, A., West, J., Fry, J., Malik, A., Giljum, S., Milà i Canals, L., Piñero, P., Lutter, S., and Wiedmann, T.: Implementing the Material Footprint to Measure Progress towards Sustainable Development Goals 8 and 12, Nature Sustainability, 5, 157–166, 2022.

Linnaeus, C.: Systema Naturae, vol. 1, Stockholm Laurentii Salvii, 1758.

Matitia, T.: Global End-Use Inventory of the Anthropogenic Mass, MSc, McGill University, Montreal, QC, 2022.

Meijer, J. R., Huijbregts, M. A., Schotten, K. C., and Schipper, A. M.: Global Patterns of Current and Future Road Infrastructure, Environmental Research Letters, 13, 064 006, 2018.

Mennis, J.: Generating Surface Models of Population Using Dasymetric Mapping∗, The Professional Geographer, 55, 31–42, https://doi.org/10.1111/0033-0124.10042, 2003.

Milsum, J. H.: The Technosphere, the Biosphere, the Sociosphere Their Systems Modeling and Optimization, IEEE Spectrum, 5, 76–82, 1968.

Müller, D. B., Liu, G., Løvik, A. N., Modaresi, R., Pauliuk, S., Steinhoff, F. S., and Brattebø, H.: Carbon Emissions of Infrastructure Development, Environmental science & technology, 47, 11 739–11 746, 2013.

Otter, C.: Socializing the Technosphere, Technology and Culture, 63, 953–978, 2022.

Pauliuk, S. and Hertwich, E. G.: Socioeconomic Metabolism as Paradigm for Studying the Biophysical Basis of Human Societies, Ecological Economics, 119, 83–93, 2015.

Pauliuk, S. and Müller, D. B.: The Role of In-Use Stocks in the Social Metabolism and in Climate Change Mitigation, Global Environmental Change, 24, 132–142, 2014.

Rauch, J. N.: Global Mapping of Al, Cu, Fe, and Zn in-Use Stocks and in-Ground Resources, Proceedings of the National Academy of Sciences, 106, 18 920–18 925, 2009.

Raworth, K.: Doughnut Economics: Seven Ways to Think like a 21st Century Economist, Chelsea Green Publishing, 2018.

Sabbatino, M.: Global Oil & Gas Features Database, Tech. rep., National Energy Technology Laboratory (NETL), Pittsburgh, PA, Morgantown, WV . . . , 2018.

Schaffartzik, A., Pichler, M., Pineault, E., Wiedenhofer, D., Gross, R., and Haberl, H.: The Transformation of Provisioning Systems from an Integrated Perspective of Social Metabolism and Political Economy: A Conceptual Framework, Sustainability Science, 16, 1405–1421, 2021.

Smil, V.: General Energetics: Energy in the Biosphere and Civilization, vol. 369, Wiley, New York, NY, 1991.

Smil, V.: Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production, MIT press, 2004.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., De Vries, W., and De Wit, C. A.: Planetary Boundaries: Guiding Human Development on a Changing Planet, science, 347, 1259 855, 2015.

Stiglitz, J. E., Sen, A., and Fitoussi, J.-P.: Report by the Commission on the Measurement of Economic Performance and Social Progress, Commission on the measurement of economic performance and social progress, 2009.

Streeck, J., Pauliuk, S., Wieland, H., and Wiedenhofer, D.: A Review of Methods to Trace Material Flows into Final Products in Dynamic Material Flow Analysis: From Industry Shipments in Physical Units to Monetary Input–Output Tables, Part 1, Journal of Industrial Ecology, 27, 436–456, 2023.

UNEP: United Nations Environment Programme, International Resource Panel, Global Material Flows Database.

UNEP: The Use of Natural Resources in the Economy: A Global Manual on Economy Wide Material Flow Accounting, United Nations Environment Programme, 2023.

United Nations Statistical Division: Central Product Classification (CPC): Version 1.1, 77, United Nations Publications, 2004.

Weisz, H., Suh, S., and Graedel, T. E.: Industrial Ecology: The Role of Manufactured Capital in Sustainability, Proceedings of the National Academy of Sciences, 112, 6260–6264, 2015.

Wiedenhofer, D., Rovenskaya, E., Haas, W., Krausmann, F., Pallua, I., and Fischer-Kowalski, M.: Is There a 1970s Syndrome? Analyzing Structural Breaks in the Metabolism of Industrial Economies, European Geosciences Union General Assembly 2013, EGUDivision Energy, Resources & the Environment, ERE, 40, 182–191, https://doi.org/10.1016/j.egypro.2013.08.022, 2013.

Wiedenhofer, D., Fishman, T., Lauk, C., Haas, W., and Krausmann, F.: Integrating Material Stock Dynamics into Economy-Wide Material Flow Accounting: Concepts, Modelling, and Global Application for 1900–2050, Ecological economics, 156, 121–133, 2019.

Wiedenhofer, D., Baumgart, A., Matej, S., Virág, D., Kalt, G., Lanau, M., Tingley, D. D., Liu, Z., Guo, J., and Tanikawa, H.: Mapping and Modelling Global Mobility Infrastructure Stocks, Material Flows and Their Embodied Greenhouse Gas Emissions, Journal of Cleaner Production, 434, 139 742, 2024.

Wiedenhofer, D., Streeck, J., Wieland, H., Grammer, B., Baumgart, A., Plank, B., Helbig, C., Pauliuk, S., Haberl, H., and Krausmann, F.: From Extraction to End-Uses and Waste Management: Modelling Economy-Wide Material Cycles and Stock Dynamics around the World, Journal of Industrial Ecology, https://doi.org/10.1111/jiec.13575, accepted.

Wiedmann, T. O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., and Kanemoto, K.: The Material Footprint of Nations, Proceedings of the national academy of sciences, 112, 6271–6276, 2015.

Zalasiewicz, J., Williams, M., Waters, C. N., Barnosky, A. D., and Haff, P.: The Technofossil Record of Humans, The Anthropocene Review, 1, 34–43, 2014.

Zalasiewicz, J., Williams, M., Waters, C. N., Barnosky, A. D., Palmesino, J., Rönnskog, A.-S., Edgeworth, M., Neal, C., Cearreta, A., and Ellis, E. C.: Scale and Diversity of the Physical Technosphere: A Geological Perspective, The Anthropocene Review, 4, 9–22, 2017.