~~Resolving~~ Delineating the Technosphere: Definition, categorization and characteristics

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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. ~~It~~ The technosphere enables the rapid extraction ~~and processing of materials from other spheres, combusts fossil fuels~~of natural resources and the combustion of fossil fuels, impacting biodiversity and causing climate change ~~, and transports materialsand people across the planet surface. It provides a vast range of services to humans, such as supporting the production~~ while producing copious waste materials. At the same time, the technosphere supports the provision of food, shelter, transportation and long-distance communication, and ~~entertainment. However~~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 ~~, and an End-Use Technosphere categorization , EUTEC, that is theoretically aligned with human activitiesand wellbeing. The~~ 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~~enable~~ , we delineate basic attributes of the technosphere~~to be delineated~~, including its mass distribution among components and ~~in space~~across the Earth surface, as well as its first-order temporal dynamics. In particular, of the roughly 1 ~~Tt of~~ trillion ton technosphere mass, we estimate that one ~~third~~ half is comprised of ~~residential~~ buildings and one third ~~by the transportation system~~transportation infrastructure, both of which we globally map at one-degree resolution. ~~Moreover, we~~ 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 ~~technosphere mass~~ the technosphere since 1900 ~~follow~~ are consistent with an autocatalytic process, resulting in exponential growth with long-run ~~growth rates~~ increase of >3% y^{-1}, ~~consistent with autocatalytic behaviour, allowing it to become an ever-more dominant component of the Earth system. The~~ equivalent to a 20-year doubling time. Building a stronger quantitative understanding of the technosphere ~~remains rudimentary, and is in great need of further work~~ can help to better integrate it ~~with~~ 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 ~~often~~ been referred to as the ‘technosphere’ ~~. Humans construct and maintain~~ (**?**). Humans create the technosphere to provide diverse end uses such as transport, comfortable living spaces and communication, ~~and~~ as well as for social reasons (**??**). We are also entirely dependent on it to keep us alive - ~~we could not provide~~ no more than a few million humans could be provided with food, drinking water, or shelter without it (**???**).

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 **??**). 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 ~~has autocatalytic features, supporting~~ supports its own growth over time by increasing the rate at which materials can be extracted, processed, transported, and transformed to final products (**?**). 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~~ . For example, the mass of human creations has ~~recently~~ likely exceeded the dry mass of all living organisms (roughly 1100 Gt dry mass) (**?**), the rate of primary energy conversion within the technosphere (roughly 20 TW) is roughly half that of terrestrial above-ground net primary production ~~(roughly 20 TW)~~ (**?**) and continues to increase (**??**), and the rate of mass dislocation at the Earth surface by machines (roughly 320 Gt y^{-1}) ~~exceeds~~ appears to exceed all natural geomorphological processes by an order of magnitude (**?**). 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 (**?**) and the wellbeing of humans (**??**). 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 (**?**). 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 (**??????**). 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.

~~The remainder of this~~ This paper aims to ~~contribute to the study~~ improve the resolution of the technosphere by ~~reviewing and proposing a refinement of its definition, presenting an end-use~~ 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, ~~assessing its composition , providing preliminary~~ 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 activity-based categorization, and provides maps of its first-order distribution across the Earth surface~~, and discussing~~ . Section 5 discusses basic empirical features of ~~its temporal dynamics . We aim to contribute to building an interdisciplinary foundation for linking the material composition~~ the temporal dynamics of the technosphere~~with its functionality, its associated energy and material fluxes, its interactions with the remainder of the Earth system, and its contributions to human wellbeing, as informed by multiple fields of research~~, 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 ~~apparently first used~~ was apparently the first to use it in a 1960 article (**?**). It was subsequently used by systems engineer John Milsum (**?**) and, the following year, by biologist Julian Huxley in a reflection on the first moon landing (**?**). More recently, geologist Peter Haff ~~has~~ effectively promoted the term to encapsulate the global proliferation of human technology at the heart of the concept of the Anthropocene (**??**). 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 (**?**) 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 (**?**), and is generally equivalent to commonly used terms in industrial ecology, including 'in-use stocks' (**?**), 'material stocks' (**?**), 'manufactured capital' (**?**) and 'technomass' (**?**), as well as 'artefacts' in the early socio-ecological literature drawing on ecological anthropology (**?**). Throughout the years, the technosphere has been defined in many different ways, sometimes including human-disturbed soils, or even ideas.

~~Here, we propose a refined~~ 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 ~~nature~~ properties of the matter of which it is comprised (i.e. state variables), rather than in terms of ~~specific processes or fluxes~~processes (i.e. fluxes). In other words, to use the terminology common among industrial ~~ecology and ecological economics~~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~~ . There are many processes that occur within the atmosphere, such as convection, precipitation and cloud formation, but these ~~do not~~ are not what define the atmosphere. ~~We also strive to create a clear distinction from the Earth system spheres with which the technosphere interacts, so as to avoid overlooking or double-counting components~~ 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 ~~states~~ entities that ~~achieve~~ can provide end-uses ~~intended by~~ 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~~, and we ourselves are living organisms now as much as we ever were~~. 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' (**?**) and which promulgates a false dichotomy between ~~the~~ natural and artificial worlds. Because of these exclusions, the technosphere definition proposed here implies a much smaller mass than that estimated ~~with~~ using the definition proposed by Zalasiewicz (**?**), 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 ~~mental~~ 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 (**?**). 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 ~~activity~~ society from the technosphere preserves the independence of human agency, which was identified by Donges (**?**) as a conceptual problem with the technosphere of Haff (**?**).

Third, we draw a boundary where the state of an ~~in-use component ceases to be fit~~ entity deteriorates so as to be unfit to serve an intended end-use~~, given the allocated amount of maintenance activity. This boundary is often subject to social characteristics that determine the willingness or ability to maintain or repurpose items, but is nonetheless observationally quite easy to identify. As such, an~~ . An object that undergoes repair remains in the technosphere, while an object that is discarded or irreparably damaged ~~is not. This can be~~ 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 ~~the idea of~~ 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 (**?**). 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 ~~foraminifara~~ 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 ~~on the soil~~ 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. ~~The~~ Although external to the technosphere, persistently identifiable wastes can be termed 'technofossils', as suggested by Zalasiewicz (**?**). 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 ~~Earth surface~~ atmosphere billions of years ago (**?**).

As illustrated in Figure 1, we distinguish the in-use portion of the technosphere from substances that have been extracted or produced from ~~Earth system materials~~the other Earth system spheres, but remain in an intermediate state ~~, as well as those that are used in a way that causes them to be chemically transformed~~as materials or components. We also separate substances that are chemically transformed, in a single use~~. We refer to the latter~~ , 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,

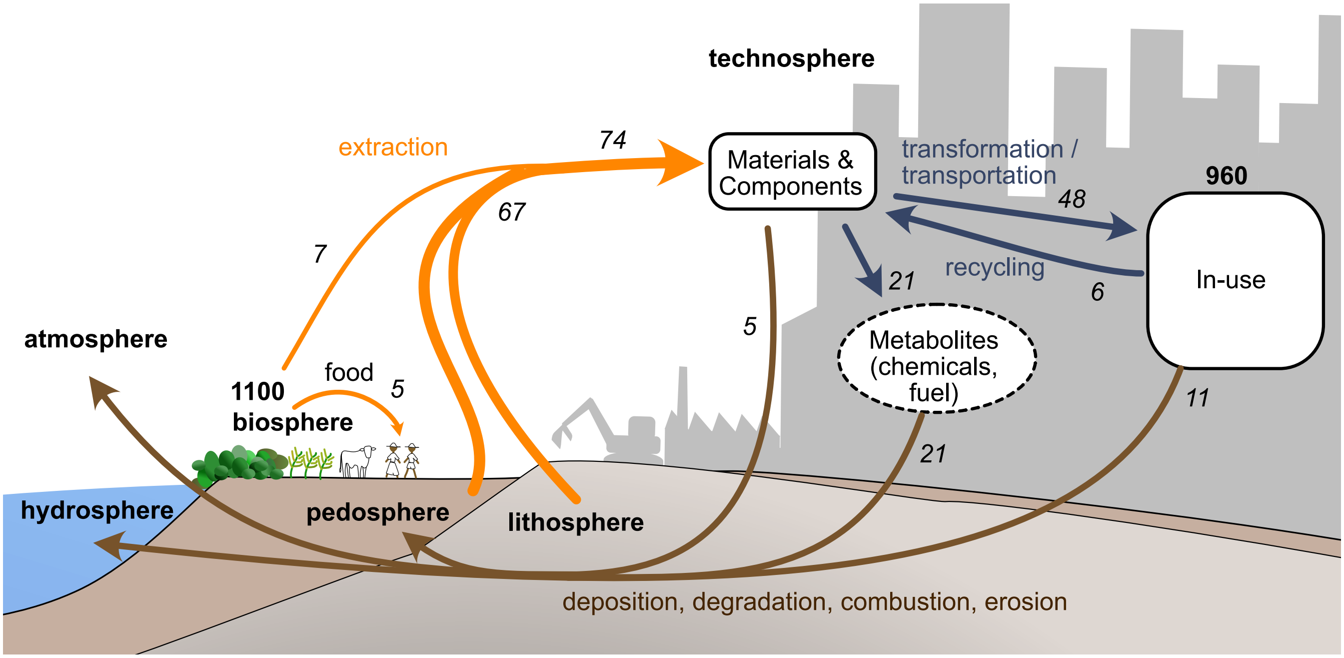

Figure 1. Schematic of the Earth system including the technosphere. Italicized numbers show fluxes in ~~Gty^{-1},~~ $Gt\,y^{-1}$ and bold number shows the in-use mass in Gt, as estimated by Krausmann et al. (**?**) for the year 2015. The dry mass of the biosphere as estimated by Elhacham et al. (**?**)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

fertilizers and pesticides) and pharmaceuticals. ~~As noted above, food~~ Food – the organic matter produced by organismal growth and consumed by living humans – ~~remains within the biosphere~~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 (**??**) ~~, after~~ 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 ~~Analysis~~ Accounting (ew-MFA, see below) which is helpful for estimating fluxes (**??**).

3 Categorizing the technosphere

~~Our interest here is to understand the technosphere as a dynamic, interacting, physical component of the Earth system, created because of socially-coordinated human motivations to produce specific outcomes that are supported through its existence and use. A systematic categorization of the entities that comprise the technosphere , such as that provided for the biosphere centuries ago , can provide a conceptual basis for its description, and can help identify relationships within it~~ 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 (**?**) continues to prove a useful framework for the biosphere, despite the fact that it cannot ever capture the underlying reality of phylogeny (**?**).

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 (**?**) provides an exhaustive and exclusive categorization of ~~traded~~ 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 ~~Earth~~ 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. ~~Similarly, “Tools, tool bodies, tool handles, broom or brush bodies and handles, boot or shoe lasts and trees, of wood” lumps together diverse intermediate components with final goods, presumably based on the commonality that all are made of wood. The CPC also frequently focuses on details of consumer goods, with specific categories such as "Dolls representing human beings; toys representing animals or non-human creatures", while all industrial buildings are included in a single category.~~

~~Another~~ A more Earth-system relevant set of categorizations has been used within the framework of economy-wide ~~material flow accounting~~ 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 (**??**). 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~~, and currently reports annual~~. 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 (**???**). 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 (**???**). 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 ~~. Work within this framework has primarily categorized fluxes and in-use stocks by their material properties, or focused only on specific end uses within a subset~~ (**???**). 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 (?) 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~~, although Wiedenhofer et al. () have recently proposed a grouping of global material stocks into 13 end-use categories.~~ . 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 (??).

~~We propose here a novel categorization that is intended to provide an improved mechanistic understanding of the technosphere, as well as integration with Earth system processes. The categorization is deliberately aligned with end uses, for two reasons. First, human~~ We therefore choose to focus on physically-oriented end-use outcomes that are aligned with activities. Human-centred, end-use outcomes are ~~what motivates the existence~~ essential aspects of the technosphere, since they are are what motivate its creation - every component of the technosphere ~~was motivated by~~ can be associated with at least one type of intended end use. ~~Second,~~ Many end-uses ~~are mechanistically linked to~~ 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 ~~based categorization~~ perspective connects naturally to both human and Earth system outcomes. ~~Because the technosphere is intimately entwined with~~

To facilitate quantitative connections with existing records of human activities, ~~our categorization is also aligned with a classification~~ we align the end uses with the Motivating Outcome-Oriented General Activity Lexicon (MOOGAL) (??). The MOOGAL was created to provide an exhaustive and exclusive categorization of human activities ~~in order to help mechanistically link the technosphere to activities . We call the categorization the~~ 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 (?). 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 Classification, EUTEC. The EUTEC~~ 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.

Our classification follows the following principles:

Most of our categoriesassociate technosphere components with the human activitiesthey specifically support through their end use . However, we identified a number of human creations which do not clearly support or modify

3.4 Catalytic properties

Many technosphere entities operate in direct support of human activities, in a way that materially alters the outcomes of specific activities, but instead change the background the activities. For example, the ability to catch fish is enhanced by the use of a fishing boat and fishing gear, while a highway 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 spend their time , or contribute non-specifically to diverse activities by interacting with human neural processes through symbolic information 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,

$$\frac{dx}{dt} = A_x N T_x \epsilon_x \quad (1)$$

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. **?**) 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.

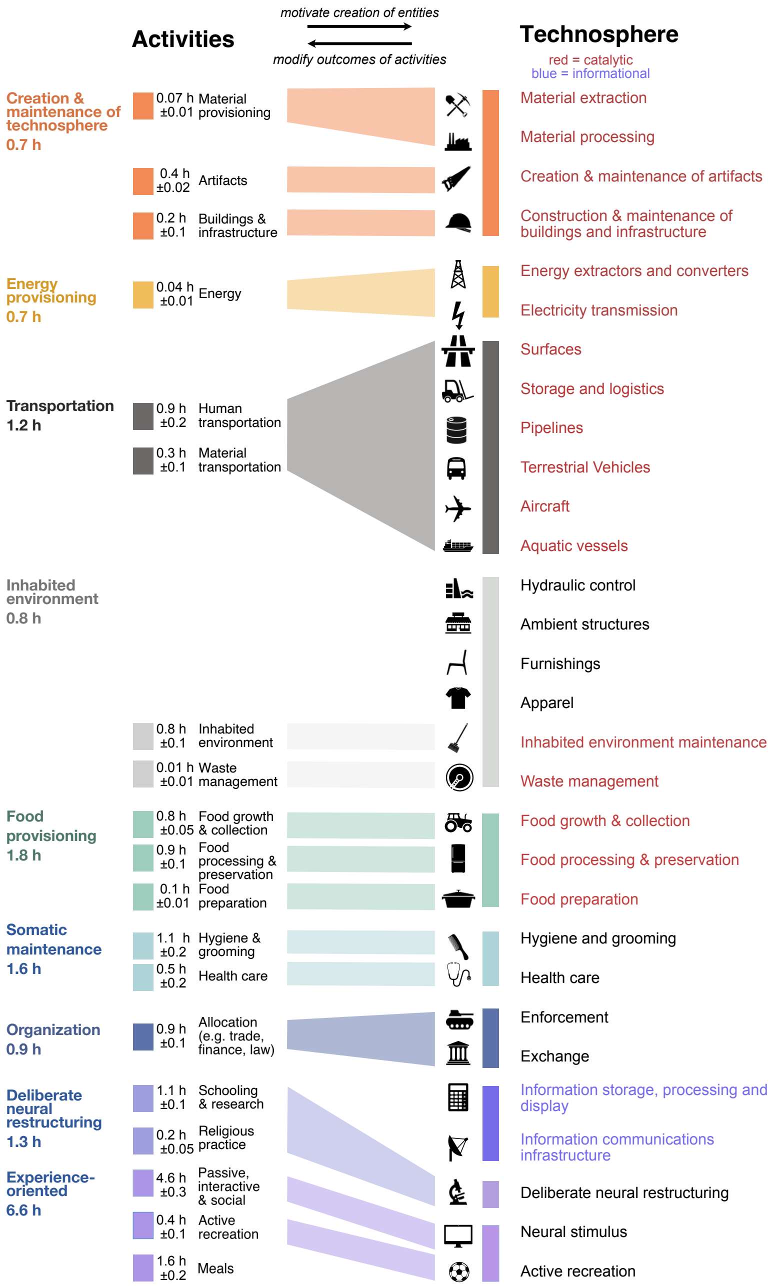

Figure 2. Connecting human activities with the technosphere. Strong associations between categories are shown by shaded polygon connections. Technosphere categories that do not have clear associations to individual activities are found in the Inhabited environment and information-related categories.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

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 **?** and indicated in blue font in Figure 2. Information and Communication Technologies play essential roles in human societies, by providing high quality communication (**?**) 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 **?**, 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:

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. ~~This led to the following three high-level categories~~

First we apply the categorization to lists compiled by ethnographers for two hunter-gatherer societies, as reported by Kelly (**?**). 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 **??**, 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 (**?**).

~~The three categoriesand their components are~~ We also applied the MEUTEC categorization to the Central Product Classification (**?**), 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 ~~**??**, and a decision tree to mitigate ambiguity in classification is provided in Appendix Figure A1.~~ 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 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 ~~are now in a position to characterize the~~ now characterize basic features of the technosphere~~in a holistic, exhaustive and exclusive manner.~~

4.1 ~~Distribution of mass within the technosphere~~

~~Approximate distribution of mass among technosphere end-use categories. The area of each coloured region is proportional to its mass. The uncertainties for many of the smaller categories are a factor of 2 to 5, mostly due to lack of observational constraints on the distribution of mass among non-residential buildings and infrastructure. See Appendix B for estimation methodology.~~

~~First we~~ . We first provide an overview of how the mass of the technosphere is partitioned among the ~~EUTEC~~ MEUTEC categories and across the planet surface, circa year 2019. The ~~total mass of the technosphere, as estimated by Krausmann et al. () and extrapolated by Elhacham et al. () was 1100 Gt in 2019. The~~ overall mass of technosphere components is not necessarily the most relevant ~~thing~~ 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~~– however, it~~ , 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 ~~way~~ starting point with which to understand the physical scale of the technosphere's main components.

4.0.1 ~~Contributions of EUTEC categories to total mass~~

~~As described in Appendix B, we combine estimates from Wiedenhofer et al. (), which are derived from the dynamic Material Inputs Stocks and Outputs version 2 (MISO2) model, with bottom-up estimates from Matitia () and multiple other sources to quantify a subset of~~

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. ~~We emphasize the fact that many of these estimates are very poorly constrained.~~ Global studies of in-use material stocks have only been available for a little over a decade (**???**) and uncertainties frequently exceed a factor of 3, even for large aggregated categories (**?**). 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, ~~these estimates~~ the estimates provided here should be seen as preliminary, and we hope that they will become better constrained through future work.

~~As shown~~ With those caveats in mind, we combine estimates from Wiedenhofer et al. (**?**), which are derived from the dynamic Material Inputs Stocks and Outputs version 2 (MISO2) model, with inventory-based estimates from Matitia (**?**) 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 **??** 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 **??** ~~,~~ for the total technosphere mass (including all of the built environment) and for movable objects on their own.

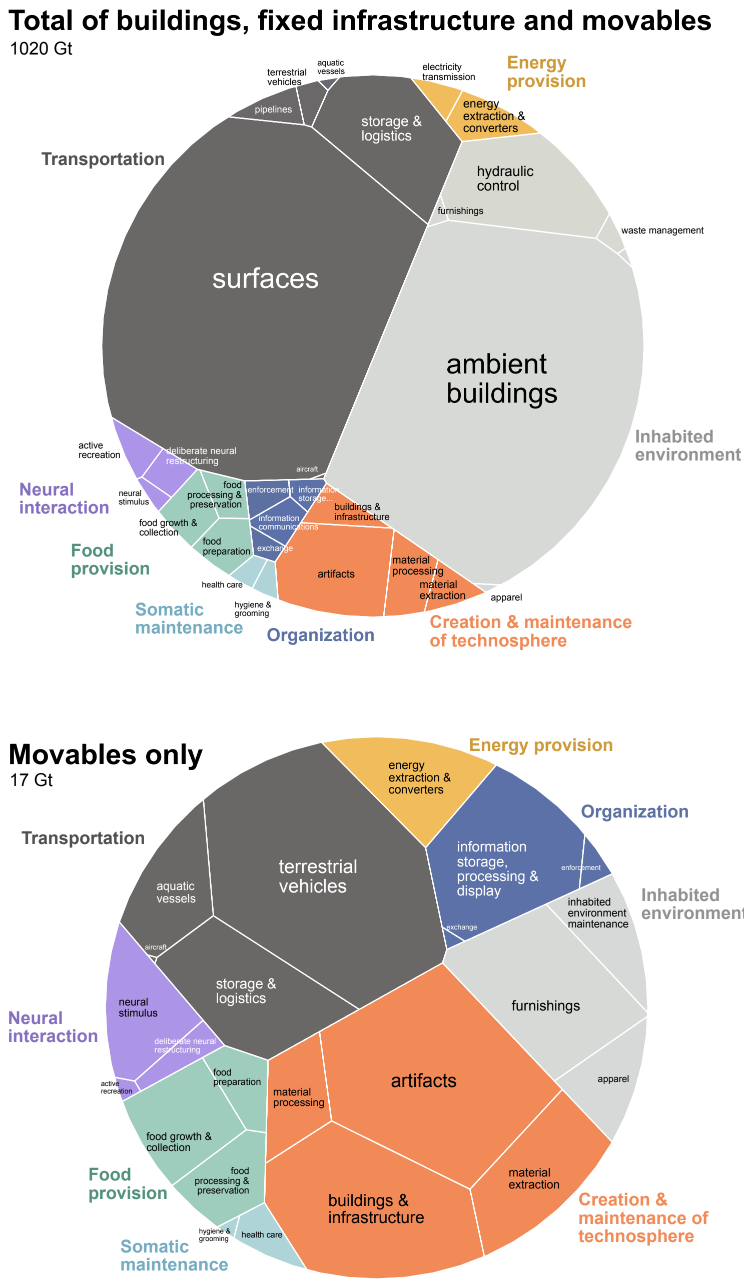

Figure 3. Approximate distribution of mass among the technosphere end-use categories. The area of each coloured region is proportional to the estimated mass. The top circle includes all fixed buildings and infrastructure as well as movable entities, while the lower circle shows only movable entities. 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.

Despite the large uncertainties, it is quite clear that the largest two components of the technosphere~~by mass are Ambient Context and Transportation~~, by mass, are the non-movable elements of the Inhabited Environment and the Transportation system. Transportation is dominated by surfaces (~~32~~37% of total, comprised of roads, railroads, bridges and tunnels), and also includes associated logistical infrastructure~~(4% of total), vehicles and aquatic vessels (0.5% of total). The ambient context is comprised almost entirely~~ . The inhabited environment is comprised mostly of residential and service buildings (~~34~~ 36 % of total mass)~~. The Informational category, despite its prominence in human affairs and experience, accounts for only a small portion~~ , though dams and water infrastructure are also significant.

The movable parts of the technosphere account for only about 1.6 % of the total mass, ~~most of which is the communications infrastructure (poorly constrained)~~$\approx$ 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) (**?**). 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. ~~The other activity-specific technosphere components account, together, for roughly one quarter of the total.~~

~~Spatial distribution of the two largest components of the technosphere by mass, at 1-degree resolution. 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.~~

4.1.1 ~~Mapping the technosphere~~

4.2 Mapping the technosphere

We also provide ~~, in Figure **??**,~~ an estimate of the overall spatial distribution of the two parts of the technosphere that comprise most of the mass: ~~the ambient context~~ buildings, and the transportation system (Figure **??**). Together these account for an estimated ~~two thirds~~ nine tenths of the technosphere. As detailed in Appendix ~~C~~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. ~~The~~

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, ~~Europe and East~~ and eastern Asia.

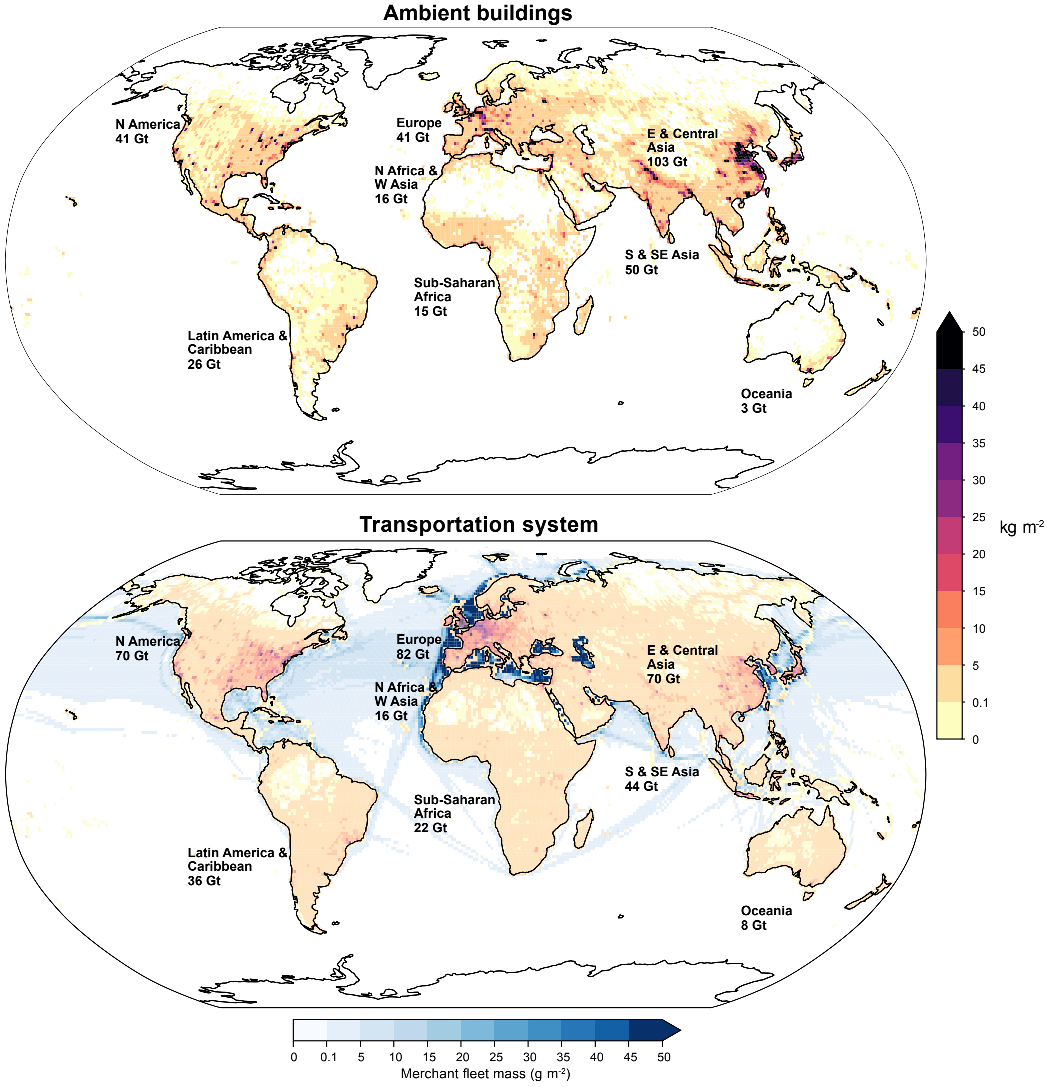

Figure 4. Spatial distribution of the two largest components of the technosphere by mass, at 1-degree resolution. Buildings (top) are taken from Haberl et al. (?). Transportation system data (bottom) were compiled and distributed as described in Appendix B. The masses of ships used for marine transport 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.

4.3 ~~Dynamics of the technosphere~~

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 (**?**), even though the mass of technosphere in rural areas is relatively low. Nonetheless, the spatial distribution shown in Figure **??** 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. ~~Arguably~~The technosphere is a newcomer to the Earth system – arguably, the earliest components of the technosphere were stone and wooden tools, ~~roughly 3~~ more than 2 million years ago (**?**), 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. ~~Here we provide a brief discussion of how mass fluxes contribute to the growth and maintenance of the technosphere.~~

5.0.1 ~~Turnover rates within the technosphere~~

~~We can assume that for some component of the technosphere , x, the mass T_x (in kg) over some domain of the Earth surface varies according to a rate of change as where m_x is the rate at which T_x is manufactured (in g y^{-1}), Γ is a transport operator that transfers T_x between domains (in g y^{-1}), and λ_x is a decay rate, defined as the fraction of~~ The total technosphere has grown particularly rapidly over the period for which ew-MFA estimates are available, which extends back to 1900 (**??**) as shown in Figure **??**. 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 ~~stock that ceases to be usable by the local population each year (in units of y^{-1}). The lifetimes of components of the technosphere vary from weeks to centuries. For short lifetimes, we can assume that the effect of age cohorts is small, and the assumption of a constant lifetime will be reasonable . However for long lifetimes, proportionally large accumulation of stock can cause the age cohorts to play a major role in determining the time evolution of a stock~~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.

5.0.1 ~~Autocatalytic growth of the technosphere~~

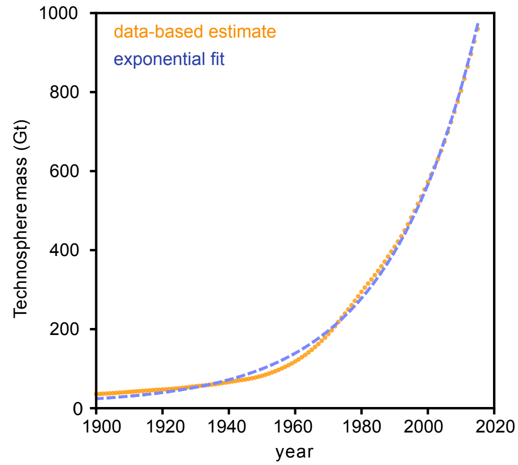

Figure 5. Growth of technosphere since 1900. Dots show estimated technosphere mass from Krausmann et al. **?** with humans and domesticated animals removed. The ~~left panel is plotted on linear scales, while the right panel~~ blue line shows ~~the logarithm of mass. Blue lines show~~ an exponential fit with growth coefficient $c = 0.036$, ~~while the three grey lines in the right panel show piecewise linear regressions with coefficients~~ equivalent to a doubling time of roughly 20 years.

~~The total technosphere has grown very rapidly over the period for which ew-MFA-based mass estimates are available, which extends back to 1900 . This rapid~~ This rapid exponential growth can be attributed, at least in part, to ~~its autocatalytic properties . Autocatalysis~~ the autocatalytic properties of the technosphere. *Autocatalysis* occurs when the products of a process increase the rate of ~~(i.e. catalyze)~~ the same process that produced them, thereby accelerating 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 ~~continued extraction and processing, thereby leading to an acceleration of~~ overall growth.

~~Importantly, the~~ 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~~ . 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 ~~mass~~ masses of these other constructions are bound tightly to the ~~mass~~ 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 ~~character of technosphere growth can be encapsulated in~~ growth of the technosphere at a given point in time can be described by a simple equation,

$$\frac{dT}{dt} = cT \qquad (2)$$

where ~~T is the mass of~~ the ~~technosphere (~~rate of change of the technosphere mass (T, in g) ~~, and c is a coefficient~~ is a linear function of itself. The coefficient c (in s^{-1}) ~~that~~ captures the degree to which a given increment of technosphere growth accelerates its continued growth. ~~If~~ 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. ~~As shown in Figure **??**, the increase of technosphere mass~~

The relatively good exponential fit of the technosphere growth since 1900 ~~is indeed well approximated by an exponential with a slope of $3.6\% y^{-1}$. Interpretation of the details~~ 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~~growth rates must be made with caution, given the inherent uncertainties. The material flows of major components are modeled from sparse data, and in-use lifetime assumptions (related to the value of λ in the formulation here) are relatively simple. With those caveats in mind, it is notable that the agreement is nearly perfect since 1970, the period during which the data is likely to be most reliable compared to earlier time periods.~~

, and c can unquestionably vary. Prior works have ~~discussed~~ identified changes in technosphere mass fluxes over the 20th century ~~by identifying changes~~ that were coincident with prominent historical events~~. Here, we take a broader view, separating the technosphere growth curve based simply on the major features of its shape. When divided into 3 segments, with divisions at 1950 and 1980, linear fits of log(T) vs. year suggest exponential rates for these three periods of 1.6%, 4.4%, and 3.4%, respectively ($r^2 > 0.995$). The sharp break in slope near 1950 is consistent with the idea of the 'Great Acceleration' following World War II~~ , reflecting impacts of human social dynamics on the value of c (**?????**). 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 (**??**). 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.

~~Although~~ In addition, although we do not have ~~direct~~ detailed information on the size of the technosphere prior to the 20th century, ~~it is clear~~ 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 (**?**), 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 definitionto help integrate the , 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 (**?**). Unlike most prior categorizations of the technosphere, which were based on material types, the EUTEC MEUTEC introduced here is based on the end-uses that motivate the creation of technoshere technosphere components, in alignment with human needs and desires. By basing the majority of 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, the EUTEC we hope that the MEUTEC can help to bridge the core features of economies and societies with Earth system processes.

As shown by global ew-MFAthe 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. These 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 (**?**). 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.

Future work on the technosphere could 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 the links between and link chemical elements within the technosphere and with their Earth system sources and consequencessinks, to build a unified understanding of how they contribute to global biogeochemical (or, perhaps, 'technogeochemical') cycles. ~~Better understanding of physical constraints on the functioning~~ There are many ways that the data compilation here could be used as a starting point for modeling aspects of the technosphere~~could also help to elucidate possible~~ , 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 **??** will be provided as part of the Surface Earth System Analysis and Modeling Environment (SESAME) dataset **?** and as an electronic supplement on Zenodo.

Appendix A: ~~Categorization flow chart~~

~~Logical flow chart for assigning technosphere components among the three high-level categories.~~

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 **?** material flow analysis.

Because buildings comprise a large part of the total mass and contribute to many ~~EUTEC~~ 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. (**?**) provide an estimate of building mass drawing on satellite observations of building volume (**?**) 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 ~~identification~~ buildings is methodologically challenging and should be seen as approximate.

Deetman et al. (?) 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, ~~simply saying that it was very hard~~given the lack of statistical data on floor space.

~~The~~ Wiedenhofer et al. (?) use the MISO2 model ~~provides ew-MFA-derived stock estimates for~~ to provide economy-wide, country-level estimates of material stocks across 13 ~~categories, 2 of which are buildings. MISO2 estimates for buildings are~~ 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, ~~with a roughly~~ 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 ~~EUTEC~~ MEUTEC categories, to which we assign ~~an uncertainty rangeof a factor of 3.~~ 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 ~~EUTEC~~ 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 ~~EUTEC~~ MEUTEC categories as described in the notes. Uncertainties tend to be large, with estimated ranges ~~commonly~~ of 3 to ~~5. These~~ 10. These MISO2 estimates were supplemented additionally as follows.

For transportation surfaces, we ~~used the~~ supplemented the MISO2 estimate with the global estimate of 314 Gt in year 2021 from Wiedenhofer et al. (?) of all roads and railway infrastructure, including tunnels and bridges, constructed with archetypal material intensities applied to Open Street Maps data. We ~~take the average of this estimate and the~~ also used the similar estimate of 377 Gt provided by Matitia (?) 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 ~~mass of electrical grids, transformers and power plants was taken from~~ masses of electrical transmission grids, distribution grids and transformers were taken as the median estimates of Kalt et al. (**?**) ~~as 10.4 Gt . The estimated fraction from MISO2 civil engineering is significantly larger (total 56 Gt) to account for aggregate in large~~ 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, ~~as well as~~ and 0.7 Gt of fossil fuel extraction and refining infrastructure, ~~with~~ of which 0.1 Gt is offshore oil platforms (**?**). These estimates have significant uncertainty (range factor 4). The mass of pipelines was taken from Le Boulzec et al. (**?**) as 3 Gt, which compares well to the independent estimate of Matitia (**?**) of 1.8 Gt (uncertainty range factor 3).

We used bottom-up estimates from Matitia (**?**) 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~~and populationas predictors~~, total population, crop production, harvested area, percentage of urban population, year, and income class as predictors for machinery mass. We also used Matitia (**?**) estimates for textiles, and the plastic components of furniture, electronics and health equipment as lower bounds on the corresponding categories.

Appendix B: Estimating spatial ~~distribution~~distributions

The spatial distribution of some technosphere components can be observed directly, such as roads (**?**). 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 (**??**). The dasymetric method allocates data from jurisdictions to 1-degree grid-cells by using appropriate variables (referred to as surrogate variables). The jurisdictional data 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 ~~Agricultural machinery~~

~~Agricultural machinery data was collected from 1999 to 2009 for 124 countries, focusing on 4W and 2W tractors provided by FAOSTAT, as well as combines . The average horsepower for 4W tractors was determined using John Deere and Caterpillar products, whereas 2W tractor and combine horsepower were calculated using previous studies and global product averages . Steel mass was estimated at 85% for tractors and combines, and 50% for 2W tractors. Because the data has significant gaps, a random forest machine learning algorithm was used to fill those gaps. GDP, total population, crop production, harvested area, percentage of urban population, year, and income class were used as predictors for machinery mass data. The country-level machinery mass data was dasymetrically mapped using cropland area as a surrogate variable. Cropland area data was collected from MODIS Terra Aqua Land Cover Types .~~

B1 Aircraft

Commercial aircraft data ~~was~~ 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 (?). 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~~precisely without specific data~~, 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. (?) and regridded to 1-degree resolution. Note that the mapped data are shown as previously published in Figure ??, 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 (?) 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. (?). 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 ~~Building material stock~~

~~Matitia () complied country level building material stock data from Deetman et al. () and Marinova et al. (). The Global Human Settlement Layer built-up volumes served as the surrogate variable in this case.~~

B4 Oil and gas pipelines

~~Oil and as gas pipeline data was~~ The spatial distributions of pipelines were collected from Sabbatino (?). The oil and gas pipelines were converted from line to grids based on sum of pipeline length per pixel. ~~For the physical characteristics of the pipelines, an outer diameter of 89 cm and a thickness of 1.9 cm were assumed, both derived from Bai and Bai (). Pipeline materials were assumed to have an average density of steel equivalent to 7,900~~ kgm^3

B5 Roads and railways

The distribution of road and railway masses is taken from Wiedenhofer et al. ? 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 (**???**). 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 ~~Land~~ 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 (**?**). 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. ~~Material composition of the vehicles are estimated based on total curb weight. Steel, cast iron, plastic composites, aluminum, rubber, glass, and copper are comprised on 80% of a vehicle's total curb weight. Characteristics and intensities of various materials are defined from various sources such as the GREET 2.7 model, a life-cycle analysis of U.S. light-duty vehicles, and lifecycle inventory studies. Finally, the~~ The country-level vehicle mass was distributed assuming that 5% of vehicles remained on the road, and thus distributed based on road density (**?**) while the remaining 95% of vehicle data was distributed based on population density (**?**).

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