Foundational Issues of 'Technosphere Science' – the case for a new scientific discipline

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Abstract:

This paper submits the case for establishing 'technosphere science' as an independent scientific discipline that draws on results of many other disciplines, reaching from physics to the humanities, with economics as a major contributing discipline. My argument is ontological, that is I posit several fundamental assumptions about the type of entities that are studied by technosphere science and their causal relationships. This is motivated by the recognition that in the Anthropocene, the technosphere has emerged as encompassing also the biosphere, thus rendering the ontological distinction between 'nature' and the artificial obsolete. This requires a thorough reconsideration of the concept of 'technology' that combines engineering approaches with the humanities and philosophy, resulting in a new concept of 'artefact'. This concept provides the foundation for a central ontological notion of technosphere science, distributed agency or 'agencement', following Actor-Network-Theory. Agency is no longer seen as a property exclusive to humans, but as emerging from networks of entities, including humans, artefacts and living systems. Hence, technosphere science draws on many general and abstract insights of various uses of the concept of 'networks' across many disciplines, which allows for positing distinct forms of causal processes: prominent examples include the concept of autocatalytic cycles (building on their conceptual role in explaining the transition from non-life to life) or power laws and scaling laws. On a most general level, technosphere science establishes a universal evolutionary framework that generalizes over biological evolution, and approaches technology as an evolutionary phenomenon. In this general framework, thermodynamics assumes a foundational role in approaching both the technosphere and the biosphere as consisting of entities that accumulate information that enables the utilization and expansion of energetic throughputs. This follows from the ontological determination of the technosphere as an open, non-linear and non-equilibrium system feeding on energetic throughputs. In this perspective, the human economy is the central medium by which human action is functional relative to the reproduction and growth of the technosphere. I conclude with considerations about human autonomy and ethics in the technosphere.

Keywords: Anthropocene; anthropocentrism; technology; artefacts; general theory of evolution; functions; networks; agencement; energy and information; thermodynamics; maximum power; categorical imperative

JEL codes: B52, O44, Q40, Q57

1. Making the case for a new scientific discipline

The definition of the new geological age of the Anthropocene centres on one specific phenomenon, namely the massive occurrence of human artefacts in the most recent geological sediments (Zalasiewicz et al. 2017). These artefacts are products of human technology. Therefore, some authors have introduced the term ‘technosphere’ for identifying the origin of these artefacts (Herrmann-Pillath 2013: 485ff; Haff 2014a; Donges et al. 2017). In this paper, I will discuss basic conceptual aspects of the technosphere to provide the foundations of the science of the technosphere. I believe that it is necessary to develop a new science of the technosphere in analogy to biology as the science of the biosphere. There is a problem of linguistic design here (see Arthur 2009: 12ff) since ‘technology’ already appears as an ‘-ology’, therefore I leave it with ‘Technosphere science’, in analogy to ‘Computer science’ or ‘Geoscience’. Yet, the term ‘technosphere’ motivates considering a new disciplinary frame, because it deliberately creates the analogy to the biosphere: The alternative would be to confine ourselves to the term ‘biosphere’ (for example, Smil 2003) and to approach the human part as a subsystem of the biosphere. Obviously, that would lead us to question the term ‘Anthropocene’, too. In this context, the alternative suggestion of ‘Anthropocene studies’ seems to be under-determined, because it refers to the geological age only, without further specifying a particular empirical domain and type of objects of inquiry. In the geological notion of ‘Anthropocene’, this is narrowed down to the analysis of the corresponding geological phenomena, such as sediments, which would preclude, say, the explicit study of the human economy just because it emerged in that geological era.

My exercise is an ontological one, hence can best be characterized as a philosophical work, in the sense of a science-based ontology à la Bunge (1977). Doing ontology means to reflect basic categories of ‘being’ and establish their systematic relationships. As such, ontology is fundamental for any kind of science, especially in defining the characteristics of certain scientific disciplines vis à vis the others. So, for example, many philosophers of chemistry would argue that ‘substances’ stay at the core of chemistry as being different from physics and biology (Brakel 2000); biology focuses on ‘life’, which raises the ontological question how we characterize ‘life’ as a basic form of being that differs from non-life (Mayr 1982); or, economics resolutely rejects any causal claims that would assign existence to supra-individual entities (‘methodological individualism’) (Rosenberg 2001). So, if we wish to establish ‘technosphere science’, what are the most fundamental ontological constituents? Evidently, this might be ‘technologies’. However, this seems to stay in tension with the basic inspiration of the concept of ‘Anthropocene’: In the latter, humans seem to reign absolutely, and technology is just a human creation (hence, the “human age”, see Monastersky 2015). Yet, if the central phenomenon embodied in the geological strata is the artefacts that are parts of the technosphere, we might ponder whether a better designation of that geological era would be the ‘Technocene’. As we shall see, that is not merely playing with words.

If we look at human technology, there is no specific science devoted to the study of it. On first sight, that might be engineering, however, this is the science of creating and applying technology, and not the science investigating the phenomenon as such (see the discussion in Mitcham 1994). Apart from engineering, the study of technology is fragmented across many disciplines, such as ‘Science and Technology Studies’ as a field in the humanities and sociology, the cultural sciences and anthropology, economics, or complexity sciences, just to name a few. The reason for this seems to be rooted in a hidden ontological assumption, namely that technology is the product of human action and design, and that it serves human purposes. Accordingly, if we study humans, that would include technology, if we move beyond engineering. As said previously, this may be implied by the term ‘Anthropocene’. There would be no need for a ‘technosphere science’ beyond multi-disciplinary research into technology.

I want to radically question this approach and suggest a ‘Copernican turn’ in the study of the Anthropocene in raising research into the technosphere to the status of an independent scientific discipline with its own fundamental concepts and own methodological standards. In this paper, I do the first steps in discussing the ontology of the technosphere. The radical nature of this step is to reject the implicit anthropocentrism of the notion of the ‘Anthropocene’: In simplest terms, if we notice the ubiquity of artefacts in geological sediments, I take it for just what it is, namely evidence for the emergence of the technosphere. And the technosphere is the sphere of technology, in which humans play a role, but not necessarily the central role. Compare it with the study of biology in the context of ecosystems that are massively shaped by human intervention: We would not define ‘life’ as a phenomenon that became ‘human’ for that reason, and would not substitute biology by anthropology. In the same vein, I will argue that the technosphere needs its own scientific discipline, beyond the treatment of technology by the human sciences or engineering.

Technosphere science draws on many disciplines, reaching from engineering to economics, the social sciences or biology. This is straightforward to see if we look at existing research of technology. We can approach technology in many ways:

- We can adopt the engineering and science perspective, which defines technology as artefacts that mobilize physical phenomena in the broadest sense: this is a conception that is also often adopted by economists (Arthur 2009). This would exclude other kinds of artefacts, such as a symphony, on first sight. However, evidently a symphony activates physical phenomena, too, so that we meet a first issue in discussing technosphere ontology: What is ‘physical’ about artefacts? The engineering and science perspective is essential in technosphere science because it highlights physical mechanisms and constraints that operate in the evolution of the technosphere. As we shall see, this implies, among many other insights, that energy and energetic transformations are a major object of study in technosphere science; this compares, for example, with economics in its current state, which treats energy only in specialist subdisciplines (Hall et al. 2001; Kümmel 2013).
- We can adopt the social science perspective in recognizing that artefacts always tie up with human action, in various ways. This relates to both the producer and the user side of technology (which is today also emphasized by engineers, see Spreng 2014 in the context of energy research). In this view, technology is not centred on artefacts primarily, but on the behavioural patterns, routines or institutions that govern the actual performance of artefacts in the context of human societies. In the social sciences and the humanities, this has sometimes led to the conclusion that all technology, and even science, is socially constructed, thus radically questioning the narrow science and engineering perspective (overview in Sismondo 2008). Within technosphere science, we need to balance such opposing views and aim at a synthesis. In any case, in the technosphere artefacts and human action, mediated by human sense-making and interpretive creativity, are deeply enmeshed with each other.
- Another perspective is provided by biology. This is suggested by various arguments. A classical approach in the philosophy of technology approaches technology as extensions of human organs (originally suggested by Kapp, see Berger 2014); in a more modern version, we can view technology as a manifestation of adaptation, fulfilling biological functions (such as protection against hostile climatic conditions by heating and cooling, see Corning 1983, 2005). Then, technology appears to be a part of the ‘extended phenotype’ of the human species which creates continuities with other artefacts in the biosphere, such as nests built by birds (Dawkins 1982).

In this paper, I concentrate on issues of cross-disciplinary integration that mainly involve these three scientific disciplines. My aim is to mobilize their insights to establish a set of ontological propositions about the technosphere that will result in proving the need for establishing a 'technosphere science' as an autonomous scientific discipline which differs from the contributing disciplines in various and important ways.

2. The analytical obsolescence of 'nature' in technosphere science

The value of the three-disciplinary way towards the ontology of the technosphere is salient if we consider the simplest question, what is an artefact? In geological accounts of the Anthropocene, these appear as 'things', in fact mostly debris, hence defunct artefacts, though including phenomena such as CO_2 accumulating in the atmosphere as a product of human technology (Zalasiewicz et al. 2017). However, there are difficult conceptual issues in delineating 'artefacts' from 'natural entities' (Perlman 2009). This is most obvious in the context of biotechnology, but of course there are earliest forms of the domestication of plants and animals which would imply that, for example, a dog is an artefact and hence a part of the technosphere. In terms of cross-disciplinary relations, this would blur the borderline between engineering and biology. This problem becomes even more tricky if we take the ecosystem perspective. This raises the question of how to account for indirect impacts of human action on ecosystems, including unintended consequences (Mitcham 1994: 174ff). Should we only include an entity into the category of 'artefact' if it has been deliberately created by human intention and serves a humanly defined purpose? Or should we adopt a concept of causation that is independent from human intentionality and counts as 'artefacts' all entities that are causally connected with human action, but not necessarily with human design (see the discussion in Longy 2009)?

The ecosystem perspective plays an essential tole in current debates about the Anthropocene as far as the practical relevance of the concept is concerned. To come back on the CO_2 example, the phenomenon of global warming is an unintended effect of human action. It results in so many and far-reaching impacts on the Earth system, so that we might be justified in concluding that the Earth's climate has been transformed into an artefact (as I do in Herrmann-Pillath 2013). Then, geo-engineering approaches to manage climate change would only be the necessary consequence. That would imply, in turn, that all constituent phenomena in the Earth's ecosystems which are influenced by climatic conditions also morph into artefacts. The common distinction between 'nature' and 'culture' or 'technology' would collapse.

I endorse this interpretation as being one of the foundational ontological assumptions of technosphere science: In the Anthropocene, there is no distinction anymore between ‘nature’ and other domains of the Earth system that are influenced by human action. In fact, the distinction between ‘nature’ and ‘culture’ always was deeply problematic on epistemological grounds, as what we identify as ‘nature’ is itself determined by our human conceptions about the borderline between the two ontological domains (Latour 2012; compare Adorno 1985: 166f). Nature, in this sense, always has been a human epistemological construct, and not objectively given. In the context of the technosphere, this problem remains valid and has even political implications, because considering ecologically oriented policies, and strands of thought in Ecological Economics such as ‘deep ecology’, there is at least the implicit belief that there is a domain of ‘nature’ that is autonomous from human action, and is being disturbed by it in recent times (Spash 2013). More specifically, this is often related to notions of ‘equilibrium’ (nature as seen as staying ‘in equilibrium’) and human actions as pushing nature into disequilibrium. Accordingly, for example, there have been serious debates about the legitimacy and meaning of ecological restoration projects, in which the claim might be raised to ‘re-create’ nature, though actually producing an artefact by human design (Light 2009). In technosphere science, this understanding of nature is discarded for principled reasons, with many implications, such as the uses of the equilibrium notion (compare section 7)

The upshot of this brief reflection is that we need to reconsider the relationship between the technosphere and the biosphere as well, with the latter being a conceptual equivalent to ‘nature’. Humans as members of the biosphere have created technology, but with the emergence of the technosphere this relationship has been reversed: the biosphere has become an artefact and part and parcel of the technosphere. By implication, this means that the biosciences need to be an essential part of technosphere science. This is an important conclusion, the justification for this is both an epistemological and an empirical one. This view stands in line with the original ideas in Earth system science, especially Vernadsky, in including the biosphere as a regulatory mechanism of the Earth system, which have been further systematized in the notion of Gaia (Lovelock 1990; Latour 2015). In this tradition, technosphere science approaches the technosphere as the overarching regulatory system (without any implications on systematic coherence and closure, see Latour 2015) of the Earth System in the Anthropocene. In my concluding section, I will briefly discuss the implications for the role of specifically human characteristics in the technosphere, as they have been seen in the Western tradition of modernity, such as freedom, autonomy and reflexivity.

3. Artefacts and the chemistry of the technosphere

Returning to the question of how to conceive of artefacts, it seems now necessary to develop an ontological notion of artefact that is independent from human intentionality, but includes all unintended causal effects of human action in the Earth system context. But this consideration seems to short-cut many important deeper questions about the role of humans in the technosphere and in the biosphere. If we approach the biosphere as a part of the technosphere, and hence render the distinction between the 'natural' and the 'artificial' obsolete, we need to define a common criterion how to refer to the constituent entities. This is one of the most basic ontological issues in technosphere science.

I will now unfold the thesis that fundamental ontological categories of technosphere science are 'function' and 'information', and that these two terms build the ground on which more specific cross-disciplinary syntheses can proceed. This is a vast and complicated field, and I can only present some preliminary thoughts, mostly without the necessary discussion of alternatives and possible objections. A full treatment can be found in Herrmann-Pillath (2013); related approaches include the seminal work of Ayres (1994) and the recent contribution of Hidalgo (2016).

My discussion of the artefactual can be also turned upside down: We can also ask, what makes technological artefacts similar or even ontologically identical with living objects? In standard approaches to the artefactual, there is a confusion between epistemological and ontological meanings of the common assumption that this distinction relies on the role of human intentions in defining the artefactual, and the Darwinian rejection of any role of design, hence intention, in biological evolution (Vermaas 2009). However, this focus on the role of intention is itself expression of an anthropocentric bias in analysing technology.

For dealing with these issues, it is most fruitful to go back to origin of life theories, because these need to draw a borderline between life and non-life on the other end of the biological spectrum, so to say. There are many alternatives, and the issues are not settled, but what appears to be most promising in the context of technosphere science is the view that a living system is a compound of evolving information that enables the activation of energetic throughputs to sustain and reproduce the material structures in which this information is embodied (for example, Lahav et al. 2001; Elitzur 2005). Hence, in this view the two concepts of information and energy are systematically related. I submit the claim that the same approach applies for technology, if we just substitute 'technology' for 'living system'. To complete this conceptual integration, we only need to add the bridging concept of physical work. Both living systems and technological systems generate work that exerts physical impacts on the environment. In distinguishing between 'work' and other physical impacts, the notion of information is indispensable in the sense that distinguishing between work and 'heat' implies reference to identifiable macro-states which are distinguishable on informational terms (compared to the most probable state resulting from the dissipation of heat, hence dissipation of energy, and increasing entropy) (see Collier 1996; Atkins 2007: 32f).

One possible way of conceptual integration is Stuart Kauffman's (2000: 49ff) notion of 'autonomous agent': An autonomous agent is capable to realize complete thermodynamic work cycles, in which work ultimately serves the purpose of reproducing the autonomous agent. From this basic definition, all other abstract features of life follow (Lahav et al. 2001):

- metabolism, which is the processing of energy and matter in interactions with the environment;
- autonomy, which is the capability to maintain and reproduce boundaries with the environment;
- teleonomy, which is the emergence of structure in interactions with the environment;
- and learning, which is the accumulation of information that enables the performances underlying those features.

If we look at single technological artefacts, they would certainly not appear as autonomous agents, such as a hammer. If humans work with a hammer, the work flowing via the hammer does not reproduce the hammer as an artefact. But the term 'technology' is under-determined here, as this often refers to much broader systems of technological artefacts, such as a car, or, for that case, the entire systems that support the production and usage of cars in society. At this point, suffice to mention one example of a technological system which most straightforwardly allows the application of the abstract concept of 'autonomous agent': a city. A city has a metabolism, it maintains its borders relative to the environment, it manifests structural change and growth, and it learns. Or course, as any kind of living systems, cities also decay and die.

So, if we posit a conceptual integration based on the concept of autonomous agent, this term obtains an analytical role in relation with investigating into technology: The question is what kinds of artefacts factually operate as autonomous agents, and which are just components of them. A city might be an autonomous agent, whereas as hammer is not. But once we include humans, the hammer plus a human can be regarded as an autonomous agent: The hammer is a part of the human extended phenotype.

The term ‘autonomous agent’ naturally raises the question about the meaning of ‘agent’ which leads us to consider the role of agency in artefacts, which I discuss in the next section. At this point, it is firstly necessary to look in some more detail at the formal structures that characterize the processes in question. Kauffman refers to autocatalytic cycles here. Indeed, autocatalytic structures are centrepieces of most origin of life theories, while at the same time transcending the life/non-life distinction. Generalizations of the chemical model of autocatalytic cycle have been seminally suggested by Maynard Smith and Szathmáry (1995) or Ulanowicz (1997) as universal models of the biosphere or ecosystems, far beyond the fundamental level of biochemistry. Following early arguments by Padgett et al. (2003), this suggests a role of chemistry as a general model of technosphere science, in two senses: The first is to approach the technosphere as a network of components, which might be categorized into certain types (such as firms or countries, in correspondences to chemical substances), and which stay in certain regular kinds of interactions with each other, driving the generation of effects (‘production’). The second sense is that a central feature of these interactions are energetic transformations, and how certain patterns of interactions lower energetic thresholds (‘costs’) of the former. This points to the phenomenon of catalysis.

The model of autocatalysis refers to all kinds of interdependent processes in which products are generated that lower the thresholds for the reproduction of those processes, eventually resulting into a most simple mechanism of reproduction and growth, as in models of origin of life. As I will discuss in more detail below, the precondition is selective pressure of the environment, which induces competition over scarce resources (such as different substances in a chemical solution in which autocatalytic cycles might eventually consume all available inputs, relative to other possible kinds of reactions). Thus, we reach the important conclusion that autocatalytic structures imply directionality of change, hence teleonomic phenomena. This is the simplest sense in which we can speak of an ‘autonomous agent’, as the goal-oriented dynamic that appears like a manifestation of agency (‘design’) is just a teleonomic process. In this process, components emerge as having functions in reproducing the larger dynamic pattern.

I conclude that the abstract model of autocatalytic cycles can serve to substitute the intention- and design based concept of artefact by a more general concept that is based on teleonomy emerging from self-reinforcing and self-reproducing structures (for a related approach that also refers to an abstract notion of ‘catalyst’, see Romano 2009).

4. Distributed agency in the Technosphere

The discussion of autocatalysis raises one of the central questions of the ontology of the technosphere: What is the ontological status of the agent and agency in relation to artefacts? Here, recent developments in the social sciences become highly relevant that critically review their traditional notion of agency, and hence offer a huge potential for cross-disciplinary integration. I refer to schools of thought such as Actor-Network-Theory, among others, without necessarily endorsing all their specific assumptions (Latour 2005). But what is most productive in understanding the technosphere is the notion of ‘agencement’, which is the emergence of agency in networks among humans and artefacts (Callon 2008). In agencements, humans lose their primordial status as owners of agency, and artefacts themselves become at least co-carriers of agency. In more radical approaches, even the artefacts themselves obtain agency (Bennett 2010). Obviously, these ideas would provide ideal foundations for cross-disciplinary integration between the social sciences and the natural sciences, especially with engineering. Further support of this perspective is provided by recent developments in the cognitive sciences, which highlight the role of distributed cognition in defining the ‘mental’: Here, mind is conceived as being extended over networks of artefacts and social interactions mediated by them (Hutchins 1995; Clark 2011). This offers fascinating perspectives on the older tradition of ‘Geisteswissenschaften’ as established by Dilthey (1883) as a constituent part of technosphere science, since these included artefacts into their conception of ‘Geist’ (in the context of the pertinent Hegelian tradition, therefore ‘Geist’ is mostly not translated as ‘mind’, but ‘spirit’) (for a comprehensive treatment of these issues, see Herrmann-Pillath and Boldyrev 2014).

These ideas offer many perspectives on transcending the distinction between artefacts and biological entities. Going back to the example of the hammer, a hammer is co-constitutive of human agency in the sense that the hammer constitutes an ‘affordance’ (Gibson 1979; Herrmann-Pillath and Boldyrev 2014: 85ff), hence motivates certain actions on part of the user. Affordances constitute the agencement of the dyad of user and hammer. If we extend the scope of determinants, the specific use of the hammer is embedded in larger socio-economic systems. This leads us to consider the role of collective patterns in human agency (‘collective intentionality’, Schweikard and Schmidt 2013), which overcomes the conceptual limitations of individual agency in distinguishing between artefacts and biological entities. That means, many uses of artefacts are not directly determined by individual intentions, but by emergent forms of usages that evolve on the population level: On this level of cultural evolution, we cannot single out any specific expression of individual intentionality determining the usages (Hartley and Potts 2014). For example, the practices may be based on tacit knowledge or routines the actual function of which is not transparent to individuals.

If we combine this view with the abstract notion of autocatalytic structures, we can relate agency to the interplay of teleonomic processes and human intentionality, with agencements operating as causal linkages. That means, for example, that we observe autocatalytic dynamics of larger structures in the technosphere which would establish directionality of evolutionary trajectories, and which would interact with representations that guide human agency, hence human choice and action (an important case in point are evolutionary accounts of the Neolithic transition, see Rindos 1984; Gowdy and Krall 2016). As I will argue later, a major domain where this happens is the economy and its role in technological change.

In conclusion, a fundamental ontological notion of technosphere science is that agency is no longer exclusively assigned to humans, but to certain units in networks, often also denotated as ‘assemblages’ (DeLanda 2006). Thus, while reflecting upon agency, we have introduced another ontological concept essential for technosphere science, the notion of ‘network’, which can be regarded as a more precise term as just ‘system’. The concept is important because it allows for integrating the complete science of networks which bridges physics, biology and the social sciences (Newman 2010), and allows for referring to a very rich set of principles that govern the dynamic change of network structures across domains. Regarding technology, this suggests a further revision of the term ‘artefact’: Whereas the intuitive understanding is one of a ‘thing’, we can now speak of artefacts as networks that include different kinds of entities, which are in turn analysable as networks. For example, a hammer would not be a hammer, but a hammer and a human using a hammer in a specific context of social and physical interaction, such as cooperatively driving a mine into a mountain. The human can be further analysed into an organismic network tying up with external components, the social environment as a social network connecting humans with other humans, and the interaction with the mountain as a causal physical network mediated by the hammer. That means, even if we highlight the artefactual, we end up in a complex form of agency distributed across many ontological subdomains.

If we relate this with Kauffman’s concept, an autonomous agent would appear to be an assemblage with agency in the larger system in which it operates. In comparison with the social science notion of agency, this would add the physical notion of work and hence, reference to thermodynamics, which is rare in the former. The implications of this I will discuss below. At this point, suffice to state that in this inclusion of thermodynamics, we can finally end up with a synthesis between artefacts and biological entities in assigning agency to assemblages of artefacts, biological entities and human beings which process energy and information, hence 'autonomous agents'. However, in doing this we clearly reject the strongly individualistic notions of agency in the social sciences, and would argue that agency embodied in assemblages is a manifestation of human ultrasociality (Gowdy and Krall 2013). Ultimately, this raises the possibility that it is the technosphere itself which functions as one huge autonomous agent, in the sense of generating a flow of work that feeds into its own reproduction, and that operates along teleonomic principles (compare Garrett 2011).

5. Functions and human intentions

We can now return to the original foundational concepts of information and function. In the origin of life theories mentioned previously, information has the function to enable energetic transformations. This is a claim that I want to detail further: The concepts of information and function are deeply connected in technosphere science, thus providing the ultimate motivation for my non-anthropocentric approach. Both are powerful means to analyse human intentions and thereby achieve reduction by explanation.

Information is a pivotal term in modern science (Baeyer 2003, Hidalgo 2016). However, there is an imbalance between the quantitative uses of the term in general theory, which is the Shannon concept of information, and its practical applications in computer science on the one hand, and on the other hand the semantics of information (Floridi 2017). This is implicit in the Shannon framework with the distinction between sender and receiver. Whereas Shannon focused on the issue of channel capacity in communication systems, explicit reference to senders and receivers would highlight the semantics, or, the meaning of information.

In this paper, there is no space to discuss the intricacies of these distinctions (motivated by Deacon 2010). But what is crucial is that genuine semantics mostly tends to be understood in anthropocentric terms, because the notions of sender and receiver would commonly refer to a human sender who intends a meaning of a certain communication, and a receiver who interprets that communication. This relationship can become indirect when the human is a designer of information and communication technology, but remains valid. What is transferred is information, which is coded and decoded, with decoding reconstructing the original meaning, hence the intention of the message. However, in modern approaches to the semantics of information, this view has been radically transformed in a way that revives much earlier ideas of semiotics as established by Charles S. Peirce (for an overview, see Short 2007). This is the tradition that seems most productive for grounding the notion of information in technosphere science. Semiotics establishes a more complex idea of causality undergirding the flow and processing of information, which is triadic, hence combining an efficient-causal connection between sender and receiver with a semiotic relationship, in which the efficient-causal process is mediated and enabled by a sign. Information as embodied in signs stands for something and is for something, hence is always functional, or, in Aristotelian terms, adds final causality to an explanation of phenomena. In case of both information and function, we ask the 'why' and 'what for' question.

Thus, the simple point is that information is always 'about' something, and relative to an observer for whom that information is relevant for realizing certain functions. In semiotics, information is the sign that represents an object, but that representation does not stand alone and only becomes relevant in terms of interpretations of the sign. These interpretations are not mental phenomena, but are the actions or events triggered by receiving the sign aka the information. In other words, in answering the 'what for' question, we do not need to refer to intentions. In modern semantics, this view corresponds to the so-called 'teleosemantics' approach (MacDonald and Papineau 2006; Millikan 2009). The upshot is that meaning becomes independent from any kind of intention that would be expressed by a sender, but refers only to the interpretations qua actions of the receiver, and which, in a process of communication, feedback on the actions of the sender. This is the approach also taken by biosemiotics (Vehkavaara 2002; Salthe 2007), and which matches with modern approaches in the post-Wittgensteinian philosophy of language which claim that meaning is action and practices, hence not a mental category, and that it emerges on the level of communities or populations of interacting agents. Thus, the meaning of a human utterance does not lie in the intention of the speaker, but in the reaction of the listener, which, in turn, ties up with further reactions by the speaker, constituting a certain pattern of practices. The direct conclusion is that we can apply the category of meaning to all kinds of systems in which information flows, such as technological systems, thus working with a non-anthropomorphic conception of meaning, which tears down the borderline between the human domain of meaning, only accessible to specific approaches such as hermeneutics, and the physical world (Aunger 2003).

This brief discussion may appear as a side-line, but in fact leads us to the core of the ontological issues of the technosphere. If meaning is the action caused by the information, what is the deeper relationship between the two? Information is meaningful for the receiver, if it enables the realization of a function that the receiver realizes in a larger network of interactions that is also a precondition for the action of the receiver. That means, the semiotic approach unifies the two categories of meaning and function. This is essential for bridging the cross-disciplinary gap between engineering and the social sciences. In the engineering approach, technological artefacts, by definition, fulfil a function. This function is normally conceived as being defined by human intentions, thus anthropomorphising technology. In fact, however, most artefacts serve a function in the context of networks of artefacts, thus often relegating human purposes to higher-level functions of entire technological systems, such as energy production and distribution systems. But if we move to this higher level, the question how far functions are effectively determined by human intentions, becomes difficult to assess, beyond superficial generalities.

This transpires already if we consider the observation in studies about engineering which define engineering as finding solutions to problems that are defined by technology (Petroski 1994, 1996; Arthur 2009). Although eventually the goals of engineering might be defined by human intentions, most everyday work is guided by certain technological challenges that need to be overcome by engineering. That would imply that the function of an artefact is defined in a network of artefacts, at least on proximate terms, and that human intentions serve to realize that function. There are now two ways how this way of thinking may ultimately result into rendering human intentions obsolete as a category in understanding the technosphere:

- The first is the question what is the role of humans in networks that generate agencements: In the sense of a dualism, we might switch roles and ask for the function that humans have in realizing functions defined by technology. This is a position that comes close to technological determinism along the lines of thinkers such as Jacques Ellul. Engineers would not impose human purpose on technology, but technology would impose functions on engineers. The function of a human in automotive technology is reproducing automotive technology.
- The second is to ask for the functions that human purposes have. On first sight, the previous idea implies that possibly even users of cars would have the function to reproduce automotive technology. However, we can also extend the perspectives to biology, and hence go back to the basic similarities between the abstract models of energy and information in origin of life theories and technology. In this case, human

purposes would fulfil biological functions, which are not in turn determined by human intentions.

The second observation is especially important in the context of economics. Economics concurs with common conceptions of engineering in believing that the economy ultimately serves human purposes, more specifically, human consumption. In its very conceptual foundations, these purposes are just left undefined, in the domain of human subjectivity. This is a fundamental and extremely important ontological assumption which can be traced back to the Enlightenment and, specifically, Kant's idea that the essence of humanity is to be a purpose of itself. In this tradition, economics is based on the ideas of absolute freedom of the individual, which implies that the purpose of the economy is human welfare.

In technosphere science, we need to eschew this position, and we ask for the biological function that human consumption has (following lines of thinking as suggested by Saad 2007). Then, we can give a different meaning to the options, because the second would state that human consumption is a biological phenomenon, with technology serving functions that are defined in the biosphere, such as enabling the material reproduction of complex human societies. However, we might then pose the question what the implications are of the observation that the technosphere is now encompassing the biosphere: Does that imply that biological functions are also technologically defined? The economy obtains a different role here, namely the role of mediating the reproduction of the technosphere via subordinating human intentions to fulfilling technosphere functions. This happens via the effects of competition: For example, managers in automotive industries pursue the goal of selling as many cars as possible, and maintain and expand the competitiveness of cars in the marketplace. For doing this, they also use many managerial approaches to create the corresponding wants of users, also indirectly by shaping the larger environment of user choices (such as lobbying for more highways) so that demand for cars is stabilized or expanded. In sum, we can argue that the economy is a major medium of how human intentions are shaped as fulfilling technosphere functions.

This approach of reducing human intentions to functions in the technosphere needs to be grounded in a generalization of evolutionary theory: In place of human intentions underlying the design of technology, we would refer to a context of selection which determines the 'what for' of a function. Selection is also the force that causes the emergence of meaningful information enabling the function.

6. Evolution as unifying ontological framework of technosphere science

The analysis of functions leads to the conclusion that the unifying theoretical framework for analysing the biosphere and the technosphere is evolutionary theory. If the technosphere integrates the biosphere, however, we need to substitute the biological theory of evolution by a more general theory that applies for various kinds of entities. In many recent debates about extending the theory of evolution, the conceptual structure of Darwinism or, better, the Neo-Darwinian synthesis, was accepted. This would lead us to consider conceptual generalizations of central terms such as genotype and phenotype (such as the replicator-interactor duality, Hull et al. 2001; Wilkins and Hull 2014). I think that this can be moved to a secondary level in our ontological considerations, if we switch the perspective from the biosphere to the technosphere, and build on our discussion of functions.

Then, using the unifying concept of an autonomous agent that includes human agency, there are promising candidates of versions of evolutionary theory that allow for integration (for cross-disciplinary surveys, see Jablonka and Lamb 2006; Hodgson and Knudsen 2010; Mesoudi 2011). They build on a generalized notion of selection and heredity and strictly interpret evolution as a statistical phenomenon in which certain statistical distributions of properties are correlated through time (heredity), and where we can identify selective mechanisms that explain these correlations (a cornerstone is Price's theory of selection, see Helanterä and Uller 2011; Frank 2012). The theory of evolution would not only include genetic transmitted variation, but also non-genetic transmitted variation (Danchin et al. 2011). There are many ways how we can conceive of the latter. One is niche construction theory which assumes that there is transmission of variety via the ecological environment that is partly constructed by a population of organisms (Odling Smee et al. 2003). In this view, human technology is a form of niche construction, which supports a range of other adaptations to that niche which feedback on its reproduction. One of the central examples in human phylogeny is the domestication of fire, which may be regarded as one of the primordial technologies of the human species: It caused many and far-reaching bodily adaptations to that modified niche, which ultimately imply that fire and cooking became a biological feature of humans, yet there is no genetic adaptation explaining and reproducing the use of fire, which retains its nature as a cultural innovation that is transmitted via non-genetic channels (Ofek 2001, Wrangham and Conklin-Brittain 2003). There are good reasons to assume that culturally transmitted niches in the technosphere exert autonomous effects on human biological adaptation, even genetically transmitted (Richerson et al. 2010).

I cannot go into further details here, but just state that technosphere science would therefore be grounded in a generalized theory of evolution that includes both biological and cultural evolution, and posits a co-evolutionary framework for analysing the interaction between the biosphere and the technosphere (Donges et al. 2017). One important implication is that we would no longer approach technology as a phenomenon subject to human design and purpose.

There have been many proposals how to analyse the evolution of technology as following an evolutionary dynamic of its own (for a seminal collection of views, see Ziman 2000). This does not imply that human intentions do not play a role, but they are reduced to intermediary causal variables. If we keep with the general structure of evolutionary theory as distinguishing between variation, selection and retention, human intentions would just be one source of variation. This is evident if we consider the simple fact that technology as a system cannot be overviewed and understood in all detail by any human individual or group: This implies that human design is always based on incomplete knowledge of the consequences of any technological innovation. By implication, viewed from the systemic perspective, human choices will always be dysfunctional, or errors, and in this sense conceptually equivalent to random variations (following Campbell's 1974 seminal insights).

In fact, this view is even implicit in research about single inventions. Even on the individual level, inventions mostly go back on a long process of tinkering and bricolage, until the unifying scheme suddenly emerges from that process. Following such 'heroic' stages, innovations diffuse and further evolve on the population level, with a complex interplay of producer and user practices, which operate as selective forces. If we look at this process from the side of technology, it means that human actions operate as triggers for the evolutionary self-organization of technology.

That idea that technology is self-organizing has been ventilated by many authors, with diverging evaluations. The point is easily established if we adopt the network view on technology (Arthur 2009). Then, we conceive of technology as a complex evolving network of humans and artefacts, in which certain entities are combined in producing a certain phenomenon. This opens up a huge and exponentially growing space of adjacent possibilities for new combinations that create new phenomena. However, this huge space of opportunities is determined by the existing state of technology, and not by human design or imagination. Therefore, the process of recombination creates many dynamic phenomena, such as path-dependencies or lock-in effects, which constrain and channel the range of human choices, and impose a directionality of technological evolution which is determined by technology itself. These phenomena are well-researched in the context of Evolutionary Economics, which therefore is an important part of technosphere science (Metcalfe 1998; Witt 2008).

The self-organization of technology is mediated by human action via different mechanisms; as argued, one most important is that technological innovation is mainly driven by solving problems that are created by technology, thus subordinating human intentions to the conditions and demands of a certain technological niche in the evolving network of technology. Even if human design guides the process, another mechanism is the endogeneity of wants that are expressed by humans (Witt 2000). Technological possibilities create the wants that proximately drive technological evolution, and the realization of wants is channelled via the economy. Yet, in most research on technology, the economy is strangely absent. However, if we look at the driving societal forces of technological change, we can safely say that the two leading forces are the economy and the military, with religion coming next (such as in architecture). I think that the dominant force is the economy and limit my discussion on this.

Economic processes are the most important channel by which human wants are endogenously created and impact on technology, and by which constraints on the evolution of the technology space are expressed in human action. Therefore, the economy must be conceived as a constitutive and even central part of the technosphere. Simply relating human intention with technology is misleading because it overlooks the fact that intentions are being shaped by an evolutionary dynamic in the economy, which is itself only partly governed by human intentions: most economists approach the market as a complex system that generates the information which enables human intentions, but cannot be subject to human design and control (for a most influential view, see Hayek 1973). However, evolutionary forces in the economy differ from evolutionary forces in technology because the intervening parameters which determine the selective processes are socially constructed, such as prices and interest rates. This is most salient when considering a core phenomenon in the current evolution of the Earth system, global warming, where prices governing decisions about energy usage inadequately reflect the externalities caused by it, and interest rates insufficiently internalize future effects of current decisions. However, the fundamental problem is that there is no objective criterion how to connect valuations across the different domains of the biosphere and the technosphere (Pyndick 2013; Goldberg and Garver 2016). This means that there is a fundamental uncertainty about any kind of human technological choice that is taken in the economy, including external political interventions, such as regarding alternative approaches to engine design. In the economic context, this is reflected in the emphasis on entrepreneurship, which, in the evolutionary view, is a major aspect of variation in the larger scheme of variation, selection and retention.

The difficulties of constructing a universal standard for valuation in the technosphere crystallize in the debates over GDP as an appropriate measure for assessing the performance of the economy, or, in our context, even the evolutionary status of the technosphere. GDP is a manifestation of the anthropocentric nature of the economy, as it is conceived as expressing the market valuation of economic productivity, ultimately reflecting consumer preferences as expressed by monetary demand (Stiglitz et al. 2008). In this sense, if we judged technosphere evolution according to GDP, we would strictly apply an anthropocentric measure. As has been well established in the decades-long controversies about GDP, one can even question whether GDP is the right anthropocentric measure (alternatives include ‘happiness’ indices, see Helliwell et al. 2017), but certainly must accept that GDP in no way reflects the status of the technosphere as including the biosphere, and hence the entire status of the Earth’s ecosystems (Kubiszewski et al. 2013). That means, even though the economy is the centrepiece of the technosphere, as far has the endogenization of human action is concerned, we cannot apply economic categories in evaluating technosphere evolution.

7. Are there universal laws of technosphere evolution?

The analysis of the economy raises one most principled question about the technosphere: Can we identify any kind of empirical regularities or even laws that apply across all domains, and that can be used independently from reference to human intentions for explain technosphere evolution? I think that we already know many regularities and law-like hypotheses which we can put at the centre of technosphere science, and which have been discovered in neighbouring disciplines.

I have already mentioned all hypotheses that have been established by network analysis, and which only presuppose the empirical identification of certain structural characteristics of an empirical network in question. For example, we have the analytical tool of power laws at hand (Newman 2006; Gabaix 2016). Power laws have been neglected by economists until most recently, although there are important areas where their central significance has been established early, such as in Economic Geography, especially the evolution of cities (Krugman

1996). Clearly, since urban agglomerations are an essential feature of the technosphere, and may even count as autonomous agents, power laws governing urbanization would emerge as a specific set of hypotheses in technosphere science. Urban agglomerations are also the empirical reference for applying network regularities that have been established in analysing metabolism (Bettencourt et al. 2007, Bettencourt 2013). These relate to economic conceptions such as returns to scale, and are another expression of power laws, mostly specified as allometric scaling laws.

As I have said, in all these generalizations the empirical application rests upon the proper identification of the network properties. However, we can also make some general ontological commitments and characterize systems in the technosphere, or even the technosphere itself, according to certain most universal distinctions among types of systems. There are different characterizations available, such as distinguishing between open and closed systems in the thermodynamic sense, or between linear and non-linear dynamics regarding the formal characteristics of causal processes operating in the technosphere. I argue that there are abstract arguments which would lead us to express an ontological commitment to a specific kind of system. Based on this commitment, we can immediately draw on a pool of more specific hypotheses that commonly apply for that type of system cross-disciplinary.

My commitment is that the technosphere is an open, non-linear non-equilibrium system, and that this property is shared by the biosphere and the technosphere, and applies for the Earth system in general. This is based on the simple observation that these systems are thermodynamically open because they feed on external inflows of solar energy, which also directly explains that they are non-equilibrium systems (Kleidon 2016). The assumption of non-linearity is reasonable because complex systems normally contain many feedback circuits and interdependencies with these properties. From these general characteristics, many more specific formal hypotheses can be deduced that could be checked empirically regarding the specific parameters and causal factors. This is no longer part of my ontological considerations. However, it is important noticing that those general features also apply for the different subsystems: Ecological systems can be described along these lines, as well as the human economy, even though their constituent units only partly overlap (such as in agriculture).

In my view, this fundamental ontological characterization has one single, but most essential theoretical implication, which, however, has a direct empirical consequence, if we connect this discussion with the previous one about the status of evolutionary theory. The question is whether we can make more fundamental assumptions about the dynamic of evolution: This must build on physical principles, because only these can apply for both biological systems and technology. I suggest that this is Lotka's Maximum Power principle (Lotka 1922a, b), which ties up with Maximum Entropy Production Principle in recent studies of the Earth system (Kleidon 2011; for a recent collection of papers, see Dewar et al. 2014). I claim that a unifying concept for both the biosphere, the technosphere in the sense of technology, and the economy, is 'maximum power'. One way to arrive at that conclusion is to argue that open, non-linear non-equilibrium systems would follow the Maximum Entropy Production Principle, which means that they realize trajectories of structural change that result in new states which export higher amounts of entropy to the system environment (Sciubba 2011). Through time, and drawing appropriate system boundaries, that would reflect a tendency to maximize entropy production. In other words, the general thermodynamic argument involving the Second Law would not refer to the evolutionary process per se (which, for a closed system, would predict dissolution of order and complexity), but to the system-environment conjunction.

Looking at living systems, Lotka's Maximum Power principle specifies the intermediary causal mechanism that highlights the tendency of natural selection to create structural patterns (organisms, demes etc.) that maximize throughput of energy, which ultimately would be transformed into useless energy, hence entropy production. There are similar conclusions that can be drawn from analysing the network dynamic of flow systems (this is the 'Constructal Law' as suggested by Bejan and Llorente 2010, 2013). Or, we can refer to more general considerations about power production as an evolutionary force in the biosphere (Vermeij 2004). The Maximum Power Principle has also been elaborated in the context of Ecological Economics (Odum 2008).

Thus, based on the general ontological characterization of the technosphere as a system, I posit that the evolution of the technosphere manifests Maximum Power and Maximum Entropy Production. This has important implications for our understanding of the role of the economy in the technosphere, because it also implies that the economy maximizes power throughput, hence energy flows. This can at the same time explain why the economy grows, even in terms of GDP growth, but certainly in terms of growth of matter-energy throughputs (such that, for example, population growth would also be a form of economic growth) and of the growth of structural embodiments ('capital formation' in economic terms) (Ayres and Warr 2009, Kümmel 2013). Therefore, in the end we can explain the growth of the technosphere and the transition to the Anthropocene. Indeed, the two crucial transitions in human cultural and economic evolution clearly go back on radical and comprehensive breakthroughs in mobilizing energetic throughputs, the Neolithic transition to agriculture and the Industrial Revolution and its mobilization of the carbon economy (Smil 2003; Gowdy and Krall 2013). This vindicates earlier views on energy as central feature of human civilization, which includes even the cultural sphere (Bataillie 1949; White 1949). Indeed, we can also refer the notion of maximizing energetic throughputs to recent sociological theorizing about the secular 'acceleration' of modern societies (Rosa 2010).

This allows for completing the retreat from anthropocentrism even in the context of the economy, as we would now state that economic growth does not have the function to enhance the potential for the fulfilment of economic wants, but is a manifestation of Maximum Power and hence fulfils this function. A complete argument would have to show that the mechanisms in the economy (such as competition, or the transition to capitalism as an institutional form) enhance the potential for realizing Maximum Power (Herrmann-Pillath 2013; Haff 2014a).

The final step in my treatment of basic ontological features of the technosphere is to relate Maximum Power with information, As I have stated previously, the relationship between energy and information is implied in the concept of autonomous agent and the notion of work. Indeed, energetic theories of economic growth focus less on energy per se, but the generation of useful work, which is also close to the ideas of Maximum Power (Ayres and Warr 2009). Thus, we can state another general ontological hypothesis, namely that the technosphere manifests the accumulation of embodied information via the maximization of energetic throughputs (Hidalgo 2016).

This is an idea that has been pursued in recent work on 'big history'. Big history research can be regarded as an important part of technosphere science, because it aims at highlighting evolutionary tendencies that bridge different ontological domains, reaching back from human culture to life and even cosmological evolution (Aunger 2007). One central indicator is the 'free energy rate density' which measures the energy throughput per time and space (Chaisson 2001, 2015). The entities with the highest density are those ones with the highest informational complexity and highest capacity for processing information. This is the most concentrated expression of the fact that in general evolution, energy flows and information flows are physically and hence, ontologically related. The deeper physical basis for this is provided by Landauer's principle which quantifies the thermodynamic costs of information processing (Faist et al. 2015).

As I have argued elsewhere (Herrmann-Pillath 2014, 2016), this ontological proposition has many implications for analysing the interaction between the economy and the technosphere, especially in the future, when information technology becomes the central material and infrastructural component of the economy. Whereas many views assume that ITC can help to decouple energy throughput and economic growth, technosphere science would predict strong positive feedbacks ('rebound effects', 'backfire') between growth, digitalization and energy flows.

8. In lieu of conclusion: Human autonomy in the technosphere

I have tried to present the case for an independent science of the technosphere, which pulls together many contributions across different disciplines, reaching from the sciences to the humanities. The rationale for this endeavour is that the technosphere as the defining feature of the Anthropocene is, in the famous expression by F.A. von Hayek when referring to the economy, a product of 'human action, but not of human design'. This requires the resolute rejection of any form of anthropocentric reasoning in analysing the technosphere. This is possible if we adopt a universal theory of evolution that can bridge the biosphere and the technosphere.

Yet, understanding human action remains a central task of technosphere science. However, this requires a radical rethinking of fundamental notions of human agency that have dominated humanities and social sciences since the enlightenment. The ground has been prepared by the recent surge of 'new materialism' in the humanities. These suggest a non-anthropocentric view of agency as being inextricably tied up with human bodies, but emerging in complex networks in which these bodies are physically connected with other entities, especially artefacts created by human action.

However, this view can also avoid the pitfalls of technological determinism: The mirror image of anthropocentrism is the idea that technology is a system that is ontologically separate from humans, thus falling into the same ontological misconception as when dealing with 'nature' as being independent from human action (this is the famous 'dialectics of enlightenment', see Horkheimer and Adorno 1947). My view follows recent interactionist ontologies (such as Barad's 2007) in arguing that agency is always and necessarily emerging from interactions between different constituents of the technosphere, including the biosphere. This has far-reaching implications for approaching the economy as a centrepiece of the technosphere: The economy is the domain where functions of the technosphere are realized via human action. The economy is not seen as being subordinate to human design and human needs and wants, but is the evolved medium which ties up the biosphere and technology. In sharp contrast to the self-image of economics, I argue that economics should not be based on the ontological assumption of individualism, but is the domain where distributed agency in the technosphere is mediated.

That leaves open the question where we human beings stand in terms of our conceptions of ourselves. I think that refuting the anthropocentric view of the technosphere does not imply that we lose our dignity and autonomy as human beings. In fact, we could even argue that the idea of freedom and morality is a necessary component of technosphere evolution, and hence is fulfilling a central function in the technosphere (this argument is anticipated by Sommers 2007). In this view, human intentionality would be conceived as an evolutionary innovation by which evolution could overcome the short-sightedness of biological mechanisms of endogenous goal-formation (continuing on an argument suggested by Dennett 1995). The central phenomenon is reflexivity in information processing. There is large group of phenomena, such as anticipating long-term effects of actions in complex systems of interaction biological entities, where reflexivity and consciousness create distinct advantages for enhancing adaptive performance and evolutionary potential. Today, this is the accepted evolutionary explanation of the emergence of human forms of thinking, and, more specifically, human language and symbol processing (Tomasello 2008).

Therefore, my hunch is that we can combine the emphasis on a distinct humanity with a non-anthropocentric conception of the technosphere. In a nutshell, this would go back to the Kantian argument in favour of freedom and rationality: Our human autonomy can only be constituted by setting the law which governs ourselves in a rational and responsible way (Kant 1788). It is straightforward to extend Kant's Categorical Imperative here: We only need to broaden the reach of its application, hence the scope of the universal laws, beyond the boundaries of humans and human society. This has been even anticipated in one formulation of the Imperative as coined by Kant himself: "Act as if the maxims of your action were to become through your will a universal law of nature." That means, we can extend beyond humanity in referring the Imperative to a general idea of ecological community, and even Earth system community of entities (compare Brown 2016, among many others). This is of highest significance for designing the economy: By means of institutional design of the economy, we can indeed set up 'laws of nature', that is, regularities which govern complex agency in the technosphere. In more practical sense, this means that we would subject the economy to an Earth system ethics, by which we check every institutional design by the Categorical Imperative. For example, current economic thinking is based on unlimited growth of wants, reflecting common conceptions of human freedom and imagination. In terms of the Categorical Imperative, unlimited growth of wants cannot become a universal law of the technosphere which includes all living beings.

That raises an intriguing thought: As I have argued, technosphere evolution is governed by the Maximum Power Principle: In this perspective, unlimited growth of human wants has a function in realizing this law of nature. But the Categorical Imperative would stay in conflict with this law of nature. This where another famous principle established by a German Idealist comes into play, namely the notion of 'Second Nature' by Hegel. We could conceive of the technosphere as our Second Nature, in which human autonomy is essential to establish new Laws of Nature, in our example the ethical prescription to contain the growth of human wants, and hence contain the workings of Maximum Power, which is not just in our own interest, but a necessary condition for sustainability of the Earth System and the biosphere.

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