SPECIAL FEATURE: INTRODUCTION

Industrial Ecology: The role of manufactured capital in sustainability

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In 1992 PNAS presented a Special Feature with 22 contributions from a colloquium entitled "Industrial Ecology," held at the National Academy of Sciences of the United States in Washington, DC (1). In these articles Industrial Ecology was presented as an approach to understand and ultimately optimize the total material cycles of industrial processes (2).

This PNAS issue presents the second Special Feature on Industrial Ecology, offering the opportunity to reflect on the original goals and approaches and to compare them with Industrial Ecology's achievements and its pertinent role within sustainability science.

The motivation to promote a new field as originally expressed in the contributions of the 1992 Special Feature is soberingly topical (3, 4): (*i*) the recognition that human alterations of the Earth System are progressing at an unprecedented pace; (*ii*) the insight that humankind has become a planetary force; and (*iii*) advocacy for a real-world sustainability transition that would be as fundamental as the industrial revolution of the 18th century.

Since the first Special Feature in 1992, the pace of growth in global greenhouse gas emissions, material use, and energy use has not slowed down or stopped, but rather has accelerated, especially after the year 2000 (5–7). Human-induced alterations of the Earth System have reached such a scale (8, 9) that a new term for the current geological epoch, the Anthropocene, was proposed (10). Climate-sensitive tipping elements of the Earth System have been detected and described (11). Those tipping elements (such as the Indian monsoon, the Amazon rainforest, or the Greenland Ice Sheet) have been stable since the beginning of the Holocene but have the potential to irreversibly flip into fundamentally different regimes once triggered by a global mean temperature above certain thresholds. Some of those thresholds appear to be within the reach of current climate-change pathways (12). Advocacy for a sustainability transition has increased in parallel, and the technological and economic feasibility for such a transition has been demonstrated, especially for the energy system (13, 14).

How did Industrial Ecology originally define its scope in what we now call sustainability science and what is its role today? If there is one compelling motif apparent in virtually every paper of the 1992 Special Feature, it is a concentration on the physical basis of industrial societies as the analytical end point. This focus still persists, but its scientific justification, which engendered lively discussions in 1992, has changed significantly.

One original line of reasoning stressed the need to overcome the dominant paradigm of pollution control in the 1970s and 1980s, which focused on technical end-of-pipe fixes, and treated use of natural resources (water, energy, biomass, metals, and minerals) and disposal of wastes and pollutants to environmental media (such as air, water, and soil) as separate subjects. The concept of industrial metabolism—that is, a holistic approach of quantifying the flows of materials and energy into and out of society (15, 16)—has since then been instrumental in developing an increasingly detailed and quantitative understanding of the life cycle of materials.

The specific Industrial Ecology approaches toward transforming the industrial metabolism to reduce its environmental impacts and the pressure on resources while maintaining its function for human well-being are still pretty much in place: enabling a circular materials flow economy, the importance of product design in recycling, the use of nontoxic materials, the mimicry of ecological systems, and decoupling economic growth from resource use, all of which were already proposed in 1992. With a few exceptions, however, the presentations in 1992 were largely devoid of data, whereas in today's Industrial Ecology data abound, and analysis and interpretations are becoming central.

The lack of quantitative results over two decades ago was paralleled by a compelling underrepresentation of methodological suggestions. Among the few exceptions in those early papers were Ayres' material flow analysis of toxic heavy metals (17) and Duchin's proposal to use economic input-output analysis (18) to describe and analyze the metabolic connectedness among physical factors of production, industrial production, and consumptions sectors. Those two approaches have developed into core methods of Industrial Ecology today (6, 19–25). The research articles included in the present Special Feature provide ample evidence for Industrial Ecology's success in applying and further developing these methods and in quantifying the industrial metabolism for different industrial processes and across different scales in many of its ramifications.

In hindsight, it is also compelling to see that although the methods and the empirical basis had been so much more limited, the expressed range of Industrial Ecology goals and topics was much broader 20 y ago than it is today. This reflects the increasing specialization in sustainability science that has occurred since that time.

Although a direct confrontation between economists' claim that, given the appropriate price signals, the market economy will efficiently "squeeze the maximum human satisfaction out of the limited human and natural resources" (26) and the physicists' approach that "long-term ecological sustainability is incompatible with an open materials cycle" (17) has become almost absent in Industrial Ecology, the original ambition to reconcile the fragmented goals diverting physical and economic rationales has shifted to two related avenues.

One avenue is the pragmatic cooperation between academia and industry jointly seeking ways to simultaneously reduce economic costs and metabolic throughput, such as in research on eco-symbiosis (27), waste management and recycling (28–30), criticality of

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metals (31–33), or the long-term stock and flow dynamics of basic industrial commodities (22, 34). The second avenue is to further develop a theoretical concept to describe, quantify, and eventually simulate the physical economy, thereby providing a solid, quantitative description of the interface mediating the coevolution between social and environmental change (35–37).

Some topics from the 1992 Special Feature deserve our attention, not because they quickly became part of the Industrial Ecology mainstream but because they anticipated decisive research avenues that are only now coming to the forefront. The ambition that Industrial Ecology research would focus on the future has not quickly materialized, although scenarios of the future have become more dominant in recent years (34, 38). It seems that the founding generation severely underestimated the existing lack of knowledge and the difficulties of establishing reliable datasets of historical socio-metabolic trajectories to define plausible scenario restrictions.

The analysis of carbon and energy efficiency as presented by Ausubel (39) and Ross (40) is still the subject of study in large specialized fields. The interesting aspect is that those two papers hinted at the possibility of linking the analysis of carbon and energy use more directly to the use of materials. The recent Industrial Ecology literature, including this Special Feature, demonstrates how Industrial Ecology helped to create new insights into de-carbonization and energy efficiency potentials by finding new ways to analyze carbon emissions and energy use in its causal relation to the dynamic of the material industrial metabolism (22, 34, 41–44) and to economic growth (45).

Finally, we ask which currently important topics were underrepresented or even neglected in 1992. There are a few: urbanization and the role of urban areas in the industrial metabolism (46–49); the increasing role of trade in allocating metabolic flows associated with production and consumption to national economies or other spatial units and in creating new responsibilities for environmental damage and supply risks (43, 50, 51); the systemic linkages between material, energy, water, and land use (52); energy as a factor of production (45); the scale of the global metabolic transition created by rapid industrialization (53–55); the increasing reliance of the industrial production system on almost all elements of the periodic table (56); the changing importance of land and biomass for the social metabolism (57–61); and the role of energy and the built environment in providing human welfare and at the same time causing human-induced environmental change at a planetary scale (34, 62, 63).

The Role of Manufactured Capital for Sustainability

In recognition of the fundamental importance of ecosystem services for human well-being, sustainability science has accumulated a large body of work on natural and human capital and their interrelations (64). Most interactions between natural and human capital are not direct, however, but are mediated by manufactured capital in the form of industrial production facilities, communication devices, and extensively built infrastructure. This aspect has thus far received relatively little attention in sustainability science. The manufactured capital is the entire physical man-made stock, produced and reproduced by society. It comprises buildings, transport, energy, water, and waste infrastructure, industrial production facilities, and all durable production and consumer goods, such as machinery, cars, airplanes, or computers. Reproducing the manufactured capital requires a socially organized continuous flow of material and energy from and to the environment that collectively defines the industrial metabolism.

Transforming the industrial metabolism to reduce its environmental and resource impacts, while maintaining its function for human well-being, is the crucial challenge for sustainability. Meeting this challenge requires a degree of understanding of key interactions among human, natural, and manufactured capital (Fig. 1) and their implications for sustainability. On the one hand, manufactured capital provides essential goods, services, and shelter for human well-being. In doing so it consumes natural resources and induces anthropogenic environmental change, such as climate change and habitat loss. This, in turn, necessitates changes in human, natural, and manufactured capital and their interactions. Examples are the rapid growth in renewable energy infrastructure to cope with climate change, the increasing possibility of failures in material supply chains, and a surge in the speed of human communication as a consequence of modern technology. Driven by these developments, manufactured capital has undergone unprecedented changes in both its structure and scale during the last decades.

At this point it is important to note that manufactured capital is much more than simply a conduit: causally connected to the

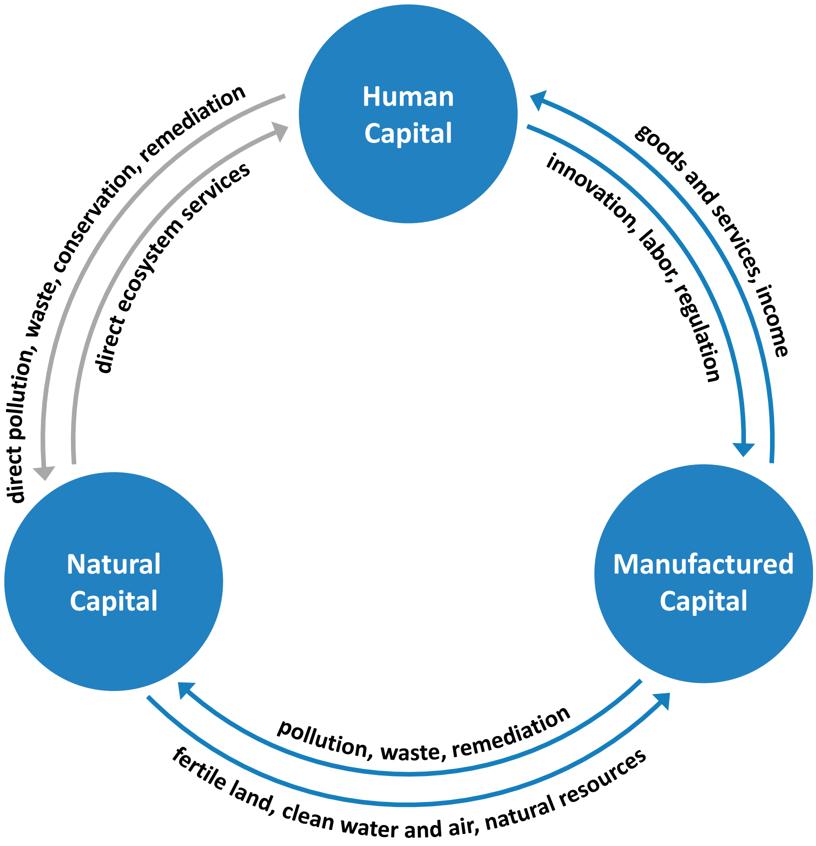

Fig. 1. Interactions between human, natural, and manufactured capital.

massive use of fossil fuels, the existing manufactured capital is the engine that enabled humans to transform the natural environment at an unprecedented scale and speed (65, 66). The capability to produce and reproduce the manufactured capital reflects the ability of modern societies to mobilize and transform materials and energy at that massive scale. Associated with this is the dividend of bringing millions of people out of poverty, increasing material standards of living, and extending individual life. It is also important to realize that manufactured goods, such as agricultural and mining machineries, mechanically cultivated agricultural products, and mined ores require and foster each other to keep this societal machine going. Such a coevolution of manufactured capital and the complexity of the interactions among its components are a defining property of the industrial metabolism that has enabled the unprecedented rate of human transformation to occur, and has changed the face of Earth.

In this Special Feature we highlight ways in which Industrial Ecology developed into a frontier science to understand the systemic mechanisms that created and sustained the manufactured capital, a precondition to identifying feasible intervention points for a sustainability transition. The six research articles that constitute this Special Feature were selected to demonstrate recent achievements in Industrial Ecology that go beyond single case studies. All articles quantitatively address fundamental problems of global importance, using established, advanced, or new Industrial Ecology methods. The articles are organized into three larger topics, with each representing cutting edge achievements in newly framing and answering salient questions regarding the role of manufactured capital for sustainability.

The Evolution of Material Use and Manufactured Capital. In the 20th century, especially after World War II, two developments significantly changed anthropogenic material use: a boost in size and a transformation of the composition of the manufactured capital, as well as the globalization of material supply chains (67, 68). Both developments contributed significantly to human well-being but also changed the spatial and temporal patterns as well as the scale of the associated environmental pressures. The two opening articles present detailed accounts of the composition and evolution of in-use stocks in the United States, and of the role of global supply chains in providing raw materials to national economies.

Manufactured capital is expressed in the form of products capable of providing services that are desired: mobility, communication, cooking, shelter, and so forth. Unlike financial capital or materials use, however, information on product stocks over time is widely scattered and has been regarded as of uncertain integrity. By drawing on very diverse and extensive sources of information, Chen and Graedel (69) have examined the histories of more than 100 product stocks in the United States. The authors note instances of product saturation or substitution, and present a product-based argument for a "fifth Kondratieff wave" based on telecommunications and information technology (69).

National material efficiency policies rely on adequate metrics. Wiedmann et al. (51) argue that governments overestimate material productivity gains in developed countries because the metrics they use do not take into account the raw materials embodied in traded goods. The authors propose a new metric: the "material footprint." This indicator allocates all raw materials used in the global production of goods and services to the domestic final consumption in each country. Wiedmann et al. calculated the material footprint of 187 countries over 20 y using a multiregional input-output model of the world economy in high resolution, complemented by a detailed database of material flows. Their results demonstrate that the reported material productivity gains in Organization for Economic Co-operation and Development countries over the past two decades completely disappear when material productivity is measured as material footprint per gross domestic product. China had by far the largest absolute material footprint in 2008 (16.3 Gt) followed by the United States, Japan, and India, with material footprints amounting to half (United States) or one-fourth (Japan and India) of China's. Australia has the largest material footprint per capita (35 t/cap), but other high-income countries have comparably high per capita material footprints. Wiedmann et al. conclude that overall material use does not decline when countries get wealthier, and that material-efficiency policies should be informed by indicators, such as the material footprint, that take into account the increasing spatial separation of production and consumption.

Links Between Manufactured Capital and Climate Change Mitigation. The recently released fifth Assessment Report of the Intergovernmental Panel on Climate Change (70) revealed that a number of fundamental questions regarding the link between components of manufactured capital and climate change mitigation are still insufficiently understood. Such questions are addressed in the next two articles.

A global transition to a low-carbon electricity system is a crucial element to effectively mitigate climate change. Its implementation will require a large-scale restructuring of the global energy infrastructure. Hertwich et al. have investigated the amount of materials used and emissions generated by a global implementation of a low-carbon electricity generation infrastructure (38). They base their analysis on two energy scenarios provided by the International Energy Agency: a climate-change-mitigation scenario and a business-as-usual scenario. To investigate the environmental consequences of the two scenarios, Hertwich et al. used a newly developed integrated hybrid Life Cycle Assessment model. In contrast to traditional Life Cycle Assessments, this model consistently integrates different energy technologies into a single analytical framework, and computes the impacts of a changing technology mix on the electricity production system itself, on pollution, and on material demand. The authors show that by 2050 low-carbon electricity generation technologies (photovoltaic, solar thermal, wind, hydropower plants, and fossil fuel power plants with carbon capture and storage) could provide twice the current amount of electricity at stabilized or even reduced life-cycle emissions and associated environmental impacts. The requirements for cement, iron, copper, and aluminum per unit of electricity produced, however, would be substantially higher.

Urban agglomerations represent the largest and most complex components of the manufactured capital. They also disproportionally contribute to global energy use and greenhouse gas emissions (71, 72). The huge diversity of cities and a lack of comprehensive and comparable data at city scale have so far prevented reliable estimates of a global urban mitigation potential. Creutzig et al. (73) analyzed a dataset of 274 cities representing all city sizes and world regions, using advanced statistical methods. They calculated the relative importance of the different drivers of direct urban energy use represented in this database, and created a typology of cities according to the combination of driver attributes. Their results show that urban energy will increase to 730 EJ by 2050 in the business-as-usual scenario. A combination of fuel price increases and appropriate urban planning could reduce this expected increase by about 190 EJ. The reduction potential and appropriate policy mixes differ across city types. In mature cities higher gasoline prices combined with compact urban form are most effective, whereas for rapidly growing cities in developing countries urban form and transport planning can avoid the lock-in of carbon infrastructures. About 57% of the global mitigation wedge is in Asia and 29% in Africa and the Middle East; the potential in the Organization for Economic Co-operation and Development countries is only about 6%.

New Frontiers in Chemical and Material Design. The impacts of new chemicals on human health and ecosystems as well as potential raw materials scarcity are recurring environmental concerns dating back to the classics of environmental science, such as *The Coal Question* (74), *Silent Spring* (75), or *Limits to Growth* (76). The closing articles in this Special Feature provide novel approaches for such complex chemical and material design problems.

Designing environmentally more benign chemicals was a topic addressed in preliminary fashion in the 1992 Special Feature (77, 78). Since then, green chemistry has developed into a specialized field with little connection to Industrial Ecology. Kostal et al. (79) argue that the systemic insights into the adverse impacts of material use and processing that are generated in Industrial Ecology must be connected to knowledge on the inherent nature of these materials. A pertinent challenge is that the large number of newly introduced chemicals makes comprehensive human health and eco-toxicological testing infeasible. However, advances in computational chemistry have the potential to provide new and faster screening methods. The article by Kostal et al. presents a computational approach that elucidates the probability that an organic compound with particular properties exhibits a certain toxicity profile. The results show that defining cutoff levels for properties related to bioavailability and reactivity eliminate 99% of the chemicals in the highest acute aquatic toxicity category. This approach has great promise in the consideration of design guidelines for safer chemicals.

Inorganic materials also provide opportunities for more-informed design choices related to the production technologies that enable the large-scale use of high-tech products, such as computers, cell phones, airplanes, or wind power plants. These specialized components of the manufactured capital are indispensable for our modern way of life. Graedel et al. (80) demonstrate that the impressive technology evolution of the past decades was enabled by an equally rapid evolution in material complexity. The growing number of metals contained in single products (a modern computer chip incorporates more than 60 different metals) is the result of a material design strategy that aims to increase performance. However, the long-term availability of these metals is not assured, and substitution by other materials may be limited. In their article Graedel et al. study the substitution potential of 62 different metals in all their major uses and assess the performance of potential substitutes. Their results reveal that for 12 different metals no adequate substitute exists for all major uses. Moreover, for none of the 62 metals studied are adequate substitutes available in all major uses. Graedel et al. conclude that an extremely successful material design strategy directed at improving product performance has created a higher societal vulnerability toward raw material supply shortages, because price-induced substitution is bound to fail as a generic solution to supply risks in many cases.

Concluding Comments

The intellectual roots of Industrial Ecology date back to the 19th century (16, 81, 82). Seminal methods had been published already by the late 1960s and early 1970s (83, 84), but it took until the late 1980s before a scientific field began to take shape (85). Nearly three decades later, Industrial Ecology has become a field dedicated to the quantification and transformation of the Anthropocene. A scientific society, a specialist journal, and a biennial Gordon Research Conference are dedicated to Industrial Ecology, but many more scientific societies, journals, and conferences are promoting, publishing, and discussing Industrial Ecology research. Industrial Ecology is increasingly looked to for a better understanding of the interactions among society, technology, resources, and the environment. The papers in this Special Feature provide a window into the rich and diverse research currently being generated within the Industrial Ecology field.

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