sustainability

Commentary

The Material Stock–Flow–Service Nexus: A New Approach for Tackling the Decoupling Conundrum

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Abstract: Fundamental changes in the societal use of biophysical resources are required for a sustainability transformation. Current socioeconomic metabolism research traces flows of energy, materials or substances to capture resource use: input of raw materials or energy, their fate in production and consumption, and the discharge of wastes and emissions. This approach has yielded important insights into eco-efficiency and long-term drivers of resource use. But socio-metabolic research has not yet fully incorporated material stocks or their services, hence not completely exploiting the analytic power of the metabolism concept. This commentary argues for a material stock–flow–service nexus approach focused on the analysis of interrelations between material and energy flows, socioeconomic material stocks ("in-use stocks of materials") and the services provided by specific stock/flow combinations. Analyzing the interrelations between stocks, flows and services will allow researchers to develop highly innovative indicators of eco-efficiency and open new research directions that will help to better understand biophysical foundations of transformations towards sustainability.

Keywords: socioeconomic metabolism; economy-wide material flow analysis; in-use stocks of materials; stock-flow relations; dynamic stock model; decoupling; socioecological transformation

1. Introduction

Human impacts on the earth are escalating, as evidenced by the ongoing debates on global environmental change [1], proposals to introduce the Anthropocene as a new geological epoch [2], calls for sustainability science [3] and planetary stewardship [4,5]. Key environmental impacts have accelerated significantly in the last century [6]. Seventeen Sustainable Development Goals (SDGs) have been agreed at the UN General Assembly in September 2015, including goals such as ending poverty and hunger by 2030 and combating climate change. The UNFCCC COP21 agreement adopted in Paris in December 2015 aims at limiting global warming to 2 °C or less. The challenge is to achieve key social and economic goals such as the provision of high-quality education and good sanitation for all, the global reduction of infant mortality or the eradication of poverty and hunger, while keeping humanity's use of natural resources and wastes/emissions within earth's safe operating space [7,8].

The concept of socioeconomic metabolism has become a cornerstone of sustainability science [9,10]. It has been used in international assessment reports [11] and can help improving integrated assessment models [12]. Many sustainability problems are related to the mass of resources extracted (e.g., depletion of non-renewable resources, effects of renewable resources) or wastes/emissions discharged per unit of time, thus motivating analyses of yearly flows of materials or energy. This focus allowed researchers to analyze links between human agency, institutions, policy, economic prosperity, trade, development or social conflicts on the one hand with environmental issues like climate change, wastes and emissions, pressures on biodiversity or deterioration of ecosystems on the other hand [13]. It also underpinned analyses of relations between economic activities and resource use. One example are analyses of environmental impacts as a function of population, affluence and technology [14,15], where affluence is often measured as Gross Domestic Product (GDP) and impacts are assessed using a wealth of different environmental indicators, including material and energy flows.

The concept of eco-efficiency, i.e., the amount of resources used or pollutants respectively greenhouse gases (GHG) emitted per unit of GDP, became central to strategies aimed at progressing toward sustainability, from the micro-level (e.g., enterprises, households) up to the macro-level (national economies) as well across spatial scales, from local to global [16]. However, improvements of eco-efficiency have so far not reduced global resource use, as they were overcompensated by economic growth and rebound effects [17]. Growing skepticism regarding the possibility of reducing resource use adequately through eco-efficiency [18] motivates discussions on transformations towards sustainability [19–21], sufficiency [22] and de-growth [23]. Although comprehensive analyses of transformation processes at the global level are missing [24], many experts agree that moving towards sustainability will require fundamental changes in resource use patterns [25].

In recent years, the crucial role of in-use stocks of infrastructures and buildings for resource use patterns and as the biophysical spatial structures of society have increasingly come into focus [26–28]. Early pioneering work already highlighted the importance of the specific services demanded by society, for example m^2 of living space, as the driver of building stock accumulation and subsequent material flows [29,30]. The majority of that research was focused on specific substances or materials, especially metals [31], and increasingly construction minerals [32]. Economy-wide material stock accumulation across all resource flows and consistent with harmonized methods of economy-wide material flow accounting have recently been published [26,33,34]. This line of research is a prerequisite for a more systematic and comprehensive approach to investigating stock-flow relationships because it aims to cover all resource flows and subsequent material stock dynamics. Recent research then started to investigate the socio-economic drivers [35] and comparatively the patterns of stock accumulation [34], the state of global economy-wide circularity [36], and more comprehensive perspectives on the resource efficiency of economy-wide stocks and flows [26].

We here argue that major progress could be achieved by systematically complementing the current flow-centered approach of economy-wide socio-metabolic research with two key elements, namely (a) in-use stocks of materials (short: material stocks) and (b) services provided by these stocks and flows. Similar concepts have been introduced in the "dynamic material flow analysis concept" proposed by Müller et al. [29], but not based on the economy-wide material flow analysis concept in focus in this article. Systematic investigation of these two elements will allow analyzing critical interrelations between the flows used to build-up, maintain and use these stocks and the services they provide (Figure 1).

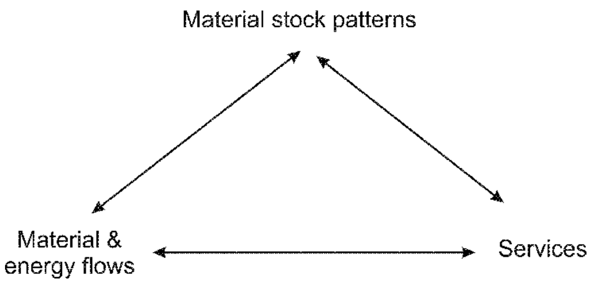

Figure 1. The material stock–flow–service nexus approach could provide new orientations for Social Ecology, Industrial Ecology and Ecological Economics. Source: own figure, see text for explanation.

Analyzing the stock–flow–service nexus shown in Figure 1 will provide key pieces of information missing in current definitions of eco-efficiency. Such analyses will enable researchers to undertake comprehensive and powerful analyses of options to decouple societal wellbeing from resource requirements:

1. Resource flows do not suffice to provide services (e.g., shelter, mobility, communication), i.e., creating benefits for societal wellbeing—they can only do so in combination with material stocks such as machinery, buildings or infrastructures [28]. The location as well as functional types of material stocks and their specific qualities determine both the resource requirements related to the provision of key services, e.g., transport, and spatio-temporal characteristics of their provision, as well as disposal in terms of end-of-life wastes, or their availability for recycling; the latter being crucial knowledge for closing material loops [27,36].
2. Approximating "affluence" or even societal wellbeing with measures of economic activity has been criticized. Many scholars believe that indicators such as GDP may be a part of the problem; see the "beyond GDP" [37,38] and "degrowth" [23] debates. Service indicators can provide complementary insights that will help forging alternative or at least complementary concepts of socio-economic wellbeing whose relations to material stocks and flows may be at least as important as efficiency measures such as materials or energy used per unit of GDP. We think that a shift from mainstream economics towards a service-based approach can help determining the societal needs underlying certain flows and the stock–flow–service linkages due to its ability to compare different options to address the same services and the societal needs behind them.
3. Many individual and collective decisions concern purchases of long-lived goods and investments into buildings, infrastructures and machinery, i.e., into building up material stocks. However, this also results in legacies that narrow future option spaces.

This commentary outlines the stock–flow–service nexus approach and discusses how it could help advancing scientific understanding of social metabolism. We first clarify the difference of stocks and flows in economy-wide socio-metabolic research and review the current state-of-the art in that area (Section 2). Then we discuss how the stock–flow–service nexus approach could enrich studies of eco-efficiency and outline its potential contributions to sustainability transformation research (Section 3), followed by short conclusions.

2. Stock-Flow Relations in Socioeconomic Metabolism Research

2.1. The Concept of Socioeconomic Metabolism

The notion of socioeconomic metabolism transfers the biological concept of metabolism, i.e., the material and energy in-and outflows of organisms and the biochemical processes providing them with energy, maintaining their biophysical structures, reproduction and functioning, to human society [39–41]. One major strand of socioeconomic metabolism research is focused on analyzing flows of materials [42] and energy [43] following a top-down research strategy ("economy-wide material and energy flow analysis", abbreviated EW-MEFA) using data from statistical offices. EW-MEFA has started with nation states (national economies) as basic unit, hence its name, but has been extended to lower levels such as provinces, cities and villages or households, as well as higher levels such as groups of countries or world regions [44,45]. It complements other approaches by comprehensively depicting the material and energy throughput of a defined socioeconomic system. By contrast, substance flow analysis zooms in on specific substances (e.g., metals or chemical elements [46]), whereas life cycle assessment (LCA) is focused on the specific supply chains and uses of products [47].

The study of material and energy flows associated with socioeconomic activities can be traced back into the 19th century [40,41]. Concepts of material flow analysis were pioneered in the 1970s [48,49]. Meanwhile, material flows are reported by statistical offices and international bodies like UNEP, using standardized EW-MEFA methods [42]. Systematically appraising the uncertainties of MEFA data is still a major research topic, however [42,50,51]. Energy is a key resource of all biophysical systems [52–54]. It drives all biophysical processes, including the biogeochemical cycles of water or carbon as well as socioeconomic material flows. The study of socioeconomic energy flows has a venerable tradition [55–58] and plays a key role in the current sustainability discourse [59]. Studying the energetic metabolism of society in a manner that is compatible with material flow analysis is key for linking social and natural sciences in interdisciplinary studies [43,60,61]. Many aspects of socioeconomic metabolism have recently received much attention, as summarized in Table 1.

Table 1. Examples for socio-metabolic research.

Empirical Content Generated	Questions Addressed	References
Analyses of long-term changes of material and energy flows on national and other levels	Changes in supply and demand of biophysical resources and related sustainability problems	[62–67]
Assessment of material and energy flows in different regions	Cross-country comparison of resource demand related to production and consumption	[17,64,68–70]
Establishment of physical trade data bases, including upstream requirements	Analysis of unequal exchange and problem shifting between regions	[71–73]
Creation of databases of flows of specific chemical elements such as metals, carbon or plant nutrients	Analysis of specific problems such as eutrophication, toxic emissions, scarcity or climate change	[46,74–78]
Indicators relating material or energy flows and land use, e.g., the ecological footprint or the human appropriation of net primary production	Evaluation of the role of land as a resource; Analysis of land-use competition; Data basis for analysis of land grabbing; Clarification of the role of land as limited resource	[79–82]
Investigation of specific material cycles through socio-ecological systems, mainly for stocks and flows of metals	Materials management potentials in material cycles and potential future secondary resources and wastes	[31,83–87]
Linking cycles of material stocks and flows through society to energy use and GHG implications	Investigation of stock accumulation patterns during economic development and subsequent GHG implications due to life cycle emissions	[26,28,88–90]
Quantification of stocks and flows related with building dynamics and construction minerals at various scales	Recycling potentials in the building sector, resource demands for expansion	[32,91–94]
Dynamic modeling of stocks for scenarios of stocks and flows	Forecasting of potentials for improved loop closing due to growing secondary resource supply from obsolete stocks	[29,75,86,89,91,95]
Spatially explicit databases of in-use stocks for various scales	Spatial optimization of waste management strategies, investigations of urbanization dynamics	[27,96–99]

2.2. Stock-Flow Relations in Socioeconomic Metabolism Research

A stock is a variable measured at a specific point in time, whereas a flow is a variable measured over a period, i.e., per unit of time. Stocks and flows are incommensurable, but their relations (stock/flow and its inverse, flow/stock) are meaningful and can be interpreted as mean residence time [year] respectively turnover rate [1/year] of resources. In material flow analysis, a stock is measured as mass [kg], while a flow is mass per unit of time [kg/year].

Early conceptual statements already stressed the importance of material stocks in defining and analyzing society's metabolism [100–102], Figure 2. However, the systematic analysis of material stocks and stock-flow relations has only recently begun (see review below). Usually denoted as "in-use stocks of materials" (abbreviated here as "material stocks"), material stocks may be defined as ordered and interrelated biophysical entities created and reproduced by the continuous flows of energy and materials that constitute society's metabolism. According to conventions of socioeconomic metabolism studies, material stocks comprise humans, livestock and artefacts (i.e., manufactured capital *sensu* [103]).

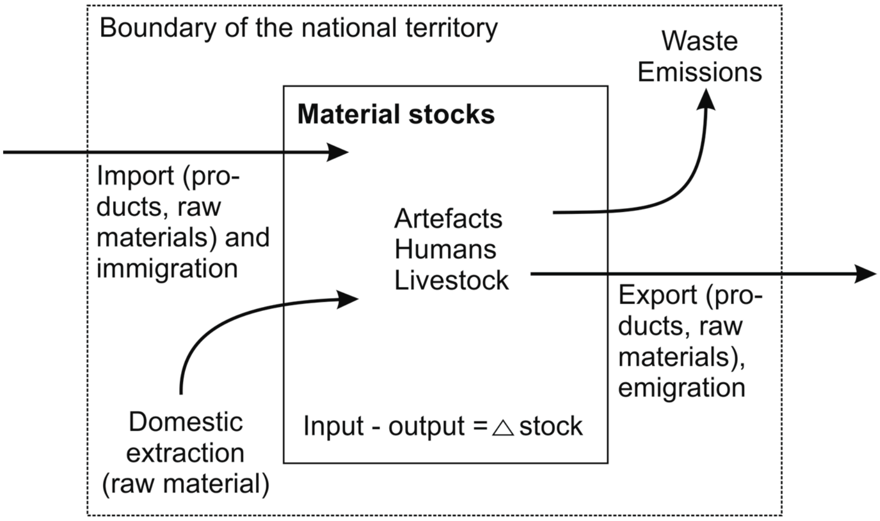

Figure 2. Stock-flow relations in socioeconomic metabolism. Source: own graph, modified after [104].

Material stocks represent the physical infrastructure for production and consumption, and hence the material basis of societal wellbeing [103]. They play a central role in deriving services required for the functioning of society such as shelter, mobility and communication from material and energy flows [28,105]. Socioeconomic material and energy flows are required to create stocks such as buildings, infrastructures or machinery in the first place, to maintain or improve them to keep them in a usable state and to serve dissipative uses required to provide services from stocks [28,76,88,91,105]. Material stocks influence flows, not only because resources are required for building, maintaining and removing them, but also due to the path dependencies for the future resource use patterns they create (e.g., transport infrastructures or heating and cooling requirements of buildings).

Some studies underline the importance of stocks for determining future resource demands, availability of secondary resources for recycling and emissions. GHG emissions from fossil fuels required to use existing energy infrastructures until the end of their lifetime in the period 2010–2060 amount to approximately one-half of the remaining emission budget consistent with a 50% chance of reaching the 2 °C target [106,107]. GHG emissions from the production of three major material resources (steel, cement and aluminum) required for a globalization of current Western levels of infrastructure stocks amount to approximately one-third of that GHG emission budget [88].

2.3. Recent Progress in Quantifying Socioeconomic Material Stocks

In Industrial Ecology, empirical studies of material stocks are rapidly advancing in the last few years, although with varying focus and different concepts according to which the metabolic framework is implemented [27,28,32,76,88,103]. Much research on material stocks has focused on specific substances or materials at various scales. Metals have received most attention [31], from global reconstructions of specific in-use metals stocks and flows [28,85,105] to national level long-term studies on specific metal uses and accumulated stocks [105]. The study of stocks and flows of construction minerals has also increased in the last years [32].

In EW-MEFA, the study of material stocks has long been almost absent mainly due to the lack of robust data. Recently much progress has been made by employing dynamic stock-flow models to estimate stock accumulation from material use and lifetime dynamics [26,33,35,108]. Dynamic stock-flow models distinguish cohorts of stocks, e.g., age of passenger cars or efficiency of industrial plants depending on the time of construction. They typically allow characterizing stocks in terms of the resource requirements involved in building, renewing and using them, as well as the related emissions [29,31,91]. Quantification of uncertainty remains underdeveloped in EW-MEFA [42,50,51], and even more so in regard to material stocks. Few authors have provided sensitivity analyses [30,85,108], multi-method approaches [95] or Monte-Carlo simulations [26,86]. Clearly, uncertainty is a topic of growing importance for MFA research and applications of the socioeconomic metabolism concept in general [31,32,50,51,109].

The role of in-use stocks for energy use and climate-change mitigation in important sectors such as housing, the steel industry or passenger cars has been analyzed using global models [88,89,110]. Aggregate material stocks have been modelled from long-term historical material flow data [26,33,34]. Combinations of bottom-up and top-down approaches have recently been published, showing the complexity of adequately capturing all in-use stock dynamics and linking them to economy-wide material flows [91,94]. The distinction between material flows for dissipative use from stock-building materials allowed assessing potentials for a circular economy [36,94]. Recently the drivers of economy-wide stock accumulation were investigated for Japan's prefectures [35] and a typology of the dynamics of stock accumulation was developed [34]. The global dynamics of socio-economic metabolism, including all material flows and stocks have recently been estimated for the 20th century [26], see Figure 3.

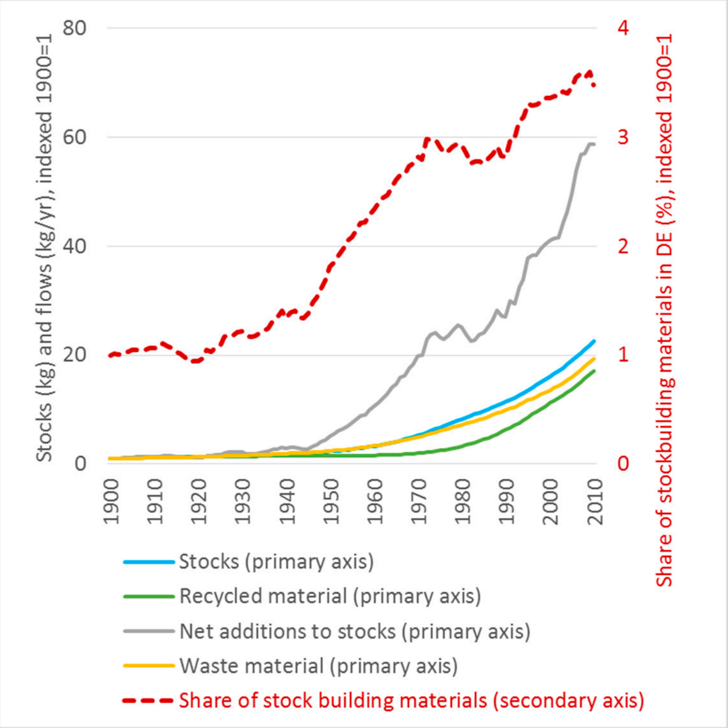

Figure 3. Long-term development of global material stocks and related flows. Material stocks (blue line, primary axis) grow >20 fold over the 20th century, net additions to stocks even almost 60 fold. The share of stock-building materials (red line, secondary axis) rises 3-fold over this time period to approximately 50% (not shown). The amount of end of life waste that is recycled grew 17 fold, but accounts for only a small share of inputs to stock. Source: own figure drawn using results from [26].

Material stocks depicted in Figure 3 were measured as kg of materials of certain aggregated categories (e.g., concrete) but not classified according to their respective functions (e.g., concrete in residential buildings versus concrete in roads, railroads or power plants). Stock estimates were modelled from material flow data using assumptions on the residence time of resources in the form of lifetime distributions. Uncertainty estimations were based on error propagation via Monte-Carlo Simulations, driven by assumptions on uncertainty for material inputs and all other model parameters derived from the literature [26]. Results show that global material stocks grow exponentially over the entire period. The study finds large differences between per capita stocks in industrial countries and the rest of the world, and high growth rates of stocks in emerging economies, which is likely to drive global stock growth in the future. While many commentators have designated the 20th century as the epoch marking the advent of throwaway societies, these numbers rather suggest that in fact we move toward stockpiling societies: The fraction of resources extracted allocated to the build-up of material stocks has tripled in the last century and amounted to 55% in 2010, the share of recycled materials in inputs to stocks remains low at 12% [26]. Reductions in resource extraction seem difficult or impossible to achieve as long as that stockpiling continues.

2.4. Resource Flows, Material Stocks, and Services

A substantial part of the sustainability debate has focused on options to raise eco-efficiency; i.e., to “decouple” economic growth and societal wellbeing from material and energy flows [16–18,111]. However, these eco-efficiency concepts have been criticized as too narrow [16,111–113], among others because societal wellbeing depends only partly on the products provided each year, but also on the quantity and quality of existing stocks of buildings and infrastructure. Raising efficiency may be important, but it is most likely not sufficient to move toward sustainability [19,114]. A focus on services from stocks such as infrastructures, buildings or machinery [28,88] can provide a new angle for that debate, as indicators for services have so far been almost entirely absent in eco-efficiency research, as was the importance of stocks for the emissions or resource flows that were sought to be decoupled from GDP.

Two recent strands of research where service indicators have been intensively discussed are those concerned with energy services [115,116] and ecosystem services [117,118]. In both debates, the aim is to understand how human societies gain benefits, either from using energy (energy services) or from ecosystems and natural capital (ecosystem services). In both contexts, services are diverse and recalcitrant against attempts to be measured in one single unit. They include items as different as provision of comfortable living space or adequate lighting, recreation, adequate nutrition, shaping of workpieces, computational services, cleaning of water, air, homes or human bodies, maintenance of biological diversity, cultural and religious services and many more. Both debates have developed concepts to analyze the multiple steps involved in the provision of services from resources.

Energy services are derived in several steps involving energy conversions from raw or primary energy extracted from deposits or diverted from natural flows to final energy sold to consumers, to useful energy delivered by machinery operated by consumers and eventually to energy services, a sequence that has been denoted as “energy chain” [115]. In a somehow similar manner, a “cascade” concept is used to understand the multi-step process through which benefits and finally their values are derived from biophysical structures and processes, which in turn influences the functioning of ecosystems and their services [119]. The importance of human agency for the delivery of ecosystem services is increasingly recognized [118]. Even more explicitly than ecosystem services, however, services from stocks are not naturally given, but a product of past work and reoccurring material and energy flows, while at the same time delimiting future development options.

Material stocks such as machinery, buildings or infrastructures are important because they are required to transform resources which are in themselves barely useful (e.g., crude oil, mixtures of minerals in a deposit, or even trees in a forest) into services such as comfortable living space, the movement of people or goods across space, or the delivery and storage of information through electronic devices or paper. Infrastructures determine which services are available where (e.g., shelter, transport or production capacity). Spatial patterns of settlements and production sites as well as available transport infrastructures co-determine the distances and energy demand required to provide transport-related services [120,121].

2.5. The Importance of Spatial Patterns and Urbanization for Resource Demand

Lack of comprehensive data on the spatial patterns of material stock data so far impedes systematic integration of spatial analysis with socioeconomic metabolism research, except for human population and livestock, which are also considered as parts of societies' material stocks (Figure 2). Population maps [122,123] are widely used to downscale national or regional data to maps, following the assumption that human drivers or impacts scale with population [124,125]. Such maps are constructed by combining census statistics with proxies from remote sensing, e.g., nighttime light [126,127]. Similar approaches allowed mapping the global distribution and environmental impacts of livestock [128–130].

One key spatial aspect related to material stocks is urbanization. Settlement patterns, urban form and population density influence transportation energy use and emissions [114,120,131–134]. It is expected that urban population will reach 5.6–7.1 billion in the mid of the century [121]. Relationships between urban material and energy flows, city size and city structure were analyzed for 27 global megacities [135]. Consumption patterns are embedded in specific urban forms. In densely settled areas, use of transportation energy use is usually lower, but higher incomes in cities lead to more consumption and larger energy and carbon footprints of households [136–139]. An integrated perspective hence needs to consider the systemic interactions between production and consumption in urban areas and rural hinterlands [140–142].

Studies of urban metabolism have quantified urban resource use, and some even stocks [27,141,143,144]. European material stocks and recycling potentials in buildings and infrastructures were assessed in a bottom-up study [91]. The interrelations between energy transitions and urbanization processes have recently been explored [145]. Spatially explicit material stock data have been explored for substances like metals [97,146], or more comprehensively for Japan [27]. Overall, spatially explicit mapping of stocks has made much progress in the last decade, although so far mostly on regional levels [27,96–98,144].

A comprehensive perspective consistent with EW-MEFA is important because services are delivered by material stocks consisting of mixtures of materials. For example, a building can be made of steel-reinforced concrete, bricks, mortar, timber and many other materials. Hence only a comprehensive perspective can address substitution. In a study of stocks and flows of iron, a building made only of wood and bricks would become invisible, but it might still fulfill functions and deliver services, and it would still require material inputs during construction. The environmental impacts of the related resource flows would be different from those of a building made primarily of steel, aluminum and glass, but they would not be irrelevant. A comprehensive, systemic approach is important due to its ability to address problem-shifting and substitution, whereas substance-specific studies are required to address specific impacts [41,44].

3. Contributions of the Stock–Flow–Service Nexus Approach to Socioeconomic Metabolism Research

3.1. New Conceptualizations of Eco-Efficiency

Analyses of eco-efficiency so far primarily used GDP as a measure of affluence and related GDP to either resource requirements (e.g., energy or material inputs) or emissions (e.g., GHG or CO_2 emissions). Service indicators can complement GDP in such analyses, as services highlight the relevance of specific combinations of material stocks and resource flows for contributions to societal wellbeing. The availability of indicators for stocks and services would allow defining innovative measures of resource intensity and emission intensity, such as the measurement of resources required or emissions resulting from achieving certain levels of material stocks or services in different world regions or changes of resource requirements per unit of service delivered along temporal trajectories. For example, one could study the resource requirements of different options to achieve sustainable development goals such as the universal provision of clean water and sanitation or clean and affordable energy. The stock–flow–service nexus approach will hence allow researchers to go significantly beyond relating resource use or emissions to economic indicators such as GDP [72], the Social Progress Index [147], or the Human Development Index (HDI) [17,90,148] by providing indicators for the services derived from specific stock-flow constellations. Novel concepts of eco-efficiency that could be derived from the analysis of the stock–flow–service nexus approach (Figure 1) will enable researchers to estimate the amount of resources sufficient for essential societal wellbeing at different spatial levels in a scientifically sound and comprehensive way.

Efficiency is usually defined as the relation between two flows (e.g., materials/GDP), hence stocks played no important role in the eco-efficiency debate, except where stocks such as population or area are used to compare flows in different countries by calculating flows per capita or per unit area [14,70,149]. Such concepts of eco-efficiency mask the importance of stocks in determining resource requirements and service provision. Indicators of material stocks as well as material stock maps could help elucidating the importance of specific qualities of material stocks respectively their spatial patterns for resource demand, waste production and closing material loops. Mapping of human activities is so far largely restricted to population density maps and other datasets mainly derived from proxies such as nighttime lights [97,127,150]. Maps of material stocks would be useful to characterize spatial patterns of material stocks and thereby analyze stock–flow–service relations and the spatial distribution of human activities on earth much more consistently than is possible today. Insights from such empirical efforts could also help improve integrated assessment models [12] that currently play a key role in evaluating transformation pathways, e.g., in analyses of options for climate-change mitigation [151].

3.2. Food for Thought for Socioecological Transformation Research

Following the recognition that a continuation of current trajectories, even when combined with efforts to raise eco-efficiency, will likely be insufficient to reduce climate change to 2 °C or less [152] and tackle other sustainability challenges [25], much research is currently focused on wide-ranging changes in society-nature relations denoted as “transformations towards sustainability”. For such a transformation, material flows need to be reduced to an ecologically sustainable level, which requires at least a stabilization of stocks (Figure 4)—quite contrary to the global trends depicted in Figure 3. Sustainability transformation research builds on approaches such as the “sociotechnical transition” concept [153–155] as well as analyses of technological transitions related to energy [151,156–159]. The importance of infrastructures for providing services and stabilizing practices of production and consumption [160], for future energy system transformations [59] or for reaching climate-change mitigation targets [151,152] has been acknowledged. Lock-ins into emission-intensive pathways resulting from existing stocks have recently be analyzed [90]. The material and energy repercussions of a future global low-emission electricity system were found to be significant, but manageable [161].

However, so far transition management approaches mainly focus on developed countries and lack a global perspective [162]. Their focus on technology and innovation underpins important leverage points for targeted interventions, but will require complementary approaches to address rebound effects and other transition barriers and to provide a more realistic understanding of the biophysical and societal constraints involved. A “Great Transformation” [20,163] involves not only technological innovations, but also major shifts in resource production and consumption [164] and socioeconomic metabolism [9,19] at various spatial and temporal scales.

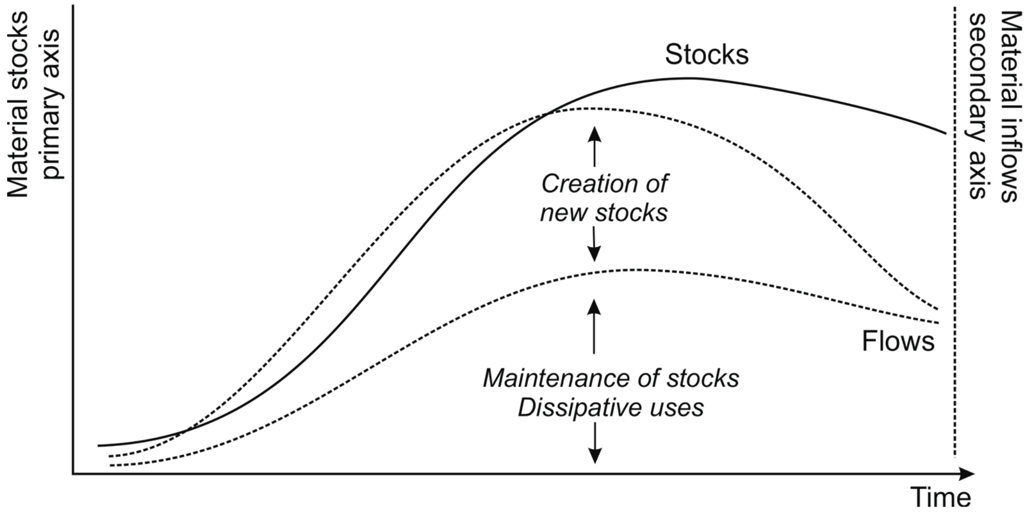

Figure 4. Hypothetical stylized representation of stock-flow relations over time in a national economy. So far, stocks do not seem to be stabilizing even in industrialized countries, which could explain lacking success in reducing flows. Source: own graph.

The study of shifts between socioecological regimes such as hunter-gatherers, agrarian, industrial, or a yet unknown future sustainable society [19,165] has so far been focused on changes in resource flows [64] and land use [166] at larger scales. Links to changes in population trends related to so-called demographic transitions [167] have been analyzed in these approaches [165] but could profit from being better linked to the analysis of socioeconomic interests and the power relations behind them that may hinder or block sustainability transformations. An important aspect are transformations in energy systems, e.g., from biomass to fossil fuels during the agrarian-industrial transition [53,168,169] which today, due to climate change and the quest for alternatives to fossil fuels, stimulates far reaching conflicts at and between several spatial scales, including increasing land use conflicts.

Until now transformation research is marked by an analytical gap to address ongoing tendencies towards unsustainability and challenges for shaping societal relations with nature. What is required is a more comprehensive analysis of the crisis-driven and contested character of the appropriation of nature and the power relations involved as discussed under the concept of social-ecological transformations (see [170], in this issue). Neither material stocks nor services have so far featured prominently in these analyses. However, the arguments laid out above suggest that the inclusion of material stocks and services can improve the analysis of both past and possible future transformations and thereby contribute to transformation research.

Linking stocks, flows and services can elucidate constraints to as well as leverage points for sustainability transformations that are so far poorly understood. Material stocks are products of past actions, i.e., past interventions in natural systems or transformations of socioecological systems, which constrain as well as enable further human activities and societal development by providing services for societal wellbeing. They have high value and often persist for a long time, thereby creating legacies, lock-in effects and path-dependencies. They result from complex interactions of societal and natural processes under certain institutional arrangements [171]. Thus, an analysis of these historically specific conditions can provide starting points for the identification of alternative resource use pattern. This becomes visible if compared with existing mainstream economic approaches, which are either supply-based or demand-side driven. Supply-based and demand-based approaches both lack criteria for fulfillment of societal needs and are therefore implicitly directed towards unlimited growth. In contrast, a service-based approach is able to compare different options to address a sufficient level of services and the societal needs behind them, thereby helping to determine alternative options to fulfill these needs through specific stock-flow configurations. Material stocks hence depict important conditions for transformations toward sustainability. Research can focus on questions like their malleability through targeted societal interventions, which is yet poorly understood, or the relevance of alternative stock/flow/service configurations for sustainability transformations, which currently have not been addressed systematically. Quantifications of material stocks and investigations into their relations with flows and provision of services are hence a key component of attempts to scientifically underpin sustainability transformations.

4. Conclusions

Moving toward sustainability will require far-reaching changes in socioeconomic metabolism, i.e., in the stocks and flows of materials and energy related with societal activities. The consistent integration of material stock data and maps one the one hand, and of the services provided through specific constellations of stocks and flows, can inspire new empirical research (e.g., quantification and mapping of material stocks), modelling and analysis to better understand past trajectories as well as future patterns of society-nature interaction. One critical research gap that well have to be addressed is the need for material stock accounts that do not only distinguish between different kinds of materials [26] but also their different functions. When such accounts become available, the stock–flow–service nexus approach will be able to underpin new concepts for analyzing eco-efficiency in the sense of a decoupling between societal well-being and resource demand, the contingencies and lock-ins resulting from past build-up of material stocks, as well as possible leverage points to foster sustainability transformations. Comparing alternative options for providing the same service with lower resource needs, i.e., through different stock-flow configurations than those in place today, will open up space for determining leverage points for sustainability transformations and addressing the issue of sufficiency beyond a purely normative claim.

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