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# Flow of Natural versus Economic Capital in Industrial Supply Networks and Its Implications to Sustainability

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Appreciating the reliance of industrial networks on natural capital is a necessary step toward their sustainable design and operation. However, most contemporary accounting techniques, including engineering economics, life cycle assessment, and full cost accounting, fail in this regard, as they take natural capital for granted and concentrate mainly on the economic aspects and emissions. The recently developed "thermodynamic input–output analysis" (TIOA) includes the contribution of ecological goods, ecosystem services, human resources, and impact of emissions in an economic input–output model. This paper uses TIOA to determine the throughputs of natural and economic capitals along industrial supply networks. The ratios of natural to economic capitals of economic sectors reveals a hierarchical organization of the U.S. economy wherein basic infrastructure industries are at the bottom and specialized value-added industries constitute the top. These results provide novel insight into the reliance of specific industrial sectors and supply chains on natural capital and the corresponding economic throughput. Such insight is useful for understanding the implications of corporate restructuring on industrial sustainability metrics and of outsourcing of business activities on outsourcer, outsourcee, and global sustainability. These implications are discussed from the standpoints of weak and strong sustainability paradigms. The calculated ratios can also be used for hybrid thermodynamic life cycle assessment.

## 1. Introduction

Sustainability of human activities requires that at least as large a *productive capital base* is available for its future operations as it inherited from its past (*1*). Productive capital base or the capital stock of a region is made up of *economic*, *natural*, and *social* capitals (*2*, *3*). Economic capital includes assets such as buildings, machinery, and infrastructure. Natural capital includes environmental functions such as provision of natural resources such as coal and water to production activities and dissipation and absorption of wastes from these activities (*4*). Social capital includes human resources, value systems, and social organizations through which contributions of individuals are mobilized and coordinated. All three forms of capital must be considered simultaneously to address sustainability issues. The criterion of *weak sustainability* (*5*, *6*) assumes that different types of capital are substitutable, implying that sustainability may be maintained by converting one type of capital into another. In contrast, *strong sustainability* rejects the notion of complete substitutability, since many ecosystem goods and services cannot be replaced by human-made capital. It requires preservation of natural capital in itself, in addition to other capital stocks. The implications of the results presented in this paper are discussed considering both paradigms of sustainability, without supporting or debunking either.

Since natural capital usually lies outside the market, many efforts have been made for quantifying its importance. These include monetary valuation (*7*, *8*) and analysis of material and energy flows (*9*, *10*). Many methods and metrics have been devised for evaluating sustainability at different spatial scales. These range from national measures of genuine investment that account, albeit partially, for economic and natural capitals (*11*) to corporate measures that are being used in annual sustainability reports and for evaluating socially responsible investments (*12*, *13*). However, systematic analysis of the flow of natural capital through the network of economic sectors and the corresponding economic activity is missing. Such analysis can provide useful insight into the reliance of economic activity on natural capital and guide the development of effective policies and corporate decisions. It can also complement existing techniques for sustainability metrics and environmental life cycle assessment and for the greening of industrial supply chains.

The contribution of ecosystem goods and services to industrial activity has been quantified recently by combining data and methods from systems engineering, systems ecology, and life cycle assessment (*14*, *15*). The resultant approach, called "thermodynamic input–output analysis" (TIOA), treats industrial and ecological systems as networks of energy flow and quantifies the contribution of natural capital to an industrial product or process by the ecological cumulative exergy consumption (ECEC) of ecological and industrial processes in the corresponding supply network (*16*). Exergy provides a scientifically sound common currency for combining all kinds of material and energy streams and analyzing industrial and ecological systems and is the only truly limiting resource on the planet. Unlike claims in other work (*10*, *17*, *18*), TIOA is not meant to replace preference-based valuation of natural capital but rather to complement and strengthen it with a sound biophysical basis. Exergy analysis has already found wide use for improving process efficiency (*19*) and assessing ecosystems (*20*). ECEC is closely related to the concept of emergy (*10*), but it does *not* rely on any of its controversial aspects (*21*). It uses transformity values compiled in emergy analysis, but only of *direct* ecosystem inputs, to convert the contribution of ecosystem goods and services into consistent thermodynamic units. These transformities are based on widely accepted knowledge of global geo logical–biological–chemical cycles. TIOA has been applied to the 91-sector 1992 (*14*) and the 488-sector 1997 (*15*) models of the U.S. economy. ECEC/money ratios have been calculated for each industry sector. The numerator of this ratio captures the thermodynamic basis of an industry sector and is a measure of the sector's reliance on natural capital, whereas the denominator captures monetary basis and is a measure of the sector's contribution to economic activity.

The environmental and economic aspects of supply networks have also been studied in the past (*22*–*24*). However, most studies have focused on either of the two aspects in isolation, or on a few selected emissions or resource flows, often in a univariate manner or by combining them

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without considering the laws of thermodynamics. Considering only a few supply chains while ignoring the larger economic network (*25*, *26*) makes it very difficult to derive any general conclusions. Such studies usually ignore most ecosystem goods and services, leading to severe undercounting of natural capital. Among economic aspects some studies (*25*) consider only value added and ignore intermediate transactions with other industry sectors.

The analysis presented in this paper is much more comprehensive and scientifically sound than existing studies and constitutes one important contribution. It considers total throughputs of natural capital including renewable and nonrenewable ecological goods, ecosystem services and impact of emissions on human health, and total throughputs of economic capital, including intermediate inputs to industry sectors besides value added. It also accounts for quality differences in material and energy streams via the use of exergy analysis, considers supply networks of a large number of industry sectors belonging to different hierarchical levels of the economy, and is reproducible as it is based on nonproprietary data. The results, based on data and models of the 1997 U.S. economy, reveal a hierarchical organization that bears some similarities to an ecological food chain. The basic infrastructure and resource extraction subdivisions are at the base of the economic hierarchy, whereas more sophisticated and value-added subdivisions are at the top. These results can provide insight into the effect of corporate restructuring on industrial sustainability metrics and into the relationship between global trade and sustainability in developing and developed countries. This relationship is discussed from the standpoints of weak and strong sustainability paradigms, while considering human preferences in the outsourcer and outsourcee. Some of the resulting insight matches with that from many previous studies, but new insight is also provided that deserves further exploration.

In the rest of this paper, section 2 introduces basic thermodynamic concepts and TIOA. Section 3 shows how a supply chain is selected from the supply network and how economic and natural capital flows along the selected supply chain are found. Section 4 analyzes results for the 1997 U.S. industry benchmark model in different ways via grouping into 28 major subdivisions and analysis of a few selected detailed supply chains. Finally, section 5 discusses some implications of these results to sustainability. Detailed data are provided in the Supporting Information.

## 2. Background: Thermodynamic Input−Output Analysis

TIOA determines the cumulative exergy consumption (CEC) by combining data about natural resource use and emissions with an economic input−output model. If the contribution of ecosystem goods and services is ignored, the resulting industrial CEC (ICEC) is analogous to exergy analysis in engineering (*19*), while if the ecosystem is included, then the resulting ecological CEC (ECEC) is analogous to exergy analysis in systems ecology (*10*, *16*). Examples of ecological stages in the cradle-to-gate portion of a supply chain include ecological processes responsible for producing, transporting, and concentrating natural resources, whereas those in the gate-to-grave portion include various pollution dissipation and impact functions. ECEC analysis estimates exergy consumption in the ecological stages by using results about direct ecosystem inputs compiled in emergy analysis (*10*). Hau and Bakshi (*16*) prove the equivalence between emergy and ECEC under identical system boundary, allocation rule, and approach for combining global exergy inputs. Both, ICEC and ECEC analysis can use the input−output modeling framework (*27*) to represent interactions between different units of the industrial and ecological systems. This section summarizes the main characteristics of TIO analysis, including the network algebra approach for calculating the contribution of renewable and nonrenewable resources, the contribution of human resources, and the human impact of emissions. Additional details are in ref *14*.

Whenever the underlying network structure and all the inputs to and outputs from each network unit are completely known, ECEC throughputs of selected processes, $C$, can be calculated from the exergy content of natural resource inputs, $B_n$; transformities of natural resources, $\tau_n$; and the allocation matrix for the selected system, $\boldsymbol{\Gamma}_i$, according to eq 1.

$$\boldsymbol{C} = \boldsymbol{\Gamma}_i \tau_n B_n \qquad (1)$$

Use of transformity values of natural resources enables determination of the exergy consumed in the ecological stages of the supply chain. ICEC analysis also uses eq 1 to evaluate CEC in the industrial links of a production chain but ignores the ecological stages by assuming $\tau_n = 1$ (*16*). Transformities are fundamentally equivalent to the reciprocal of exergetic efficiencies and are derived from the thermodynamics of global biogeochemical cycles. They *do not* rely upon controversial aspects of emergy analysis, such as the maximum empower principle, the emergy theory of value, or prehistoric energy (*21*).

The allocation matrix, $\boldsymbol{\Gamma}_i$, represents interactions between different processes in the network. TIOA uses monetary interindustry transaction matrixes (*28*), as they are the most current, comprehensive, and nonproprietary data describing interindustry interactions. Material or energy data could also be used, if available. For the ecological network, such a matrix or knowledge about all the ecosystem goods and services is not yet available. In this case, ECEC avoids allocation and assigns the same input CEC to all the products. ECEC assigned in this way cannot be added, since it would lead to double counting, so the maximum value of the input streams is used instead. In general, the ECEC of nonrenewable resources is *additive*, whereas that of renewable resources is *nonadditive*. This is because for nonrenewable resources such as minerals and fossil fuels, allocation is typically done in proportion to their mass fraction in the earth's sedimentary cycle. For renewable resources, however, such allocation is not possible, as they are byproducts of the same energy input to the earth system.

ECEC via human resources is based on the average ECEC of human consumption of economic goods and services allocated according to the number of people employed and their average annual payroll. Exergy is also consumed due to the impact of emissions in the form of the resulting loss of human or ecosystem services. Human impact is calculated by converting the disability adjusted life year (DALY) for the emission into ECEC via the ECEC of an average human per year. Ecosystem impact is not included in this analysis as yet, due to the lack of an appropriate method to represent it in terms of ECEC. Additional details are in refs *14*, *15*.

ECEC analysis calculates throughputs of system units by applying eq 1 to each additive and nonadditive resource independently, followed by adding all additive resources to the maximum of all nonadditive resources along each branch of the network (*16*). Briefly, the algorithm of TIOA (*14*, *15*) (i) identifies and quantifies natural resource inputs to the economic system and emissions from the economic system and their impact on human health, (ii) determines ECEC content of ecological inputs using transformity values from systems ecology and classifies the inputs as additive or nonadditive, and (iii) allocates ecological and human resource inputs through the economic system using an appropriate transaction matrix and allocation algorithm.

## 3. Approach for Supply Chain Analysis

The first task in analyzing the supply chain of a process is the selection of an appropriate supply chain from the many

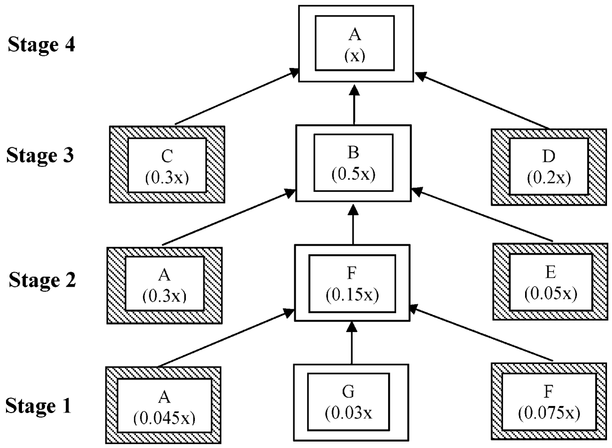


**FIGURE 1. Selection of supply chain components from a supply network.**

possibilities. In reality, for any process there exists an infinitely long supply network rather than just a solitary supply chain of finite length. In this work, this task is accomplished by using economic input−output information (*28*). The components of the supply chain are chosen from the supply network such that the most significant supplier at each stage can be included, while avoiding supply chain loops. This is explained with the help of Figure 1, which illustrates the selection of a supply chain from a supply network for a hypothetical process. In this figure, stage 4 represents process A at the top of the supply chain tree, and stage 1 represents the primary resource extraction process at the bottom. Process A has three suppliers with B being the most dominant. Hence at stage 3, process B is selected for further investigation. Process B has three suppliers, with A being the most dominant, followed by F and E. Since the choice of process A at stage 2 would lead to a loop, namely A−B−A, in the supply chain, the next most dominant process is chosen instead. In a similar way, process G is chosen at stage 1, resulting in the complete supply chain, A−B−F−G. This algorithm resembles a depth first search and is equivalent to finding an elementary dipath in a digraph (*29*) or the most important first-order path at each stage in structural path analysis (*30*). Use of economic data represents the traditional econocentric approach of identifying supply chains. Other selection rules based on throughputs of natural capital or human health impact of emissions may also be used as per the user's discretion.

After selecting a supply chain, the next task is to determine economic and natural capital flows along its length. In this analysis economic capital flows have been estimated using the economic input−output database (*28*). Natural capital flows have been calculated by propagating ECEC of inputs from nature through the EIO model, or more conveniently by multiplying economic capital flows by ECEC/money ratios of corresponding industry sectors obtained from TIOA (*15*). This is explained in greater detail via Table 1 and Figure 2.

A monotonic decrease in the ECEC/money ratios along a supply chain from source to final product corresponds to

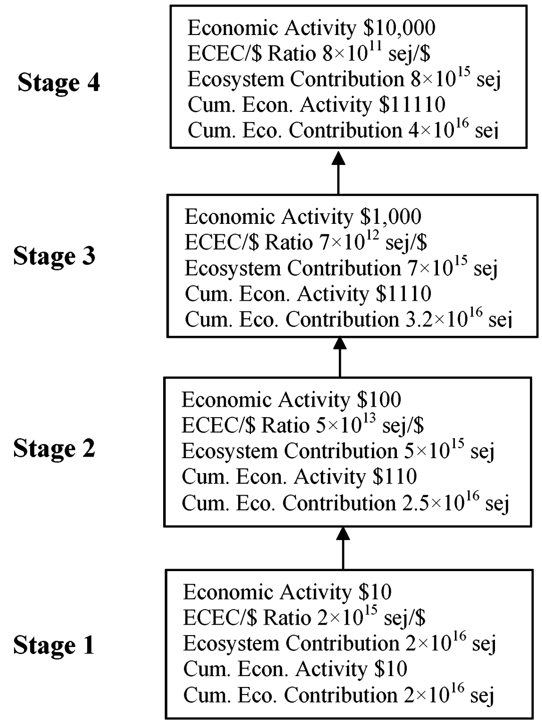


**FIGURE 2. Supply chain for the illustrative example presented in Table 1.**

a convex correlation between cumulative ecosystem contribution and cumulative economic activity. This indicates that sectors that are closer to nature (source) use more natural capital per unit of economic throughput than sectors that are farther removed from nature (product). This is explained further in the Supporting Information and forms the basis of much of the insight in the rest of this paper.

## 4. Results for 1997 U.S. Industry Benchmark Model

The approach described in section 3 is used to study natural and economic capital flows in the 488-sector 1997 U.S. industry benchmark model (*28*). This study is conducted at different levels of detail to gain greater insight. The first two subsections provide a synoptic overview via results for 28 aggregated major subdivisions, with section 4.1 analyzing the *total* ECEC/money ratio and section 4.2 analyzing the four *contributing* resource categories. Finally, supply chains of selected sectors based on the *detailed* 488-sector data are provided in section 4.3. Much of the resulting insight from aggregated data matches with the current understanding from other studies, thus partially validating the data used in this work. The comprehensive nature of the data used in this study also provides some new insight, which is discussed in this and the next section.

**4.1. Total ECEC/Money Ratio for Aggregated Sectors.** Aggregation of the 488-sector 1997 U.S. economy into 28 major subdivisions is listed in Table 2. These subdivisions are defined by the Bureau of Economic Analysis (*28*) and

**TABLE 1. ECEC/Money Ratios, Cumulative Economic Activity, and Cumulative Ecosystem Contribution for the Supply Chain Shown in Figure 2**

| | economic activity ($), $\alpha$ | cumulative economic activity, *m* ($) | ECEC/money ratio (sej/$), *r* | ecosystem contribution (sej), $\alpha \times r$ | cumulative ecosystem contrib, *e* (sej) |
|---|---|---|---|---|---|
| stage 1 | $1.00 \times 10^1$ | $1.00 \times 10^1$ | $2.00 \times 10^{15}$ | $2.00 \times 10^{16}$ | $2.00 \times 10^{16}$ |
| stage 2 | $1.00 \times 10^2$ | $1.10 \times 10^2$ | $5.00 \times 10^{13}$ | $5.00 \times 10^{15}$ | $2.50 \times 10^{16}$ |
| stage 3 | $1.00 \times 10^3$ | $1.11 \times 10^3$ | $7.00 \times 10^{12}$ | $7.00 \times 10^{15}$ | $3.20 \times 10^{16}$ |
| stage 4 | $1.00 \times 10^4$ | $1.11 \times 10^4$ | $8.00 \times 10^{11}$ | $8.00 \times 10^{15}$ | $4.00 \times 10^{16}$ |

**TABLE 2. 28 Major Subdivisions of U.S. Economy and Their Corresponding NAICS Codes Used for Figures 3 and 4**

| position in Figure 4 | subdivisions of U.S. economy[a] | corresponding NAICS codes |
|---|---|---|
| 1 | Mining and Utilities | 21, 22 |
| 2 | Government and Special | S00101−S00500 |
| 3 | Plastic, Rubber, and Nonmetallic Mineral Products | 326, 327 |
| 4 | Petroleum, Coal, and Basic Chemical | 324, 3251 |
| 5 | Ferrous and Nonferrous Metal Production | 331, 3321 |
| 6 | Construction | 23 |
| 7 | Resin, Rubber, Artificial Fibers, and Agricultural and Pharmaceutical Manufacturing | 3252, 3253, 3254 |
| 8 | Wood Paper and Printing | 321, 322, 323 |
| 9 | Cutlery, Handtools, Structural and Metal Containers | 3322−3324 |
| 10 | Ordnance and Other Metal Products | 3325−3329 |
| 11 | Vehicles and Other Transportation Equipments | 336 |
| 12 | Furniture, Medical Equipment, and Supplies | 337, 3391 |
| 13 | Paint, Coating, Adhesives, Cleaning, and Other Chemicals | 3255−3259 |
| 14 | Engines and Machinery | 333 |
| 15 | Lighting, Electric Components, Batteries and Other | 335 |
| 16 | Misc. Manufacturing | 3399 |
| 17 | Textiles, Apparel and Leather | 313, 314, 315, 316 |
| 18 | Semiconductors, Electronic Equipment, Media Reproduction | 3344, 3345, 3346 |
| 19 | Agriculture, Forestry, Fishing, and Hunting | 11 |
| 20 | Food, Beverage, and Tobacco | 311, 312 |
| 21 | Management, Administrative, and Waste Services | 55, 56 |
| 22 | Computers, Audio, Video, and Communication Equipment | 3341, 3342, 3343 |
| 23 | Trade, Transport, and Information | 42, 45, 45, 48, 49, 51 |
| 24 | Education and Health Care Services | 61,62 |
| 25 | Arts, Entertainment, Recreation, Hotels, and Food Services | 71, 72 |
| 26 | Professional and Technical Services | 54 |
| 27 | Other Services Except Public Administration | 81 |
| 28 | Finance, Insurance, Real Estate, Rental, and Leasing | 52, 53 |

[a] 1997 U.S. Industry Benchmark Model Definitions.

have also been used in economic input−output life cycle assessment (*31*). This aggregation scheme is used as it provides a more concise overview of the economy than the three-digit NAICS codes and yet is more detailed than the two-digit NAICS codes. Figure 3 shows the sorted median ECEC/money ratio of each of the 28 subdivisions along with ratios of the constituent sectors in each subdivision on a semilog plot. The resultant organization of the "economic food chain" resembles the hierarchical organization commonly observed in ecosystems, wherein primary producers constitute the base of the hierarchy and carnivores constitute the top. For the economic hierarchy, the median ECEC/money ratio decreases from the base to the top. Basic extractive and infrastructure subdivisions such as Mining and Utilities; Plastic, Rubber, and Nonmetallic Mineral Products; and Ferrous and Nonferrous Metal Products constitute the base, whereas more specialized subdivisions such as Finance, Insurance, Real Estate, and Professional and Technical Services constitute the top. Manufacturing sectors such as Vehicles and other Transportation Equipment, Textiles and Leather Products, and Semiconductor Manufacturing occupy the middle. This general trend is maintained even for other aggregation schemes.

Figure 3 leads to the following notable observations. The Mining and Utilities subdivision has the highest median ECEC/$ ratio, whereas the Finance, Insurance, Real Estate, Rental, and Leasing subdivision has the lowest. In general, the advanced manufacturing and service subdivisions have lower ECEC/$ ratios than the resource extraction and basic manufacturing subdivisions. A lower ECEC/money ratio indicates less consumption of natural capital vis-à-vis monetary throughput. Therefore, from the standpoint of the weak sustainability paradigm, which presumes substitutability between economic and natural capitals, lower ECEC/money ratio translates into a greater improvement in the productive capital base and indicates more sustainable operation. Further discussion about sustainability based on marginal cost−benefit analysis while considering human preferences is provided in section 5. A plausible reason behind higher ECEC/money ratios of basic infrastructure industries is that these industries are technologically less efficient, due to having to process a relatively dilute resource, and consequently, they have to consume a lot of raw material to produce a finished product or service. This gives rise to large *overburdens*, defined as the material moved by extraction that does not enter the economic system or, alternatively, the difference between *total domestic output* (TDO) and *domestic processed output* (DPO) (*32*, *33*).

Recycling of material in the economy would also affect ECEC/money ratios. Since recycling can reduce the consumption of pristine ecological resources, while generating economic activity, increased recycling would lower ECEC/money ratios throughout the economic network. Operating facilities for separating and sorting recyclable materials from nonhazardous waste streams and for sorting commingled recyclable materials into distinct categories have been included in this analysis via the sector Material Recovery Facilities, which is a part of the sector Waste Management and Remediation Services. Similarly, recycling of individual materials, though beyond the scope of this analysis, can also be included if corresponding data are available.

**4.2. ECEC/Money Ratio of Resource Categories for Aggregated Sectors.** Figure 4 shows median ECEC/money ratios for the four resource categories that contribute to the data in Figure 3. These categories include nonrenewable, renewable, and human resources and impact of emissions on human health. Figure 4 leads to several notable observations, some of which are discussed below along with their likely interpretation.

ECEC/$ ratios for nonrenewable resources are higher than those for renewable resources for all subdivisions except Agriculture, Forestry, Fishing, and Hunting. Agricultural and forestry activities convert sunlight and fertile soil into organic biomass and rely primarily on renewable resources. Other

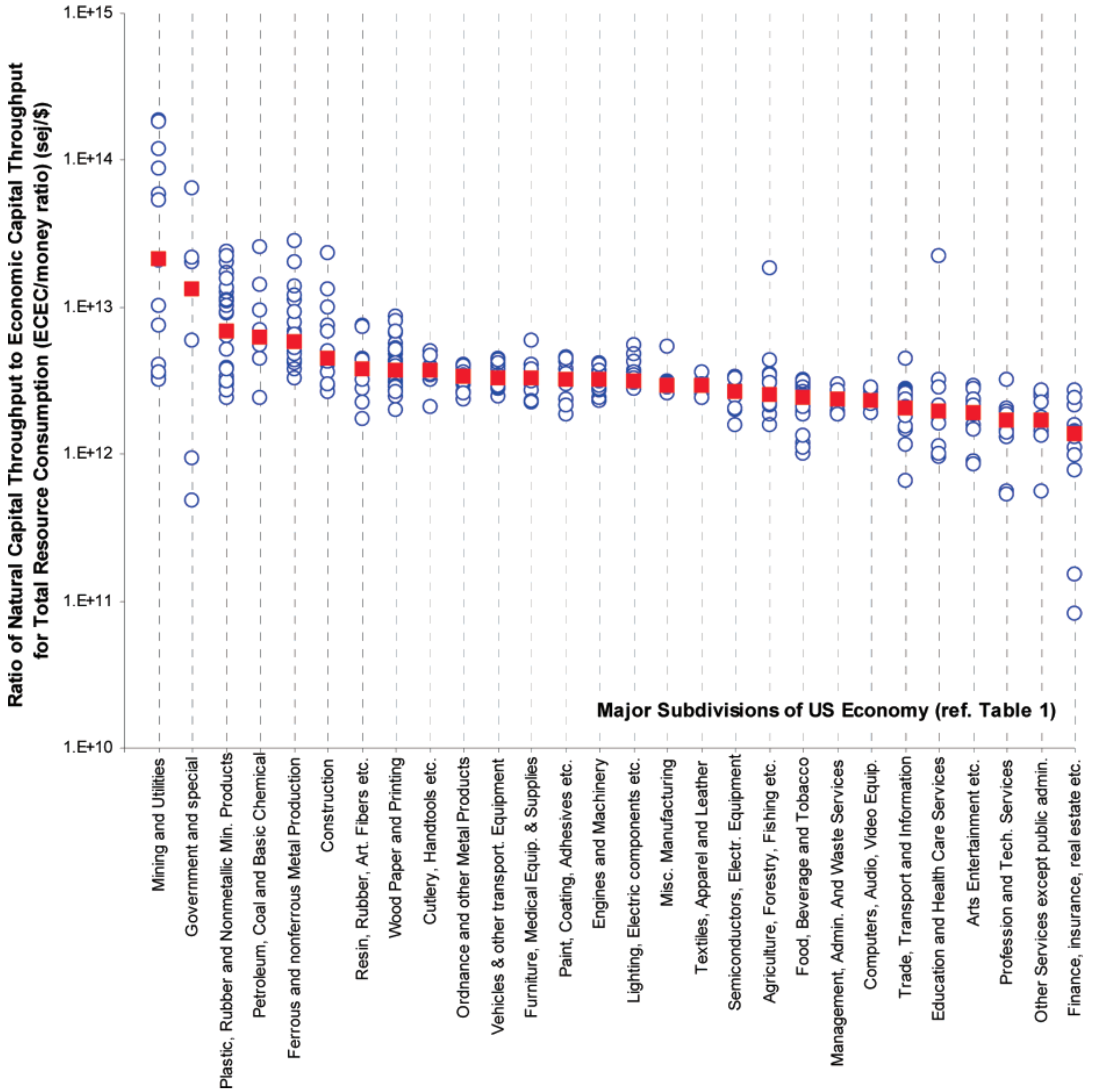


**FIGURE 3. Subdivisions of the U.S. economy organized in descending order of median ECEC/$ ratios. Open circles represent the ratio for individual sectors in each subdivision. Filled squares represent the median for each subdivision. Details about the sectors are in Table 2.**

subdivisions, on the contrary, rely more on nonrenewable resources that include metallic and nonmetallic minerals and fossil fuels.

The coefficient of variation for ECEC/money ratios of human resources is an order of magnitude smaller than that of renewable and nonrenewable ecological resources and human health impact of emissions. This seems to make sense, as human resources are likely to be better internalized in economic prices than ecological resources. For instance, human resources are paid wages commensurate with their skill level, but ecological resources are obtained for free. Relatively small variation in these ratios may also be due to the reliance on monetary data for partitioning of inputs between multiple outputs in the economic system and may simply reflect the increase in consumption of economic products with increasing income along the economic food chain.

The Government and Special subdivision has the highest ECEC/$ ratio for human resources. This is because state, local, and federal government enterprises together employ the maximum number of people among all industry sectors, but the economic throughput in this subdivision is relatively small. In contrast, contributions in the other three categories are comparable to those for the manufacturing subdivisions in the middle of the hierarchy shown in Figure 4.

If the contribution of human resources is excluded from total ECEC/money ratios, the order of the 28 subdivisions listed in Table 2 does not change drastically. Subdivisions of Government and Special, and Agriculture, Forestry, Fishing, and Hunting show the maximum shift. The former subdivision moves further up the economic food chain, from position 2 to position 16, because it depends on human resources the most. On the contrary, the latter subdivision has the least reliance on human resources and, consequently, shows the maximum shift down the economic food chain, from position 19 to position 10.

ECEC/$ ratios for nonrenewable resources dominate the total for resource extraction and infrastructure subdivisions, such as Mining and Utilities; Petroleum, Coal, and Basic Chemicals; and Plastic, Rubber, and Nonmetallic Mineral Products. In contrast, ECEC/$ ratios for human resources

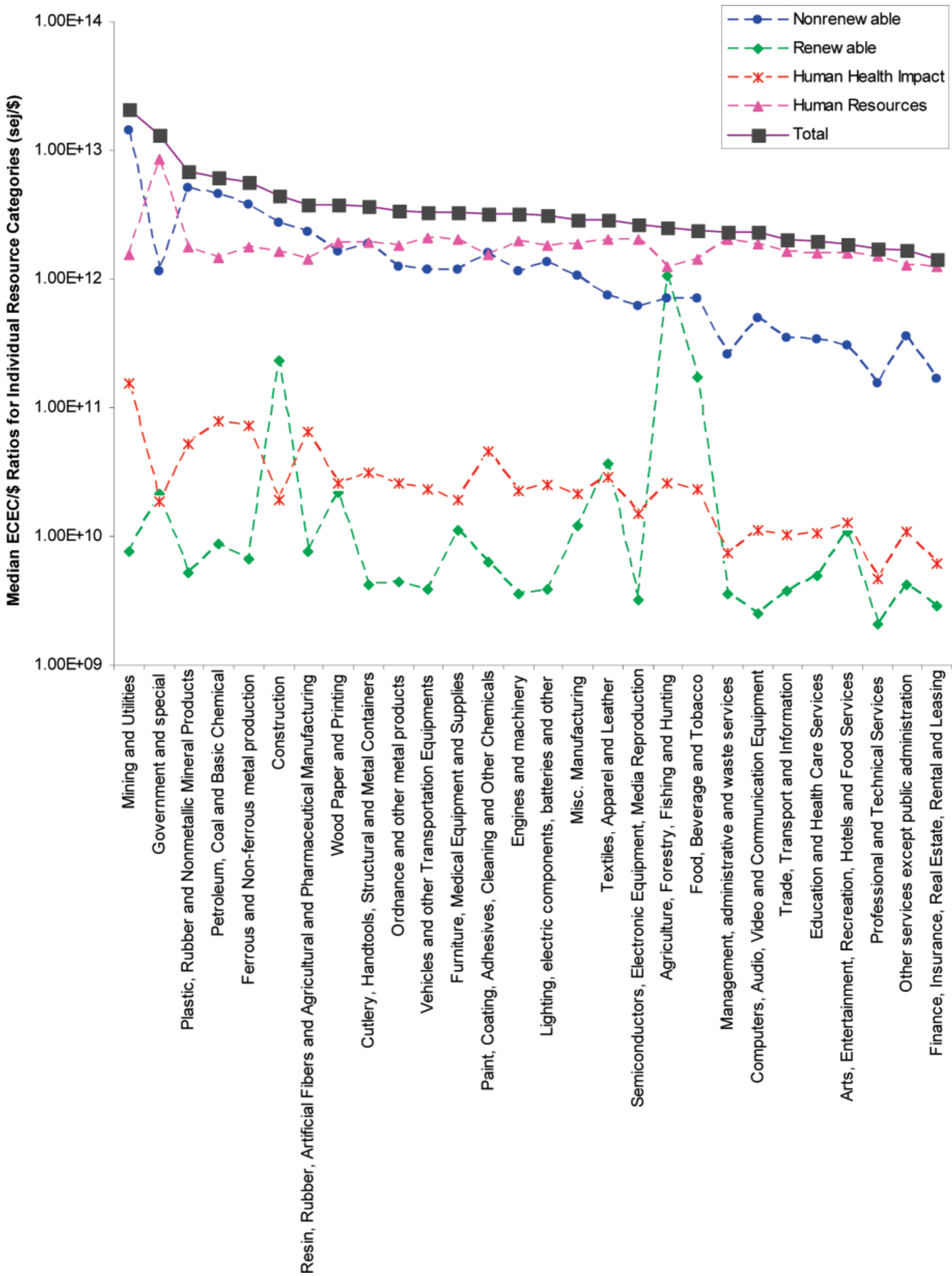


**FIGURE 4. ECEC/money ratios for individual resource categories for Industrial subdivisions listed in Table 2.**

dominate the total for advanced manufacturing and service subdivisions. This corroborates the understanding that resource extraction and infrastructure industries rely more on natural capital, whereas advanced manufacturing and service industries that represent the modern-age knowledge economy rely more on intellectual capital (*23*, *34*). This observation may also hold within each subdivision. For instance, within the Finance, Insurance, Real Estate, Rental, and Leasing subdivision, the human-resource-intensive Insurance Carriers sector has the highest relative contribution from human resources (96.4%), whereas the Real Estate sector has the lowest relative contribution from human resources (64%), implying that the latter sector may be less dependent on intellectual capital. Whether growth of intellectual capital can be decoupled from the use of natural capital and to what extent and whether there are limits to this decoupling are all relevant and interesting questions that are beyond the scope of this analysis.

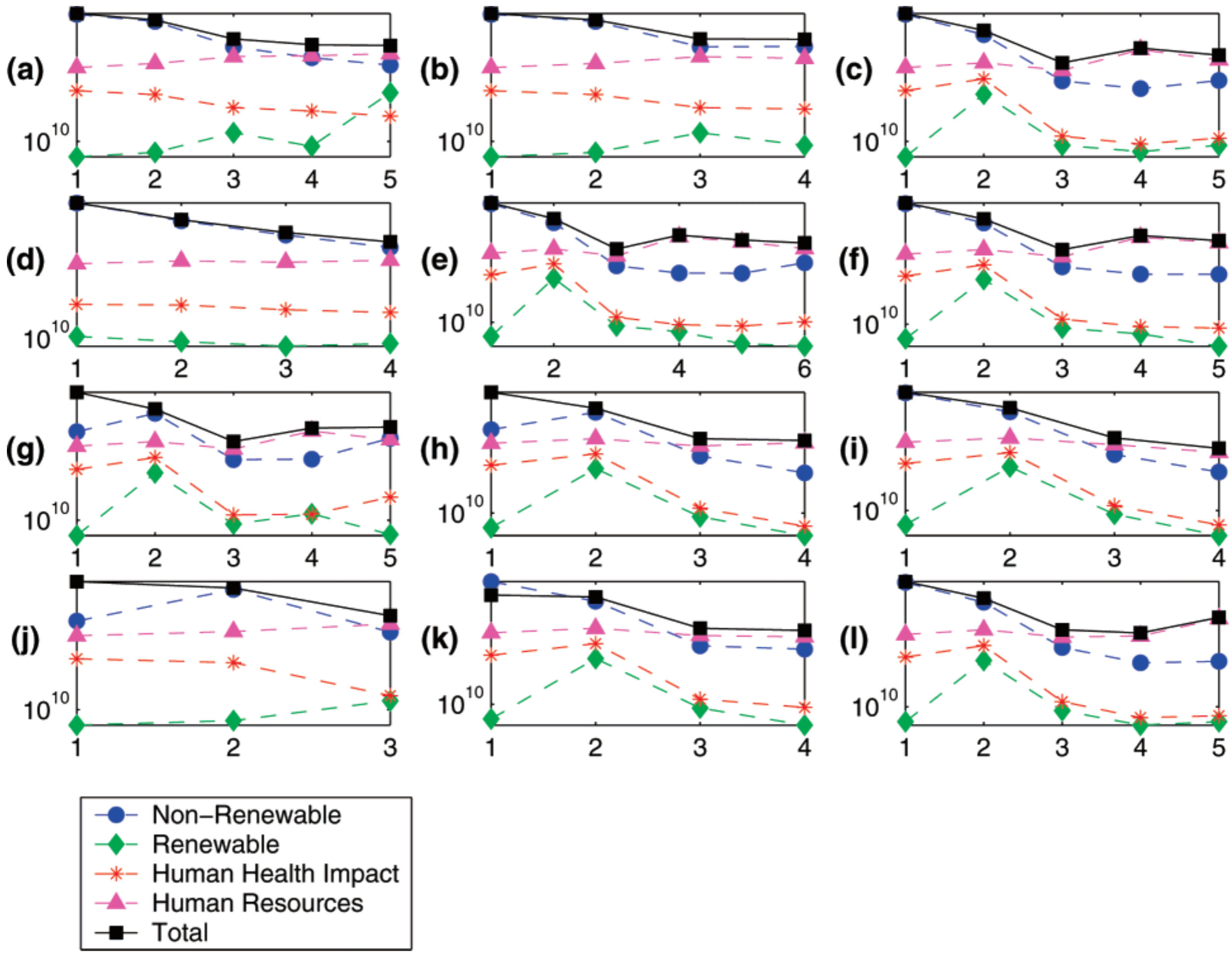


**FIGURE 5. Variation in ECEC/money ratio along supply chain stages (*x*-axis, supply chain stages listed in Table 3; *y*-axis, ECEC/money ratio (sej/$)): (a) Fiber, Yarn and Thread Mills (NAICS 313100); (b) Plastic Material and Resin Manufacturing (NAICS 325211); (c) Pharmaceutical and Medical Manufacturing (NAICS 325400); (d) Copper Wire, Except Mechanical, Drawing (NAICS 331422); (e) Semiconductor and Related Device Manufacturing (NAICS 334413); (f) Wholesale Trade (NAICS 420000); (g) Air Transportation (NAICS 481000); (h) Machinery and Equipment Rental and Leasing (NAICS 532400), (i) Legal Services (NAICS 541100); (j) Waste Management and Remediation Services (NAICS 562000); (k) Colleges, Universities, and Junior Colleges (NAICS 611A00); and (l) Spectator Sports (NAICS 711200). Additional details are in the Supporting Information.**

Focusing on outlying sectors in the identified economic hierarchy reveals that the Logging sector has an uncharacteristically high ECEC/money ratio when compared to other sectors from the Agriculture, Forestry, Fishing, and Hunting subdivision. This is because Logging taps into a relatively high transformity biospheric resource, namely, timber, whereas other agricultural sectors use lower transformity inputs and contribute to the lithosphere via return of detrital matter. Similarly, the sector Home Health Care Services has an uncharacteristically high ECEC/money ratio when compared to other sectors from the Education and Health Care Services subdivision. Here, the high ECEC/money ratio is attributable to that sector's heavy reliance on human resources. Such observations are often nonintuitive and may be relevant for policy making.

**4.3. Analysis of Supply Chains of Industrial Sectors from Detailed Data.** Analysis of supply chains of individual industry sectors selected from all the 488 sectors provides additional insight while exhibiting trends similar to those discussed in sections 4.1 and 4.2 for aggregated subdivisions. For this analysis, industry sectors were chosen so as to cover manufacturing and service subdivisions of the economy. These industries being away from the economy–ecosystem interface have relatively long supply chains. A linear supply chain was obtained from the complex supply network according to the method discussed in section 3.

Figure 5 shows the variation in ECEC/money ratios along supply chain stages of 12 typical industry sectors. These ratios are shown for renewable and nonrenewable resources, human health impact of emissions, contribution of natural capital via human resources, and their total. Additional details about supply chain components of these sectors and economic and natural capital flows through them are provided in Table 3 and the Supporting Information. In general, like the aggregate sectors, all supply chains exhibit a decreasing overall trend for the ECEC/money ratios. Graphs for the sectors Plastic Material and Resin Manufacturing (Figure 5b); Copper Wire, Except Mechanical, Drawing (Figure 5d); Machinery Equipment Rental and Leasing (Figure 5h); Legal Services (Figure 5i); Waste Management and Remediation Services (Figure 5j); and Colleges, Universities and Junior Colleges (Figure 5k) show a monotonic decrease in ECEC/money ratio for total resource consumption, indicating a consistently disproportionate increase in natural capital flows in comparison with economic capital flows along the supply chain. In these cases, the relationship between natural and economic capital flows is convex, as hypothesized by Clift and Wright (*25*).

However, for the sectors Pharmaceutical and Medicine Manufacturing (Figure 5c), Semiconductor and Related Device Manufacturing (Figure 5e), Wholesale Trade (Figure 5f), and Air Transportation (Figure 5g), such monotonic

**TABLE 3. Supply Chain Stages for Figure 5**

| Figure 5a | Figure 5b | Figure 5c |
|---|---|---|
| Oil and Gas Extraction<br>Petroleum Refineries<br>Other Basic Organic Chemical Manufacturing<br>Noncellulosic Organic Fiber Manufacturing<br>Fiber Yarn and Thread Mills | Oil and Gas Extraction<br>Petroleum Refineries<br>Other Basic Chemical Manufacturing<br>Plastic Material and Resin Manufacturing | Oil and Gas Extraction<br>Power Generation and Supply<br>Real Estate<br>Management of Companies and Enterprises<br>Pharmaceutical and Medical Manufacturing |
| **Figure 5d** | **Figure 5e** | **Figure 5f** |
| Copper, Nickel, Lead, and Zinc Mining<br>Primary Smelting and Refining of Copper<br>Copper Rolling, Drawing, and Extruding<br>Copper Wire, Except Mechanical, Drawing | Oil and Gas Extraction<br>Power Generation and Supply<br>Real Estate<br>Management of Companies and Enterprises<br>Semiconductor and Related Device Manufacturing | Oil and Gas Extraction<br>Power Generation and Supply<br>Real Estate<br>Management of Companies and Enterprises<br>Wholesale Trade |
| **Figure 5g** | **Figure 5h** | **Figure 5i** |
| Oil and Gas Extraction<br>Power Generation and Supply<br>Real Estate<br>Travel Management and Reservation Services<br>Air Transportation | Oil and Gas Extraction<br>Power Generation and Supply<br>Real Estate<br>Machinery and Equipment Rental and Leasing | Oil and Gas Extraction<br>Power Generation and Supply<br>Real Estate<br>Legal Services |
| **Figure 5j** | **Figure 5k** | **Figure 5l** |
| Oil and Gas Extraction<br>Petroleum Refineries<br>Waste Management and Remediation Services | Oil and Gas Extraction<br>Power Generation and Supply<br>Real Estate<br>Colleges, Universities, and Junior Colleges | Oil and Gas Extraction<br>Power Generation and Supply<br>Real Estate<br>Promoters of Performing Arts and Sport and Agents of Public Figures<br>Spectator Sports |

decrease is violated by a relatively small ECEC/money ratio for the sector Real Estate. This small ratio indicates that, considering its position in the supply chain, Real Estate may have an uncharacteristically high economic throughput as compared to other sectors at a similar level in the supply network.

Graphs for ECEC/money ratios for *renewable resources* for the sectors Pharmaceutical and Medicine Manufacturing (Figure 5c); Semiconductor and Related Device Manufacturing (Figure 5e); Wholesale Trade (Figure 5f); Air Transportation (Figure 5g); Machinery Equipment Rental and Leasing (Figure 5h); Legal Services (Figure 5i); Colleges, Universities and Junior Colleges (Figure 5k); and Spectator Sports (Figure 5l) show a prominent peak for the sector Power Generation and Supply. The peak occurs because Power Generation and Supply, which has the Oil and Gas Extraction sector as the most significant first-order supplier, relies more on renewable ecosystem services such as wind and hydropotential and geothermal heat, while the Oil and Gas Extraction sector relies predominantly on nonrenewable fossil fuels and has hardly any contribution from renewable resources. In general, the contribution of nonrenewable resources to each sector is much larger than that of renewable resources due to the greater reliance of the modern economy on nonrenewable resources and lower thermodynamic efficiency of creating these resources in nature. Furthermore, similar to Figure 4, graphs of nonrenewable resources and human resources intersect for the individual supply chains shown in Figure 5. This further supports the observation that infrastructure industries such as mining and utilities, rely more on nonrenewable ecological resources and natural capital whereas service industries rely more on human resources and intellectual capital.

If the contribution of human resources is ignored from this analysis, graphs of total ECEC/$ ratios closely follow those for nonrenewable resources (blue circles in Figure 5) and the monotonic decrease in ECEC/$ ratios is much more consistent for all supply chains. Moreover, certain industry sectors, namely, Real Estate, Power Generation and Supply, and Wholesale Trade, appear in supply chains of a large variety of industry sectors. Consequently, these sectors seem to be the critical nodes or keystone sectors of the economy. A marginal improvement in natural capital valuation in these sectors is likely to have a much greater impact on the economy than a similar improvement in a relatively remote and less well connected sector of the economy.

## 5. Implications for Sustainability

ECEC/money ratio is a measure of the discrepancy between thermodynamic work required to produce a product or service and the willingness of people to pay for it. Such discrepancy is known to be one of the root causes underlying the lack of integration of the “ecoservices” sector with the rest of the economy (*26*). ECEC/money ratios do not support or debunk any theory of value, but rather provide a quantitative insight into the relationship between thermodynamic work and economic prices. Such insight can be useful in rationalization of economic policies to make them ecologically more conscious. This section discusses some of the implications of the variation in ratios of natural to economic capitals along supply chains on sustainability of corporate reorganization, ecoefficiency metrics, trade, and outsourcing. Opportunities for further work are also identified.

Since basic infrastructure industries are relative underperformers of the economy as compared to the high-value-

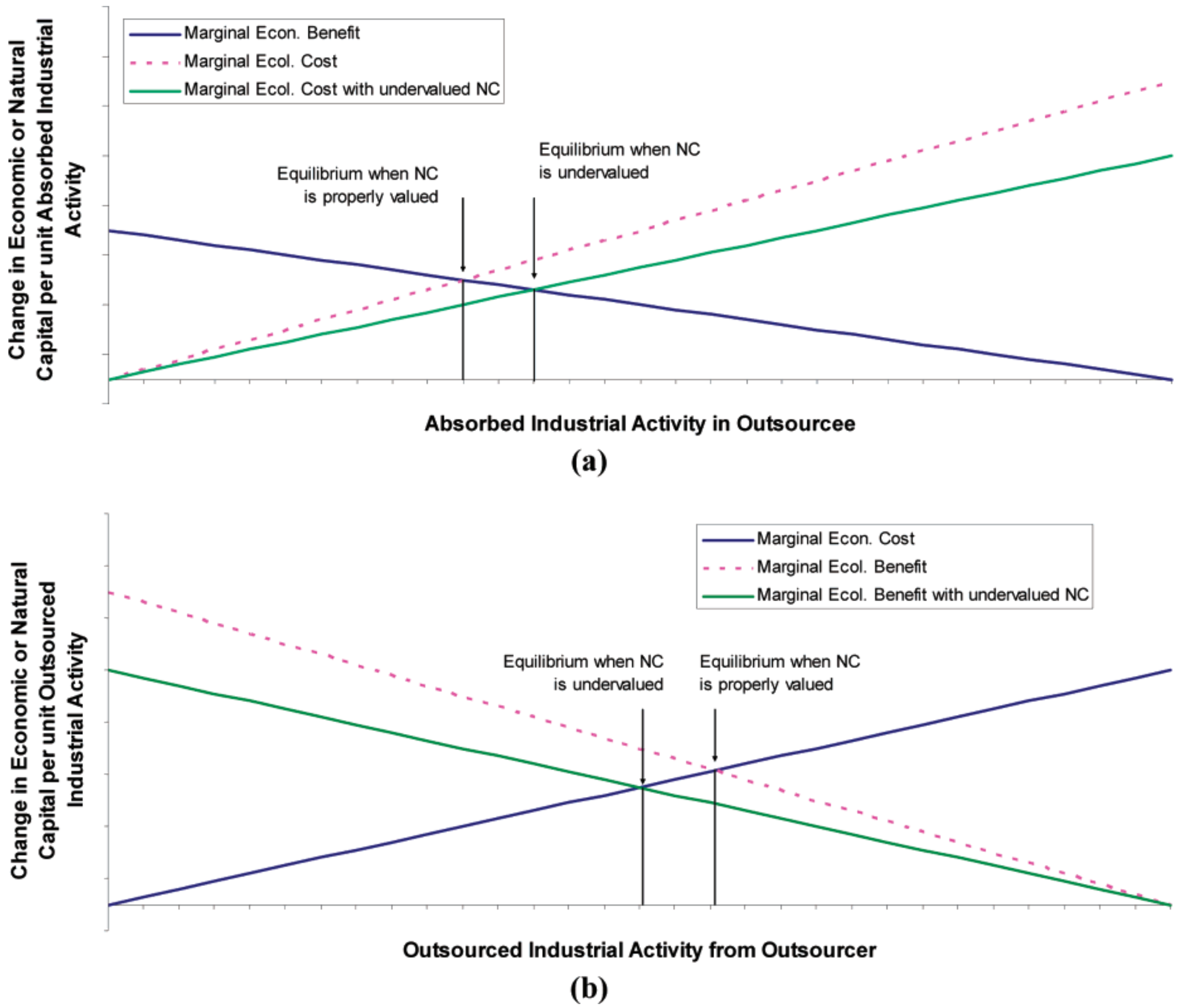


**FIGURE 6. (a) Marginal changes in economic and natural capital as a function of absorbed industrial activity in outsourcees. (b) Marginal changes in economic and natural capital as a function of outsourced industrial activity in outsourcers.**

added service and advanced manufacturing industries, corporations have often sold off or outsourced such assets to gain a strategic advantage. Such actions may also allow them to move to trajectories of higher growth by switching to emerging markets and new technologies, positioning themselves favorably in market cycles of creative-destruction (*35*). For example, DuPont spun off Conoco, and Monsanto divested its commodity chemicals business with this objective in mind (*36*). The higher ECEC to money ratio for these basic industries means that getting rid of them will also improve commonly used sustainability and ecoefficiency metrics, at least for as long as natural capital remains under valued. Furthermore, most of the existing industrial sustainability metrics normalize the environmental burden by monetary value added (*13*) and do not consider effects on economic and natural capitals at larger scales. This can create an illusion of progress toward sustainability since such indicators can be improved by simply becoming more profitable or moving up the economic food chain, while actually eroding the net productive capital base they rely on for their future operations. The data and approach used in this paper may be combined with process and life cycle information to enable the development of more holistic and hierarchical sustainability metrics (*37*). Consideration of marginal changes in economic and natural capitals coupled with identification and quantification of critical natural capital can be a more rigorous way of addressing sustainability issues.

Replacement of less value-added industries by more value-added ones is also evident on a macroeconomic scale, wherein business enterprises in developed countries are increasingly outsourcing extractive and basic manufacturing-related activities abroad and are replacing them by service industries that are better at value-addition, have higher growth prospects and returns on investment and lower risk perceptions and environmental costs. For instance, 50% of the manufactured goods bought by American people today are produced abroad, up from 31% in 1987 (*38*). Even activities such as software writing and customer help desks that are being outsourced seem to have relatively less value-addition in comparison to the activities that are higher up in their supply chains, namely, finance, health care services, banking, and insurance.

As industrial activity in developed countries shifts toward the more value-added end of the hierarchy, the result is reduced consumption of natural capital per unit of economic capital. The exact opposite situation is likely to occur in developing countries, where absorption of the outsourced activity leads to creation of economic capital at the expense of a disproportionately large amount of natural capital as compared to that consumed by more advanced economic sectors (*23*, *24*). This insight assumes that the hierarchical structure of the economy in other countries is qualitatively similar to that revealed in this work for the U.S. That is, the ratio of the throughput of natural to economic capital is higher for extractive and basic manufacturing than more advanced manufacturing and service industries, regardless of their geographic location. In other words, dirtier industries remain dirtier, regardless of their location. The validity of this assumption has been shown by many empirical studies listed in ref *23*. Of course, if data like those used in this work are available for other countries, they should be used for a similar analysis and a more comprehensive comparison, but such data are hard to find.

Even though outsourcing of industries at the lower end of the economic hierarchy uses a disproportionately large amount of natural capital with respect to the created economic capital, it need not imply that outsourcing is always undesirable, since marginal costs and benefits need to be considered as well. This is explained with the help of hypothetical marginal curves shown in Figure 6. In either case, the sustainability limit based on a *weak sustainability paradigm* would follow the theory of comparative advantages and coincide with the point where marginal changes in the net sum of economic, natural, and social capitals turn negative (*39*, *40*). This coincides with the point where marginal benefit and marginal cost curves intersect. At this equilibrium point the net capital base reaches a maximum. In practice, it is likely that the equilibria for outsourcees and outsourcers may not coincide, as valuation of economic and natural capitals may differ from region to region. Figure 6, parts a and b, also shows equilibrium points for outsourcees and outsourcers when natural capital is undervalued, which is usually the case in the current economic system. In such a case, the marginal ecological cost curve for outsourcees and the marginal ecological benefit curve for outsourcers shift downward. Consequently, the new equilibrium points represent a higher limit for sustainable absorption of outsourced activity in outsourcees and a lower limit for sustainable outsourcing of industrial activity in outsourcers. That is, outsourcing will be considered to be more beneficial than it really is to both sides, leading to more consumption of natural capital than optimal for the outsourcee and less saving of natural capital than optimal for the outsourcer.

From the viewpoint of strong sustainability, outsourcing may reduce sustainability of the outsourcees if their lost natural capital is irreplaceable or falls below a critical limit. This loss of natural capital is likely to be even more than what is indicated by the ratios calculated in this work if environmental regulations are weak or not enforced, or if the ECEC of natural capital is higher due to geographical factors such as greater biodiversity. This may result in the outsourced activity being less efficient than in the U.S., resulting in even higher ECEC/money ratios. Identification and quantification of critical natural capital is an important and active area of research (*41*). It is defined as a set of environmental resources that perform important environmental functions and for which no substitute in terms of manufactured, human, or other natural capital exists (*42*). Criticality of natural capital depends on various economic, ecological, political, and social aspects that differ in space and time (*43*). Criticality is different from an economic or ecological perspective. Examples of economic criteria for determining criticality include productive, consumptive, and option values, whereas the ecological criteria include life support value, renewability, and substitutability (*41*). Both perspectives are important from the standpoint of the strong sustainability paradigm.

This discussion implies that for the outsourcees to enhance their sustainability, they must use the economic capital available from outsourced activities to quickly move up the economic food chain toward industries with lower ECEC/money ratios, without sending natural capital below its critical limit. Similarly, compensating for any loss of economic capital and jobs for outsourcers also requires them to move further up the economic food chain via new innovations. Regional sustainability may be improved by outsourcing dirtier sectors, but such a shift toward lower ECEC/money industries does not imply complete elimination of higher ECEC/money industries from the global economic system. Basic infrastructure activities such as mining and utilities are vital to all industrial activity, regardless of the enormous stress they put on ecosystems. Consequently, from a global perspective, adjustment in market prices to reflect the contribution of natural capital is ultimately necessary for sustainability. Such adjustment may be most effective when applied to sectors that appear frequently in most supply chains. This article indicates that Real Estate, Wholesale Trade, and Power Generation and Supply may be such keystone sectors and deserve further verification. Such changes require combination of the type of analysis presented in this paper with economic principles and knowledge about the crucial role of natural capital, along with global cooperation and enlightened policies.

The data, approach, and insight from this work point toward many new research opportunities. The comprehensiveness and scientific rigor of the data should present new opportunities for integrated empirical and theoretical research of the impact of policies and trade on the environment. For example, the data may be useful for empirical study of the environmental Kuznets curve (EKC) hypothesis, which suggests that over time, as economic prosperity increases, pollution increases at first, goes through a peak, and then decreases. Since the industries being outsourced from the U.S. are lower in the economic food chain, it may indicate validity of the EKC hypothesis for the U.S. However, more careful and statistically rigorous studies that also account for temporal aspects are required. The ECEC/money ratios are also useful for hybrid thermodynamic LCA for comparing technology alternatives and corporate sustainability metrics. It should also be possible to gain new insight about other sectors and supply chains by further analysis of this large data set. The data may also be improved if information about material and energy flow in economic sectors become available.

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## Supporting Information Available

(1) details about how a monotonic decrease in the ECEC/money ratios along a supply chain from source to final product corresponds to a convex correlation between cumulative ecosystem contribution and cumulative economic activity; (2) details corresponding to the supply chains in Figure 5 and Table 3; (3) ECEC/money ratios for all the 488 sectors of the 1997 U.S. economy. This material is available free of charge via the Internet at http://pubs.acs.org.

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