Economic versus Natural Capital Flows in Industrial Supply Networks - Implications to Sustainability

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Abstract: It is widely recognized that consideration of economic criteria alone is not adequate to build sustainable industrial enterprises, but environmental and social criteria must also be incorporated in business decisions. It is understood that such a comprehensive perspective is essential to develop sustainable businesses that are lean, resilient, cost effective and add value to the stake holders. However, one of the biggest impediments in incorporating environmental and social considerations in decision-making is the lack of an accounting technique that can appreciate the contribution of a wide variety of ecological resources. Existing techniques such as Material Flow Analysis (MFA) and Exergetic Analysis do appreciate some of the ecological resources consumed by industrial activity, but have fundamental limitations to include others. For instance, MFA can only appreciate material flows but not energetic flows like sunlight and tidal waves. Exergy Analysis also fails to acknowledge various ecological products and services. Thermodynamic Input-Output Analysis (TIOA), theoretical aspects of which have been discussed in previous AIChE conferences, overcomes many of the shortcomings of the aforementioned techniques for environmentally conscious decision making. TIOA successfully incorporates contribution of ecological products and services to industrial processes by appreciating the underlying economic and ecological linkages. A thermodynamic approach provides a common currency or a way to deal with a diverse set of units, as any system – economic or ecological, can be considered a network of energy flows. TIOA is based on the concept of Ecological Cumulative Exergy Consumption (ECEC). This approach is closely related to emergy analysis but does not rely on its controversial claims. This presentation will illustrate the use of TIOA as a practical tool for environmentally conscious decision making. It will demonstrate how conventional economic analysis can be used in conjunction with TIOA to determine economic and natural capital requirements of industrial processes. Such analysis uses a rigorous multiscale data fusion framework to compile Life Cycle Inventory, and in general follows the principles of Hybrid LCA. TIOA can also be used to develop simple-to-calculate and hierarchical sustainability metrics. This presentation will demonstrate the application of hybrid TIO analysis to compute sustainability metrics for alternative electricity generation systems, and illustrate their use for decision making. Furthermore, this presentation will discuss how TIOA can be used to determine economic and natural capital flows in Industrial Supply Networks, and how such insight may be used for appreciating the relationship between supply chains and sustainability. Supply networks of basic infrastructure industries will be shown to have natural capital consumption disproportionate to their addition to economic capital. These results have important implications to on-going debates on sustainability and outsourcing, and may be used for “greening the supply chain” and to adjust international trade policies.

Sustainability of human activities requires that the productive capital base available to society in the future must be at least as large as that inherited from its past (*1*). The productive capital base consists of economic capital that includes assets such as buildings, machinery, and infrastructure, natural capital that includes environmental functions that provide natural resources to production activities, and dissipate and absorb emissions from them (*2*,*3*,*4*), and social capital that consists of human resources, value systems and social organizations through which contributions of individuals are mobilized and coordinated. The criterion of weak sustainability 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 (*5*). Since natural capital usually lies outside the market, many efforts have been made for quantifying its importance. These include monetary valuation (*6*,*7*) and analysis of the material and energy flows (*8*,*9*,*10*). A variety of methods and metrics have been devised for evaluating sustainability at different spatial scales. These range from national measures of genuine investment which account, at least partially, for the three capitals (*11*) to corporate measures of sustainability and eco-efficiency that are being used in annual sustainability reports for evaluating socially responsible investments (*12*,*13*,*14*). Estimating the quantities of different types of capital and their relative importance remains a formidable challenge facing these methods and is an active area of research.

We have recently combined existing data and methods in systems engineering, systems ecology and life cycle assessment to quantify the contribution of ecosystem goods and services to industrial activity (*15*). This approach treats industrial and ecological systems as a network of energy flow, and estimates the contribution of natural capital to an industrial product or process by the ecological cumulative exergy consumption (ECEC) of the corresponding supply network. Exergy represents the maximum energy available for doing work and captures the first and second laws of thermodynamics. It is the only truly limiting resource on the planet, and provides a scientifically sound common currency for analyzing industrial and ecological systems. Unlike claims made by others in the past (*16*,*17*), this approach is not meant to replace preference-based valuation of natural capital, but rather to strengthen it with a sound biophysical basis. Exergy analysis has already found wide use for improving process efficiency (*18*) and assessing ecosystems (*19*). ECEC is closely related to the concept of emergy and uses some of its transformity values (*10*), without relying on any of its controversial claims such as the energy theory of value or the maximum empower principle (*20*). The transformity values are simply the reciprocal of the cumulative degree of perfection (*18*), and permit representation of the contribution of ecosystem goods and services in consistent thermodynamic units.

We quantify the contribution of ecosystem goods and services to sectors of the U.S. economy with data from various public sources (*21*), and their transformities (*10*). The cumulative exergy embodied in natural capital entering a sector is propagated through all sectors of the U.S. Economy. Due to the absence of comprehensive material or energy-based transaction matrices for the U.S. economy, data about monetary exchange between sectors from the economic input-output model are used to propagate the ecological cumulative exergy consumption through the economic network. The resulting thermodynamic input-output analysis (TIOA) considers the integrated economic-ecological system as a single network of energy flows allowing use of a common currency to evaluate the flow of ECEC in various sectors. It successfully accounts for variety of ecosystem products such as coal, petroleum, timber and atmospheric oxygen; ecosystem services such as sunlight, wind and fertile soil, human resources employed in the form of labor and impact of emissions on human and ecosystem health. TIOA applies the allocation algorithm of ECEC analysis to study exergy flows through partially-known ecological networks and input-output analysis for the well-known economic networks. Similar approaches have been used by Costanza to study energy intensities of industry sectors (*17*) and Hannon to study energetic interactions in ecosystems (*22*). However, these studies are not as comprehensive as the work presented in this paper. These studies only comply with conservation of energy, but do not account for the quality differences between energy streams.

In this article, we use TIOA to evaluate the reliance on natural capital of sectors in the 1997 benchmark model of the U.S. economy (*23*). We use the ratio of ECEC to money as a measure of the natural capital needed to generate a dollar of economic activity, and study the change in this ratio in the economic network. This ratio may provide a unique insight into the discrepancy between natural capital needed to produce a product or service and willingness of people to pay for it. Activities with a high ECEC/money ratio may not even satisfy the criterion of weak sustainability since the amount of economic capital generated from the consumed natural capital is relatively small. Analysis of the ECEC to money ratio of industrial sectors and their supply chains can provide useful insight into their sustainability and help identify alternatives for greening the supply chain.

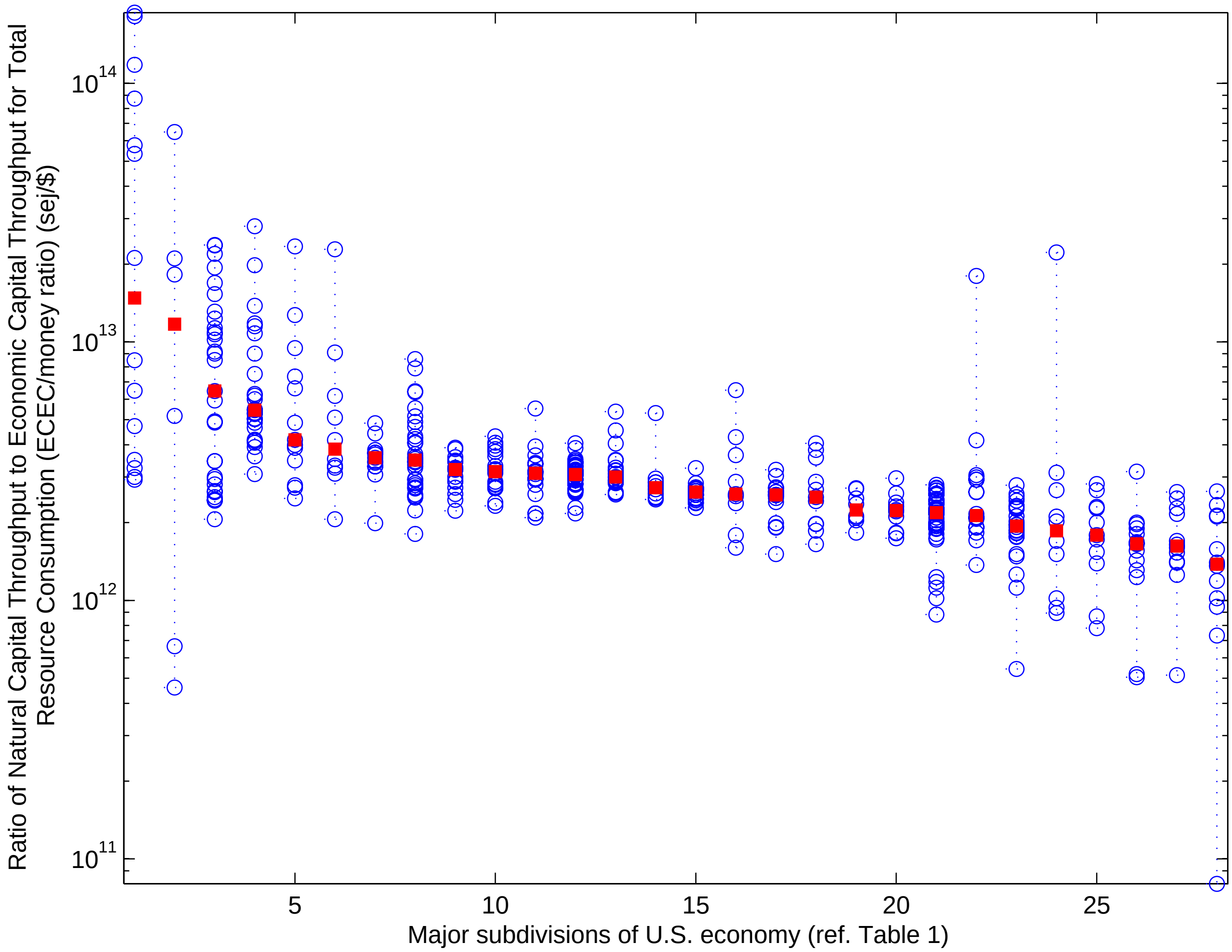

Figure 1. Subdivisions of U.S. Economy organized in ascending order of median ECEC/$ ratios

The 491-sector 1997 U.S. economy may be aggregated into 28 major subdivisions as listed in Table 1. These subdivisions are defined by the Bureau of Economic Analysis (*23*), and have been used in economic input-output life cycle assessment (*24*). This aggregation scheme is preferred in this analysis as it provides a more concise overview of the economy than the 3-digit NAICS codes, and yet is more detailed than the 2-digit NAICS codes. The trend and general conclusions are similar for alternate methods of aggregation. The median ECEC to money ratios for these aggregated sectors is plotted in Figure 1 along with the distribution of the constituent sectors in each aggregate category. The resulting 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, 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.

Table 1. 28 Major subdivisions of U.S. Economy as defined in EIOLCA and their corresponding NAICS codes

Position In Figure 1	Subdivisions of U.S. Economy (1997 U.S. Industry Benchmark Model Definitions)	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	Ferrous and Non-ferrous metal production	331, 3321
5	Construction	23
6	Petroleum, Coal and Basic Chemical	324, 3251
7	Cutlery, Handtools, Structural and Metal Containers	3322-3324
8	Wood Paper and Printing	321, 322, 323
9	Ordnance and other metal products	3325-3329
10	Vehicles and other Transportation Equipments	336
11	Furniture, Medical Equipment and Supplies	337
12	Engines and machinery	333
13	Lighting, electric components, batteries and other	335
14	Misc. Manufacturing	339
15	Textiles, Apparel and Leather	313, 314, 315, 316
16	Resin, Rubber, Artificial Fibers and Agricultural and Pharmaceutical Manufacturing	3252, 3253, 3254
17	Semiconductors, Electronic Equipment, Media Reproduction	3344, 3345, 3346
18	Paint, Coating, Adhesives, Cleaning and Other Chemicals	3255-3259
19	Computers, Audio, Video and Communication Equipment	3341, 3342, 3343
20	Management, administrative and waste services	55, 56
21	Food, Beverage and Tobacco	311, 312
22	Agriculture, Forestry, Fishing and Hunting	11
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

Analysis of supply chains of individual industry sectors also reveals a similar trend. 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 by analyzing the economic input-output data. The largest supplier at each stage was selected, while avoiding the creation of loops in the supply chain. This approach is equivalent to finding an elementary dipath in a digraph (*25*,*26*) or the most important first-order path at each stage in *Structural Path Analysis* (*27*).

Figure 2 shows variation in ECEC/money ratios along supply chain stages of 12 such industry sectors. These ratios are shown for renewable and non-renewable resources, human health impact of emissions, and their total. Furthermore, Table 2 provides additional details about supply chain components of one of these sectors, namely the sector of Plastic Material and Resin Manufacturing, and economic and natural capital flows through them. In general, all supply chains exhibit a decreasing trend for the ECEC/money ratios. Graphs for Sectors of Plastic Material and Resin Manufacturing (Graph 2(**B**)), Copper Wire, except mechanical, drawing (Graph 2(**D**)), Machinery Equipment Rental and Leasing (Graph 2(**H**)), Legal Services (Graph 2(**I**)), Waste Management and Remediation Services (Graph 2(**J**)) and Colleges, Universities and Junior Colleges (Graph 2(**K**)) show a monotonic decrease in ECEC/money ratio for total resource consumption, indicating a consistently disproportionate increase in natural capital flows vis-à-vis economic capital flows up the supply chain. This observation also conforms to the convex correlation between cumulative impact of emissions and cumulative value-added hypothesized by Clift and Wright (*28*). For Sectors of Pharmaceutical and Medicine Manufacturing (Graph 2(**C**)), Semiconductor and Related Device Manufacturing (Graph 2(**E**)), Wholesale Trade (Graph 2(**F**)) and Air Transportation (Graph 2(**G**)), such monotonic decrease is violated by a low ECEC/money ratio for the sector of real estate. This small ratio indicates that, considering its position in the supply chain, real estate may have an uncharacteristically high economic valuation as compared to other sectors at a similar level in the supply network. Graphs for ECEC/money ratios for *renewable resources* for sectors of Pharmaceutical and Medicine Manufacturing (Graph 2(**C**)), Semiconductor and Related Device Manufacturing (Graph 2(**E**)), Wholesale Trade (Graph 2(**F**)), Air Transportation (Graph 2(**G**)), Machinery Equipment Rental and Leasing (Graph 2(**H**)), Legal Services (Graph 2(**I**)), Colleges, Universities and Junior Colleges (Graph 2(**K**)) and Spectator Sports (Graph 2(**L**)) show a prominent peak for the sector of Power Generation and Supply. This is on account of the reliance of the sector of Power Generation and Supply on renewable ecosystem services such as wind energy, hydropotential and geopotential for electricity generation. In comparison, the sector of Oil and Gas Extraction has a 97.6% lower ECEC/money ratio for renewable resources. A similar trend is also observed for ECEC/money ratios for human health impact of emissions for these sectors. However, in this case the sector of Oil and Gas Extraction has an ECEC/money ratio for human health impact of emissions that is only 50% lower than that for Power Generation and Supply.

Sectors such as Real Estate, Wholesale Trade and Power Generation and Supply appear frequently in supply chains of many other sectors, indicating that these sectors are among the critical nodes of the economy. Consequently, a marginal change in the valuation of natural capital in these sectors would have a much larger impact than similar improvements in other less critical sectors of the economy. A look at how economic activity and ecosystem contribution accumulate along supply chains reveals that in most cases, as we go up the supply chain (from the process to the supplier), ecosystem contribution increases disproportionately to the economic activity. This is evident from higher ECEC/money ratios for the basic infrastructure industries and lower ECEC/money ratios for value-added service industries. Basic infrastructure industries depend a lot more on ecosystems, but contribute relatively little to the economic activity than the more sophisticated sectors of the economy. One plausible reason for this is that the basic infrastructure industries are technologically less efficient due to having to process a relatively dilute resource, and as a result, have to consume a lot of raw material to produce finished products or services. This gives rise to large *overburdens*, defined in Material Flow Analysis 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) (*9*). Another reason could be failure of market prices to fully appreciate the contribution of ecological resources. Free ecological resources are treated as externalities in neoclassical economics and, hence, are dealt with only tangentially. Another reason could be that people tend to value services and finished products much more than intermediate items, while ecosystem goods and services become economic externalities and are rarely reflected in prices.

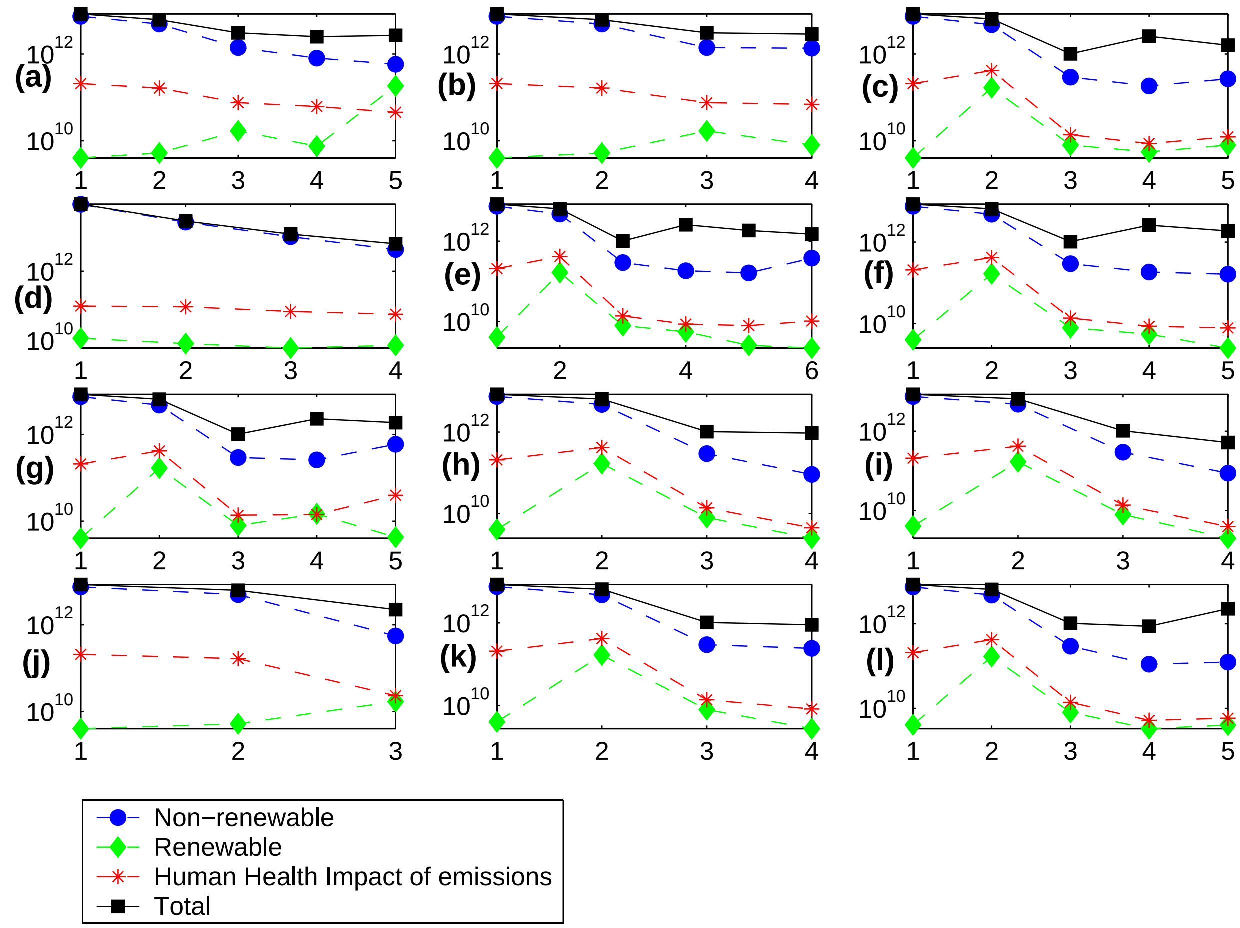

Figure 2. Variation in ECEC/money ratio along supply chain stages (*x*-axis: Supply Chain Stages; *y*-axis: ECEC/money ratio (sej/$)); (**A**) Fiber, yarn & thread mills (NAICS 313100) (**B**) Plastic Material and Resin Manufacturing (NAICS 325211) (**C**) Pharmaceutical and Medical Manufacturing (NAICS 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) (**L**) Spectator sports (NAICS 711200)

The variation in ratios of natural to economic capitals along supply chains has significant implications for sustainability, corporate reorganization and outsourcing. Since basic infrastructure industries are the underperformers of the economy because of their relatively small economic returns and higher environmental costs, getting rid of such industries or substituting them by more value-added industries is a sensible option for many business enterprises. Corporations have routinely done this through corporate restructuring, sell-off of non-performing assets and sick units, and outsourcing. This gives companies a strategic advantage as they can move to trajectories of higher growth by switching to emerging markets and new technologies, and position themselves favorably in market cycles of creativedestruction (*29*). For example, DuPont spun off Conoco and Monsanto divested its commodity chemicals business with this objective in mind (*30*). The industrial push for sustainability provides extra incentive for such divestment activities, at least until natural capital remains undervalued. Replacement of less value-added industry by more value-added industry is also evident on a macroeconomic scale, wherein business enterprises in developed countries are increasingly outsourcing extractive and 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 (*31*).

Table 2. Supply Chain Stages, Economic Activity and ECEC/money ratios for the sector of Plastic Material and Resin Manufacturing (NAICS 325211)

	Economic ($/yr)	**ADD/ECO (sej/$)**	**NONADD/ECO (sej/$)**	**EMM/ECO (sej/$)**	**HR/ECO (sej/$)**	**TOT/ECO (sej/$)**
1. Oil and Gas Extraction	11,194	7.45E+12	4.05E+09	2.08E+11	8.23E+11	8.49E+12
2. Petroleum Refineries	29,776	4.96E+12	5.25E+09	1.65E+11	1.05E+12	6.18E+12
3. Other basic organic chemical manufacturing	234,917	1.42E+12	1.69E+10	7.59E+10	1.58E+12	3.09E+12
4. Plastic Material and Resin Manufacturing	1,067,640	1.37E+12	7.99E+09	6.92E+10	1.43E+12	2.88E+12

ADD/ECO = ECEC/money ratio for Additive (Non-renewable) resources; NONADD/ECO = ECEC/money ratio for Non-Additive (Renewable) resources; EMM/ECO = ECEC/money ratio for Impact of emissions on Human Health; HR/ECO = ECEC/money ratio for Human Resources in the form of employment; TOT/ECO = ECEC/money ratio all total resource consumption

As industrial activity in the developed countries shifts towards the more value-added end of the spectrum, the average valuation of ecological resources increases, automatically discouraging their degradation through market forces. The net result is conservation of natural capital at the expense of the economic capital. The situation is exactly opposite in the developing countries where absorption of the outsourced activity leads to creation of economic capital at the expense of the natural capital. In either case, sustainability limit based on *weak sustainability paradigm* would coincide with the point where marginal changes in the net sum of economic, natural and social capitals turn negative (*32*,*33*,*34*). However, such outsourcing may reduce the sustainability of the outsourcees, particularly from the view of strong sustainability. It seems that outsourcees must use the available economic capital to quickly move up the economic food chain towards more "value-added" industries. This must be done without sending natural capital below a critical amount. Identification and quantification of the critical components of natural capital that make a unique contribution to welfare and cannot be substituted by other forms of capitals is an active area of research (*33*,*35*,*36*). Since criticality of natural capital depends on various economic, ecological, political and social aspects which differ in space and time (*37*), the sustainability limit on outsourcing of industrial activity in developed countries may not coincide with that on absorption of outsourced activity in developing countries.

Consideration of marginal changes in economic and natural capitals coupled with identification and quantification of CNC is a more rigorous way of addressing sustainability issues than other existing econometric methods such as ICI's Environmental Burden approach (*38*) and Unilever's Overall Business Impact Assessment approach (*39*). These methods normalize environmental performance per unit value added by a single global average and, in the process, ignore differences in critical and non-critical natural capital and variation in criticality criterion across spatial and temporal scales. Normalization of environmental burden by value added without considering marginal effects on economic and natural capitals and criticality criterion can create an illusion of sustainable development. Businesses can improve their sustainability indicators by simply becoming more profitable, while actually eroding the net productive capital base they rely on for their future operations. Proposed consideration of marginal effects on economic and natural capital and the criticality criterion plug this loophole in existing econometric and eco-efficiency approaches and sustainability metrics.

Natural and economic aspects of supply chains have been studied in the past, although, most of these studies have focused on either of the two aspects in isolation. Clift and Wrights' study of the relationship between supply chain environmental burdens and economic value-added is a notable exception (*28*). However, their analysis is based on proprietary data, analyzes too few supply chains to derive any general conclusions, focuses only on impact of emissions, and does not consider other components of natural capital such as ecosystem goods and services. On the economic side, Clift and Wrights' study focuses only on added value, and ignores the remaining component of economic capital, namely intermediate inputs from other industry sectors. The analysis presented in this paper is more comprehensive as it considers supply chains of a large number of industry sectors, and is based on non-proprietary data. Moreover, it considers total throughputs of natural capital including renewable and non-renewable 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 (*40*).

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