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Accounting for Ecosystem Services in Life Cycle Assessment, Part I: A Critical Review

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If life cycle oriented methods are to encourage sustainable development, they must account for the role of ecosystem goods and services, since these form the basis of planetary activities and human well-being. This article reviews methods that are relevant to accounting for the role of nature and that could be integrated into life cycle oriented approaches. These include methods developed by ecologists for quantifying ecosystem services, by ecological economists for monetary valuation, and life cycle methods such as conventional life cycle assessment, thermodynamic methods for resource accounting such as exergy and emergy analysis, variations of the ecological footprint approach, and human appropriation of net primary productivity. Each approach has its strengths: economic methods are able to quantify the value of cultural services; LCA considers emissions and assesses their impact; emergy accounts for supporting services in terms of cumulative exergy; and ecological footprint is intuitively appealing and considers biocapacity. However, no method is able to consider all the ecosystem services, often due to the desire to aggregate all resources in terms of a single unit. This review shows that comprehensive accounting for ecosystem services in LCA requires greater integration among existing methods, hierarchical schemes for interpreting results via multiple levels of aggregation, and greater understanding of the role of ecosystems in supporting human activities. These present many research opportunities that must be addressed to meet the challenges of sustainability.

Introduction

Improving the environmental performance of individual technological processes need not result in a smaller environmental impact since the impact may simply be shifted outside the analysis boundary and because a growth in the volume of products can counteract reductions in impact per unit of product. This realization has encouraged the development of systematic methods that expand the traditional engineering boundary by including the entire life cycle of products and processes. Such methods include life cycle assessment (LCA) (*1*), material flow analysis (*2*), net energy analysis (*3, 4*), exergetic LCA (*5, 6*), cumulative exergy consumption analysis (*7, 8*), emergy analysis (*9, 10*), and ecological footprint analysis (*11*). These methods are expected to help enhance the environmental friendliness and sustainability of human activities, but this expectation can be met only if the analysis boundary is large enough to account for the ecosystem goods and services that support all the technological activities in the life cycle.

Over the last several years, much research has focused on understanding and identifying the role of ecosystem goods and services for human well-being, and several studies have identified their crucial role in sustaining human activities. Examples include quantification of the human domination of the Earth's ecosystems (*12*), role of soils in carbon sequestration (*13*), and importance of pollination services for food production (*14*), etc. In one of the earliest and best known efforts for quantifying the role of nature in monetary terms, Costanza et al. (*15*) claimed that natural capital was more valuable than the global gross economic product. Despite many criticisms of this study (*16*), it was successful in drawing attention to the importance of ecosystems. Many such studies have been carried out since, mostly at national or regional levels (*17*–*19*). The recently completed Millennium Ecosystem Assessment (MEA) (*20*) is the most comprehensive study of the state of natural capital worldwide. It found that human beings have altered ecosystems more rapidly and extensively in the past 50 years than in any comparable period in human history to meet their demands. Among the 24 ecosystem services the study examined, 15 are being degraded or used unsustainably, including fisheries, erosion regulation, and pollination. Clearly, the role of such services and their status must be considered in any approach that aims to enhance the sustainability of human activities. However, existing life cycle oriented methods are not able to capture many ecosystem services. To overcome this crucial shortcoming, a thorough understanding of existing methods, in terms of their ability or inability to account for ecosystems services, is essential.

This article presents a critical review of existing life cycle oriented methods in terms of their ability to account for ecosystem services. The pros and cons of various methods are identified along with the challenges and opportunities for further research. It is our hope that the insight from this article will lead to methods for appreciating the crucial, direct and indirect role of nature in supporting all human activities, and establishing stronger links between industrial ecology, ecosystem ecology, and ecological economics. The rest of this paper is organized as follows. The next section provides an overview of the importance of ecosystem goods and services and their current state and understanding. It also includes a discussion of the challenges that must be addressed to account for ecosystem services in LCA. This is followed by a discussion of relevant research in ecology and ecological economics. These lack a life cycle orientation but are relevant to the topic of this article. A review of conventional life cycle assessment methods is next. These methods focus mainly on quantifying the impact of emissions and account for some

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resources. This is followed by a review of various physically based resource accounting methods such as exergy and emergy analysis. The next section reviews methods that provide aggregate footprint indicators such as ecological footprint, human appropriation of net primary productivity and their modifications. Finally, the challenges of accounting for ecosystem services in life cycle oriented methods are discussed.

Ecological Goods and Services

An ecosystem consists of "plant, animal, and microorganism communities and their nonliving environment interacting as a functional unit" (*21*). Ecological goods and services are life-support benefits human beings obtain from these natural ecosystems (*17*). Goods are material products resulting from past and present ecosystem processes, such as fossil fuels, food, wood, and fiber; and from geological processes such as minerals. Human beings harvest and consume them for economic activities. Ecosystem services are in most cases improvements in the condition or location of things of value (*22*), such as climate modification, nutrient cycles, and waste decomposition. Sometimes, goods and services are collectively called *ecosystem services* for simplicity (*15, 20, 23*). These services can be divided into four categories (*20*):

- *Provisioning* services are products directly obtained from ecosystems, such as food and genetic resources.
- *Regulating* services are benefits obtained from the regulation of ecosystem processes, including control of climate and pollination.
- *Supporting* services are those that are necessary for the production of all other ecosystem services, such as nutrient and water cycles.
- *Cultural* services are spiritual and recreational benefits people obtain from ecosystems, such as knowledge systems, social relations, and aesthetic values.

Specific items in each category are listed in the first column of Table 1. The Millennium Ecosystem Assessment is the most recent effort to assess the current status of the world's ecosystems at local and global scales and to make the connection between ecosystems and human well-being more explicit (*21, 24*). Like previous studies (*12, 17*), this study also concludes that many human activities disrupt ecosystems and reduce their ability to deliver vital services.

To account for these services in decision making at least three important challenges need to be met.

- *Representing the role of ecosystem services*, preferably in quantitative terms, is essential to understand their contributions to a life cycle. Provisioning services are most familiar and easiest to represent quantitatively. However, regulating and supporting services have received less attention due to their indirect role in human activities (*25*) and difficulties in quantification. Due to incomplete knowledge, these services can often be represented only qualitatively. Cultural services have been represented in monetary terms via valuation methods. Thus, accounting for ecosystem services may require handling of data represented in multiple units, quantitative and qualitative information, and uncertainties.
- *Aggregation of raw data* is useful for interpreting highly multivariate data. All aggregation methods result in loss of information and assume substitutability among the variables being aggregated. For this assumption to be valid, equivalency factors for converting the variables into a common numeraire may be used. However, finding a common numeraire and equivalency factors for ecosystem services faces many formidable challenges.
- *Accounting for direct and indirect reliance* on ecosystem services is essential to avoid shifting of impacts beyond the analysis boundary. Many life cycle oriented methods could, in principle, address this task if adapted to also account for ecosystem services.

The rest of this article critically reviews existing methods that aim to encourage or are relevant to ecologically conscious decision making in terms of their ability to account for the categories of ecosystem services identified in the MEA and their approaches for addressing the challenges listed above. The MEA focuses on ecosystem services produced by biological processes. Due to their obvious importance for technological activities, we also consider fossil fuels and minerals. Fossil fuels are produced by previous ecological processes, and both resources are available for mining due to geological and geochemical processes. Thus, we use the term "provisioning services" in a broader context. An overview of all the methods and their characteristics is provided in Table 1.

Methods from Ecology and Ecological Economics

The methods discussed in this section do not necessarily adopt a life cycle view. However, they may provide the basis through which life cycle oriented methods can account for ecosystem services.

Ecological Approaches. Many academic groups (*17, 26, 27*) and nongovernmental organizations (*23, 28*) are focusing on understanding (*29*) and addressing the challenges identified by the MEA. For example, the natural capital project (*28*) is developing tools for modeling and mapping ecosystem services and biodiversity, along with a relevant database based on the experience of conservation projects around the world. The World Resources Institute, World Business Council for Sustainable Development, and Meridian Institute have developed an approach for Ecosystem Services Review oriented toward identifying the role of ecosystems for sustaining business activity (*23*). This corporate ecosystem services review adopts a qualitative approach to identify critical ecosystem services for industrial operations. The resulting impact and assessment tool analyzes the level of impact and dependence of industries on ecosystem services. The use of this tool is, however, subjective, and depends on the user's knowledge about the role of ecosystem services. Consequently, proper use relies on user training. Challenges still remain in being able to communicate the results to decision makers since the results are mostly qualitative and do not give any simple metric to make decisions. Another important challenge is to utilize the local ecosystem knowledge. For example, a company may identify low dependence on water resources but if it is located in a water depleted region it may cause high stress on water resources of the region. It is therefore necessary to incorporate geographical knowledge in using this approach. Users also need to have adequate knowledge about the relation between company operations and ecosystem services. With more research, such a tool could provide an excellent starting point for bringing ecological considerations into business decision making. Furthermore, a life cycle view also needs to be incorporated.

Ecologists have studied ecosystems as networks of material and energy flow, and significant knowledge about such networks is available. Approaches such as emergy (*9*) and eco-exergy (*30*) are based on thermodynamics and have been used to understand the behavior of ecosystems. These methods, particularly emergy, have been extended to more holistic analysis of economic and ecological systems, as discussed in more detail in the section on Emergy Analysis. The net primary productivity on the planet and its human appropriation have been quantified, and the corresponding section describes its use. These efforts, while essential, often focus mainly on the direct role of ecosystem services, relatively short supply chains, or are not connected with engineering decision making. This has limited their impact

TABLE 1. Accounting for Ecosystem Services in Existing Methods

	aggregation method									
	LCA	MFA	energy	exergy	emergy	EF-GAEZ	EF-NPP	EF-EES	WF	HANPP
ecosystem services	hierarchy of metrics	mass	energy (J)	exergy (J)	energy (sej)	land area	land area	land area	volume	mass C
Provisioning Services. Fossil fuels and minerals; Renewable energy; Land; Crops, livestock and fiber; Wild fish and aquaculture; Wild plant and animal food; Timber; Nonwood forest products; Biomass fuel; Genetic resources; Natural medicines; Fresh water	Primarily fossil fuels and minerals; recent focus on land, water, and other services; ignores fish, plant, genetic resources.	Includes fuels, minerals, renewable resources and water.	Primary focus is on fossil fuels. Some studies consider renewable fuels, but accounting for quality differences becomes essential.	Can account for renewable and nonrenewable material and energy resources. Quality differences should be considered.	Same as exergy but also accounts indirectly for land use and food. Considers quality differences by conversion to solar equivalents.	Considers renewable resources, but less emphasis on nonrenewables; ignores genetic resources; considers carrying capacity.	Accounts for renewable resource use via NPP; considers multiple uses of land and biodiversity.	Better accounting of nonrenewables and renewables. Considers quality differences, but relies on uncertain information.	Accounts for water use only.	Considers renewable resources that rely on NPP; ignore nonrenewables, genetic resources.
Regulating Services. Air quality regulation; Climate regulation; Water regulation; Erosion regulation; Water purification; Disease & pest regulation; Waste processing; Pollination; Natural hazard regulation	Services are considered indirectly via quantity of emissions and impact.	Mass flow of some emissions, which provides partial information.	Ignored.	Abatement exergy considers technological systems to reduce reliance on ecosystem services.	Considers some services such as dissipating pollutants.	Accounts for some services such as land area for absorbing CO_2.	Accounts for some services such as land area for absorbing CO_2.	Accounts for some services such as land area for absorbing CO_2 and dissipating pollutants.	Considered partially via water needed to dilute pollutants (gray water).	Ignored.
Supporting Services. Soil formation; Photosynthesis; Primary production; Nutrient cycling; Water cycling	Ignored.	Ignored.	Ignored.	Ignored.	Many services considered via exergy flow.	Ignored.	Accounts for primary production.	Combines emergy and EF-NPP.	Ignored.	Accounts for primary production.
Cultural Services. Spiritual; Recreational; Aesthetic; Inspirational; Educational; Symbolic	May be considered via Social LCA.	Ignored.	Ignored.	Ignored.	Ignored.	Ignored.	Ignored.	Ignored.	Ignored.	Ignored.

on industrial and business activities. For example, the impact of pollination services and soil regulation on industries such as food services and fertilizer manufacturing is hardly considered, even by corporations pushing toward greater sustainability. An integration of life cycle approaches and methods from ecosystem ecology is essential to account for the role of ecosystem services in LCA and business decision making.

Ecosystem Valuation. Historically, the contribution of ecosystems has been largely neglected in economic development, and market prices do not, or at least not sufficiently, reflect natural capital and ecosystem services required in production processes (*31*). Monetary valuation methods developed in ecological and environmental economics can evaluate the economic value of an ecological system or its services to describe the interdependency of human economies and natural ecosystems (*32, 33*). To quantify the value of ecosystem services which are not in the market, indirect methods based on willingness-to-pay or willingness-to-accept are used. Variations include avoided cost, replacement cost, factor income, travel cost, hedonic pricing, and contingent valuation, etc. (*32*). In principle, monetary values may be assigned to all kinds of ecosystem services, but this approach can be controversial due to problems such as the following. Because economic valuation reflects human preference, representing ecosystem services that involve physical flows in monetary terms can give different results than physical measurements. Also, the general public's knowledge of ecological systems may be incomplete or inadequate, and it affects the value estimated via surveys. Psychological factors can also play a role in the valuation process (*27*). For example, human beings generally value "visible" species, such as tigers, more than "invisible" species, such as slugs (*34*). It has also been argued that ecological economics may lead to the idea that "nature is only worth conserving when it is, or can be made, profitable." (*35*). The often cited win-win case—Catskill/Delaware Watershed conservation—might not happen if the water filtration system was cheaper than restoration of the watershed. Although ecological economists have tried to avoid this criticism by distinguishing between instrumental value, the functional value for human beings, and intrinsic value, the value of nature by itself, the anthropocentric nature of this approach remains (*32, 36*). Monetary valuation is most appropriate to account for cultural services since these services are truly anthropocentric in nature.

An alternative approach to valuation is based on a "biophysical" view (*9, 37, 38*). Such methods quantify the interdependence between ecosystems and the economy in terms of material and energy flows (*39*). It is argued that such a view can incorporate human preferences in the long run as resource limits become apparent (*40*). The relationship between economic value and embodied energy (*41, 42*), exergy, or useful work (product of exergy consumption of natural resources and technical efficiency) (*43*) has been tested by empirical data. However, such biophysical valuation methods are far from the economic mainstream. Furthermore, mass and energy are not sufficient for quantifying all ecosystem services (*44*).

Impact-Oriented Methods: Life Cycle Assessment

Environmental Life Cycle Assessment (LCA) is a method for assessing the environmental burden, and material and energy consumption of a product or a process across its entire life (*45*). It is the most common approach for considering the broader environmental impacts of production processes, and has been the subject of intense research activity over the last several years, in terms of methodological development, applications involving technology analysis, and engineering decision making. The standardized LCA framework (*1*) is comprised of four steps: Goal and Scope Definition, Life Cycle Inventory, Impact Assessment, and Improvement Analysis.

Various approaches have been developed for obtaining a reasonable approximation of the complicated life cycle network. The *process model based LCA* approach chooses the most important processes in the life cycle and relies on detailed data about resource use and emissions of each process. This approach is standardized, and many commercial and public domain inventories are available. The *economic model based LCA* approach avoids drawing a finite, often arbitrary analysis boundary by using a model of the whole economy, and is the basis of Economic Input−Output LCA (EIO-LCA) (*46*). It provides information about many emissions and consumption of some nonrenewable resources, and has been used for several studies. Hybrid LCA combines the two approaches.

Many methods have been developed for interpreting life cycle inventory data in terms of impact on human health, ecosystem quality, and resources. Steps in impact analysis include classification, characterization, and normalization. Midpoint aggregation methods yield impact categories such as global warming potential, human toxicity, and acidification potential (*47*). Endpoint impact assessment methods further combine these categories into a smaller number of categories and even a single aggregate indicator (*48*). These methods address the challenge of assuming substitutability during aggregation. This assumption is satisfied by representing different variables in terms of a common numeraire that accounts for their relative quality. Life cycle impact assessment methods rely on characterization factors that represent emissions in equivalents of another chemical to capture their relative impact. For example, the impact due to all greenhouse gases is represented in CO_2 equivalents, and that of acidifying emissions in terms of their SO_2 equivalents. Thus, to aggregate a ton each of CO_2 and CH_4 emissions, the latter is converted into CO_2 equivalents by a multiplier of 23 for a 100-year time horizon (*47*). Endpoint indicators are defined at the end of impact pathways, quantifying ultimate damages caused by environmental problems and include damage to human health, and to ecosystem quality (*48, 49*).

Life cycle assessment also considers the impact due to the use of resources, with emphasis on abiotic resources, specifically energy and metallic minerals (*50*). Two commonly used impact indicators are Abiotic Depletion Potential (ADP) (*36*) and Surplus Energy (*48*). ADP is related to the ratio of present use of the resource to its reserve, but the standing stock size is often not readily available. It also implicitly assumes substitutability when aggregating all kinds of resources, be they fossil fuels or minerals (*36*). Surplus Energy considers the future consequences of resource extraction and is defined as the difference between the energy needed to extract a resource now and at some point in the future. Although this method avoids assumptions about the exchangeability of resources, predicting future energy requirements for resource extraction is not easy. Both these indicators are aggregated, and thereby the scarcity of a specific resource may be easily overlooked. Furthermore, an internationally accepted standard has not been established for quantifying the impact of resource use on its availability, human health, and ecosystems, due to the various assumptions involved (*48, 51*).

Inclusion of additional resources such as water and land is increasingly common in LCA. However, their impact cannot be unified by metrics such as ADP or Surplus Energy. The characterization method for these resources is often unweighted aggregation that ignores differences in their character and usefulness based on factors such as supporting biodiversity, carbon sequestration, and hydrological functions, etc. The discussion on the characterization of land use-related impact categories is far from settled (*52*).

Another major drawback of LCA is that the resources considered are primarily nonrenewable or abiotic and impact analysis is also built around abiotic resources. New methods are under development to consider more resources (*53, 54*) including wild and domesticated organisms (*50*). A few studies that have utilized ecological models along with LCA are those on biofuels (*55*). Here, technical models of processes in the life cycle are connected with models of soil erosion and soil carbon sequestration. Such models demonstrate the benefits of integrated analysis of industrial and ecological systems and confirm the need for much more work in this direction. However, no work considers the wide array of ecosystem goods and services that industrial processes rely upon, as shown in Table 1, and links between LCA and the deterioration of natural capital are mostly missing. In addition, LCA methods do not account for most of the ecosystem services that are required for dissipating the emissions and absorbing their impact. The framework of LCA is certainly attractive, as is its wide adoption for various kinds of analysis and decision making. Accounting for ecosystem services represents the next frontier that this approach needs to tackle.

Physically Based Resource Accounting Methods

Natural resources can be valued by their prices in the market, but representing them in physical units can reduce subjectiveness due to human preference. Analyzing physical exchange (material and energy flows) between human societies and their natural environments and our dependence on ecological health and productivity are important aspects of sustainable development (*56, 57*). Physical measurements also have advantages over results from monetary valuation because they are not subject to inflation and fluctuating exchange rates, which make them stable and transparent (*58*).

There is a long tradition, predating LCA, of compiling material and energy flows and interpreting them as pressures on natural systems. Bookkeeping of material and energy flows is consistent with the first law of thermodynamics, which ignores the quality difference among resources. The second law can be applied not only to fuels but also to materials, and better represents quality in terms of their ability of doing useful work. This section reviews methods that are most relevant to accounting for ecosystem services. This includes exergy analysis (*8*) and its extension to ecological systems as emergy analysis (*9*). The methods of material and energy flow analysis are described in the Supporting Information since they are more limited in their accounting for ecosystems. Although all these methods were developed much earlier than LCA, studies often employed different approaches, indicators and system definitions, making it difficult to communicate and compare results (*59*).

Exergy Analysis and Cumulative Exergy Consumption. Exergy measures the portion of a resource that can be converted to useful work. For example, the enthalpy in a hot steam cannot be completely converted to electricity, but electricity can be freely transformed into other forms of energy. Exergy can capture these differences. Exergy has been suggested as a way of quantifying resource depletion (*36, 60*) since all activities on earth rely on the availability of energy, making exergy the truly scarce resource (*9, 61*). Resource depletion is the decrease in availability, which for a resource, can be expressed in terms of its concentration because a mining process first chooses the ore with the highest concentration (*62*). The exergy value of resources includes the concentration factor, and hence the quality of an ore can be captured via its exergy value, which cannot be measured by mass and energy. The exergy content of any resource may be calculated by multiplying its quantity (grams or Joules) with a transformation factor for that resource. This transformation factor is a better measure of resource quality than calorific value or enthalpy since it considers the available energy (*63, 64*). However, it is still not able to capture differences in the quality of vastly different resources such as renewables versus nonrenewables (*65*).

Traditional exergy analysis focuses on enhancing the efficiency of a process by identifying and preventing exergy losses (*8, 66*). This has been extended to analyze broader industrial systems and supply chains via the concept of Cumulative Exergy Consumption (CExC), which is the sum of exergetic values of all resource inputs (*67*). The nonrenewable portion has been called the thermo-ecological cost (*64*). Cornelissen and colleagues adopted the LCA framework to study resource consumption of a life cycle and called their approach Exergetic LCA (*5, 68*). Cumulative exergy consumption for economic activities is an indicator of quality-adjusted resources that are removed from nature, and thereby has been considered as a possible impact indicator for LCA (*5, 60*). Bösch et al. have adopted this idea and calculated Cumulative Exergy Demand for the ecoinvent database (*69*). The concept of cumulative exergy extracted from the natural environment (CEENE) (*70*) accounts for actual exergy from natural ecosystems that is used for human activities as a way of considering resource quality. Thus, instead of considering the exergy of biomass, which is very small, or the exergy of all the incident sunlight, which is very large, this approach considers the small fraction of incident sunlight that is actually metabolized by biomass. This allows indirect consideration of land use. Unfortunately, these methods of aggregating multiple resources in terms of their exergy do not address the substitutability assumption in an adequate manner and can provide counterintuitive results (*65*). These methods are attractive for considering many provisioning services, and fossil and mineral resources resulting from past and present geobiophysical processes. However, most other ecosystem services are ignored, as summarized in Table 1.

To account for the impact of emissions in terms of exergy, the concept of Exergy Abatement Cost (EAC) has been suggested (*71*). The negative impact of emissions may be represented in terms of the limit it may place on energy availability for other activities. That is, the environment needs to expend exergy to absorb the impact of emissions, making this exergy unavailable for other activities. EAC is hence defined as the minimum exergy needed to reduce the emissions to harmless levels in the environment (*71*). This approach is claimed to provide a true picture of usable energy available for the future. However, it does not account for the ecosystem services needed to absorb, dissipate, or regulate the emissions. All the exergy based methods discussed in this subsection have originated in engineering and none of them account for ecosystem services other than some provisioning ones.

Emergy Analysis. The concept of emergy, developed by systems ecologists, is the availability of energy of one kind that is used up directly and indirectly to make a product or service (*9*). Emergy Analysis presents an energetic basis for quantification or valuation of ecological goods and services. From a biogeophysical perspective, the earth has one principal input—solar energy (*37*). Tidal energy and crustal heat are other major energy sources contributing to the global operation of the geobiosphere. Their contribution can be related to solar energy (*9*). All the other activities on earth are derived from these primary energy inputs (*72*). Fossil fuels and minerals represent millions of years of embodied energy from the sun and geological activity. Wind, rain, and rivers originate from more recent solar energy. Emergy analysis is able to quantify the exergy consumption for ecological goods and services in nature and convert them to solar equivalent joules. A key concept in emergy analysis is transformity. It is defined as the emergy input per unit of exergy output (*73*). It is determined by energy flows in the hierarchical structure of the ecosystem and is considered to indicate the quality of ecological goods and services (*74*).

The advantage of emergy analysis over other physical flow analyses is its ability to quantify the direct and indirect exergy consumption not only in economic systems but also in ecological systems. Most of the other physical flow accounting methods measure the material and energy flows from the point where they enter the economy and ignore the ecological processes that are needed for making the natural resources available. The free services received from the environment, such as sunlight and wind are just as much a requirement for human societies as fossil fuels (*73*). Another advantage of emergy analysis is that it can include the contributions from human resources and the role of ecosystems in dissipating pollution (*75*). Emergy analysis evaluates every process on Earth on the common scale of solar equivalent joules. Thus, it can help us understand the huge ecological network supporting our economic activities. Emergy may also be interpreted as an extension of the Cumulative Exergy Consumption approach, described in the section on Exergy Analysis, by including exergy flow in ecosystems (*7*). Thus, emergy is closely related to Ecological Cumulative Exergy Consumption.

Emergy analysis has been applied widely to analyze systems as diverse as ecological, agricultural, industrial, and economic (*9*) and various indices have been proposed to study the impact of resource use on the environment (*76*). Ulgiati et al. have argued that investment of emergy is required to clean up industrial wastes. Hence, emergy can be used to quantify the role of the environment in dissipating the wastes and emissions (*77*). As discussed in the section on Exergy Analysis, exergy may be used to internalize the impact of emissions on the environment, but it cannot consider the actual work done by ecosystems in dissipating the emissions. The exergy used in the EAC methodology is based on available technology, hence it only considers the work done by technological systems. However, work done by nature, as by wind energy to dissipate the emissions which dilutes the local stress of emissions, is not accounted for in this approach.

As summarized in Table 1, emergy satisfies many of the criteria for including the role of ecosystem services. Unfortunately, this approach still faces many challenges and has some shortcomings. Acceptance of the emergy concept and method as an attractive approach for life cycle evaluation has been gradual due to a historical lack of clarity about its connection with other thermodynamic concepts. Representing all resources in solar equivalents holds merit as one way of addressing some aspects of substitutability, but it relies on information about the ecological network that is uncertain and incomplete. Nevertheless, this approach can play an important role in developing an ecologically based LCA as described in ref *78*. The emphasis of emergy analysis on converting all flows into a common numeraire can also be problematic since it leads to loss of information, and more importantly, representing all ecosystem services in terms of this common unit is not yet possible. Consequently, this emphasis on a single numeraire may not permit accounting of all sources.

Footprint Analysis

This category of methods represents the direct and indirect impact of human activities in terms of aggregate metrics such as ecological footprint, carbon footprint, and water footprint. Among these, the water footprint is described in the Supporting Information since it is more limited than the other methods in accounting for ecosystem services. Another related approach discussed in this section is Human Appropriation of Net Primary Productivity (*79*).

Ecological Footprint Analysis. EF represents the impact of human activities in terms of land area. It also calculates the biocapacity in the same units. Comparing the two provides an indication of sustainability. Three variations of this approach are discussed in this section.

Ecological Footprint based on Global Agricultural Ecological Zone (EF-GAEZ). The total consumption of resources as quantified by the methods discussed in the previous two sections does not adequately reflect natural resource depletion and environmental degradation. The standing stock of nonrenewable resources and the primary production rate of renewable resources need to be compared with the consumption rate for a better understanding of the sustainability of human activities. Ecological footprint analysis is a method designed for this purpose, and provides an idea about the gap between human demand and potential availability of resources. The approach has been applied on national and global scales over recent years (*80*). The potential availability of resources is measured by biocapacity or carrying capacity which can be calculated on a global or regional level (*81*). Unsustainability is indicated if a society's ecological footprint is larger than its available bioproductivity. The ecological footprint (EF) is calculated as a biologically productive area a population needs to produce resources and absorb the waste generated by that population with the prevailing technology (*11, 81*). The implicit assumptions in the calculation of ecological footprint are that all the resources can be converted into land and water area and all resource use can be known (*82*). Bioproductive land is one of the most important natural resources (*79*) because many kinds of ecological goods and services are provided through the use of land. The land categories included in EF are cropland, forest, pasture, built up area, energy land, and water land. Since, the original EF methodology focuses on biologically productive land, it is sometimes referred to as EF-GAEZ (Ecological Footprint based on Global Agricultural Ecological Zone). The most attractive features of this approach are the intuitive conversion to land area and the intuitive understanding of overshoot beyond the carrying capacity. Consequently, this approach has become very popular for public communication about the lack of sustainability of human activities. However, this approach suffers from many limitations and shortcomings (*83, 84*).

The major limitations of EF-GAEZ are its anthropocentric view that relies on human development of technology to compensate for lost biocapacity by "boosting forest, crop, and fish yields without incurring any long-term ecological costs" (*83*), and its inability to account for unsustainable land uses that cause impacts such as soil erosion. EF also only accounts for biologically productive area and ignores vast land area that does not directly contribute to resource production. Such land area includes unmanaged lands and deserts, etc. However, for a reliable sustainability indicator it is important to consider these types of land in indicators since many complex ecosystem services and biogeochemical cycles depend on them. Hence, degradation of such land area would be an act of unsustainable human activity. Several nonbiological flows such as minerals and emissions are difficult to account for in EF, but may be considered in an indirect manner. Nonfootprint accounts are recommended for such accounting (*85*). Similarly, ignoring the importance of biodiversity in any region would lead to the assumption that human resource consumption does not impact other species which are important for formation of resources for future generations. Other limitations of EF-GAEZ include ignoring multiple uses of land, equivalence factors for aggregation of different land types, and carbon-sequestration rates based only on forests (*83, 84*). Recent modifications have attempted to overcome some of these shortcomings. These includes EF-NPP (Ecological Footprint based on Net

Primary Production) (*84*) and EEF (Ecological Footprint based on Emergy) (*82*).

Ecological Footprint based on Net Primary Productivity (EF-NPP). EF-NPP combines EF and NPP (*84*). Ecologists have attempted quantification of NPP appropriation by humans and other species (*86, 87*). New developments in EF-NPP include the following: (1) accounting for the global land area for calculating biocapacity; (2) allocating a part of NPP for other species to account for biodiversity; (3) modifying carbon sequestration rates; and (4) using NPP for calculating equivalence factors. EF-NPP includes contributions even from low NPP lands because these are interconnected to ecosystems and contribute to the carbon, hydrological, and other nutrient cycles. Venetoulis and Talberth (*84*) discuss the implications of ignoring the appropriation of NPP by other species and the resulting loss of biodiversity. This approach may give an impression that increasing NPP can support more human activities along with sustaining biodiversity. Also, it is difficult to use NPP as a sole measure of sustainability since an increase in NPP at the cost of declining landscape or biodiversity may not be a sustainable option. For example, increasing NPP at the cost of wiping out original species from a biome may have dire consequences. The challenge to come up with a specific measure still remains and needs more collaboration among ecologists, biologists, and sustainability indicator developers. EF-NPP uses gap analysis to determine the land area that should be allocated for preserving other species, particularly those that are not yet protected by conservation programs. Based on a global gap analysis (*88*) and hot spot identifications in biomes, EF-NPP deducts 13.4% from each biome's biocapacity available for humans to account for the need of supporting endangered species (*84*). The uncertainty and unavailability of ecological data affects these numbers, as well as the equivalence factors, and remains a significant challenge. Even EF-NPP fails to recognize the difference between the "sustainable" and "unsustainable" use of land. Nonetheless, it partially overcomes the shortcoming of the anthropocentric view of traditional EF-GAEZ.

Another important issue of multiplicity of land use is more difficult to handle. Every piece of land is interconnected through global cycles and provides multiple ecosystem services concurrently. EF-NPP accounts for such multiple services by considering the fact that forests provide timber and carbon sink services. Such multiple uses increase NPP since all land will be counted multiple times, and will result in a larger global biocapacity. In addition, EF-NPP considers the variation in carbon sequestration ability for different land types, unlike EF-GAEZ, which only considers sequestration in a young forest. This results in a higher footprint per unit of carbon emitted. This higher footprint of carbon emissions and higher biocapacity change the numbers for most resources. Despite these enhancements, EF-NPP continues to ignore other crucial issues such as land deterioration, nutrient runoff, etc.

Difference in the temporal scale of ecological processes poses another set of challenges. For example, the timber provided by forests is actually a stock due to past carbon sequestration, and combining it with current NPP, which is a flow, can be highly misleading. More research based on distinguishing between such stocks and flows is needed to obtain meaningful results.

Apart from provisioning services which produce resources, terrestrial ecosystems provide several other regulating and supporting services. The contributions of these ecosystem services are nonquantifiable in terms of resources consumed and hence even EF-NPP fails to account for the role of land area in such services. Considering such services, the human ecological footprint will be much higher than only considering the resources consumed as a result of NPP or bioproductivity. The EF approach based on emergy, discussed next, tackles this incomplete accounting of ecosystems contribution to an extent. EF-NPP is an improvement over EF-GAEZ, but it is still limited in terms of accounting for ecosystem services as discussed at the end of this subsection.

Emergy-Based Ecological Footprint (EEF). As discussed in the Emergy Analysis section, emergy is a way of quantifying the contribution of many supporting services to economic activities. Emergy is also claimed to be a true measure of human dependence on ecosystems, and therefore, it has been proposed as a way of calculating the ecological footprint and biocapacity (*89*) that also includes the role of ecosystems. Originally developed by Zhao et al. (*82*), EEF converts resource use and available resources into emergy units. Subsequently, the global emergy density is used to calculate biocapacity based on the available renewable resources (sun, wind, chemical energy in rain, geopotential energy in rain, and earth cycle energy) reflecting the assumption that for sustainable activities the world should rely on renewable resource inputs. The total biocapacity based on emergy is then calculated by taking their maximum value, as proposed by emergy algebra. For calculating the ecological footprint, the emergy of resources used is divided by emergy density of the region, while for biocapacity the emergy of resources available is divided by the global emergy density. The basis for ecological footprint is regional hectares, whereas for biocapacity, global hectares are used. Although both are areas in terms of the same unit, they imply a different scale, and the ecological footprint of a region is compared to global biocapacity. This EEF metric is good for representing the contribution of a region to the global impact, but it does not convey the regional stress on ecosystems or whether a region overshoots its local biocapacity. This concept can be extended for regional biocapacity if the renewable resources for a region and the regional emergy density are known, and if biocapacity is based on the regionally available area. Calculating biocapacity based on the maximum of renewable energy ignores the availability of standing biomass stocks which also contribute to the biocapacity of a region. This particular issue is again due to disparate temporal scales in the resources being aggregated because standing biomass represents stored energy. According to the emergy algebra, current and previous emergy flows are added, which will increase the biocapacity available for use as compared to the approach of Zhao et al. (*82*). Combination of emergy with NPP has also been developed (*90*). This approach accounts for the footprint of water use, NPP, and represents the results in six categories including crop areas, pasture areas, forest, and urban areas, etc. Topsoil loss and water are also considered in EEF. EEF is more comprehensive than EF-GAEZ or EF-NPP because it is able to account for many nonrenewable resources also which cannot be converted into EF-NPP or EF-GAEZ as these are not produced on land. However, the challenge of obtaining a proper transformity number for many products is an obstacle in switching to EEF. These EF methods have been combined with economic input−output models to find the footprints of economic sectors (*91−93*).

EF and Ecosystem Services. EF is attractive due to its intuitive sustainability indicator. It does account for ecosystem services and biocapacity that other methods do not consider, particularly due to the incorporation of NPP and emergy, but it can only account for biologically produced goods and services, such as crops, fish, and wood. Many essential services are not included in EF since not all ecosystem services may be converted into the common unit of primary productivity, solar equivalent joules, or land area. This includes services such as those for dissipating or absorbing the impact of emissions. Also, EF is not appropriate to account for nonbiological flows such as minerals (*94*) and many industrial emissions such as CFCs and PCBs. Ecosystem degradation related to land use, such as soil erosion and salination resulting from irrigation, cannot be quantified in the model fully such as their effect on other ecosystem services. Equally important is that, like emergy, the emphasis on a single numeraire causes information loss, and the reliance on often controversial (*95*) factors for conversion to land area can discourage the consideration of services for which such factors are difficult to find. In addition, the implicit assumption of sustainability is often inappropriate due to issues such as multiple uses of land and different rates of resource production, as discussed in this section. The difficulty of understanding specific reasons for unsustainability if only a numeraire is given is another shortcoming. EF does represent an important approach and point of view, but more work is needed before it can be more than a crude approximation of the role of ecosystems.

Human Appropriation of Net Primary Production. Net Primary Production is the net amount of solar energy converted to biomass via photosynthesis in a given period. EF-NPP was proposed to include the role of primary production in human resource consumption. However, it still fails to address the issue of degradation of a region due to intensity of land use. Human appropriation of NPP (HANPP) is the amount of NPP that is altered or harvested (*86*). Like EF, HANPP assesses land use in terms of resource extraction, waste absorption, and human infrastructure. EF calculates the necessary land area for a given population, while HANPP evaluates how intensively a defined land area is exploited (*96*). Therefore, HANPP takes an ecocentric view instead of the anthropocentric view of supporting resource consumption. EF analysis converts all kinds of land to global hectares, but HANPP measures the material and energy flow from the biosphere to human society in terms of NPP. It actually measures the impact of human activities on the environment by calculating the gap between potential and actual NPP of a region (*86*). This provides insight into the human role in disrupting and appropriating the natural energy flow in ecosystems. HANPP has been calculated on a global scale (*86, 87, 97*), and refined to provide spatial patterns (*86, 87*). There is a significant similarity between EF-NPP and HANPP, but EF-NPP accounts only for the actual NPP appropriated for the resources consumed and not the lost potential of ecosystem productivity. Therefore, even though EF-NPP is not completely anthropocentric it does still rely on information about human resource consumption. HANPP can be integrated with EF to bring the human impact factor on ecosystems. This will result in increased EF/biocapacity ratio when EF is based on HANPP and hence will reveal the lost potential of ecosystems to sustain human population. HANPP can also be used to simulate future scenarios and guide policies. The concept of embodied HANPP, like LCA and virtual water, can indicate the spatial pattern of ecosystem stress due to trade, and provide insight into the unsustainability of consumption and trade patterns (*98*). However, most of the shortcomings of EF discussed in the previous paragraph also apply to HANPP.

Challenges and Opportunities

Although human activities are not possible without ecosystem services, these services continue to be taken for granted in decision making. With greater prosperity, societies tend to become more distant from ecosystems and the role of ecosystem services in supporting modern activities is increasingly indirect (*99*). Consequently, any effort directed toward sustainability must account for the direct and indirect role of ecosystem services. Thus, a life cycle view is essential.

This article has reviewed a large number of methods that are directed toward making environmentally sustainable decisions. These methods have witnessed growing practitioner interest and research activity, and are increasingly popular for decision making by consumers, governmental and nongovernmental organizations, and corporations. Given the importance of ecosystem services and their deteriorating state (*20*), it is natural to evaluate the ability of these methods to account for these services. Methods that are unable to account for them or only consider the services partially may provide misleading results and even encourage perverse decisions.

Despite a few decades of effort, none of the existing methods is able to consider the full diversity of ecosystem services. In addition to accounting for all the ecosystem services, it is also important to take a life cycle view and develop ways of understanding the results via appropriate aggregate metrics. Table 1 summarizes the characteristics of various methods. As shown and discussed in this article, most methods tend toward aggregation in terms of a single numeraire. For example, economic valuation represents all services in monetary terms, emergy in terms of solar equivalent joules, and ecological footprint in terms of land area. Such aggregation is also practiced in LCA, but this method often uses a hierarchy of metrics. The benefit of representing a high dimensional space in terms of a single common unit is appealing since it simplifies interpretation and communication. However, such methods assume substitutability between the variables being aggregated, and require equivalency factors to ensure fair comparison between resources. Obtaining such factors in an unambiguous manner is very difficult if not nearly impossible. This is due to the multiplicity of uses and impacts of most resources and emissions, and uncertain knowledge about industrial, economic, and ecological networks. In addition, aggregation methods tend to ignore services that cannot be represented in terms of the common unit. A hierarchy of units ranging from raw data to intermediate levels of aggregation followed by a single unit may be one way of overcoming these challenges. Such an approach is popular in life cycle impact assessment, and is also developed for resource accounting in ref *78*. Nevertheless, much more research is required to determine appropriate hierarchies and using them for making decisions.

An equally important or even bigger challenge than aggregation methods is the need for adequate information about ecosystem services and their role in supporting human activities. All the methods discussed in this article consider at least some ecosystem services, but no method considers all of them. Accounting for provisioning services is easiest since data about these services is most readily available. Consequently, most methods account for these services available from current and past ecosystem activities. Accounting for other ecosystem services is more challenging. Thermodynamics can help in quantifying the role of many supporting services, as is done in emergy analysis and related methods such as the emergy based ecological footprint. However, accounting for some supporting services and many regulating services is more difficult, and for many such services only qualitative information may be available. Using such information could benefit from methods that can combine quantitative and qualitative information. Greater effort is also needed for understanding the mechanisms how ecosystem services function and how they are linked to production and consumption of marketed goods and services (*25, 40, 100*). To meet these challenges, the diversity of life cycle oriented methods needs to be converged to methods that combine the best features of existing methods, such as the ease of understanding monetary values, the framework and emissions-orientation of LCA, the physical basis of mass and exergy, the ability of emergy to account for supporting services, and the ability of ecological footprint and accounting for net primary productivity to consider biocapacity and human appropriation. Interaction among disciplines including industrial ecology, ecosystem and systems ecology, decision and policy making, economics, and statistics is also essential.

Overcoming the challenges mentioned above would certainly be important for improving the state-of-the-art. However, all the methods reviewed in this article consider mainly static systems, which rarely exist in practice. In fact, networks of industrial−ecological−economic systems are complex, nonlinear, dynamic systems. Ultimately, it is essential to develop methods that can combine the life cycle view with the understanding of complex systems via integrated models of technological and ecological systems. However, the challenges facing such methods are beyond the scope of this article.

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Supporting Information Available

Critical review of other relevant methods including energy analysis and water footprints. This information is available free of charge via the Internet at http://pubs.acs.org.

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