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Techno-Ecological Synergy:
A Framework for Sustainable Engineering

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Abstract

Even though the importance of ecosystems in sustaining all human activities is well-known, methods for sustainable engineering fail to fully account for this role of nature. Most methods account for the demand for ecosystem services, but almost none account for the supply. Incomplete accounting of the very foundation of human well-being can result in perverse outcomes from decisions meant to enhance sustainability and lost opportunities for benefiting from the ability of nature to satisfy human needs in an economically and environmentally superior manner. This paper develops a framework for understanding and designing synergies between technological and ecological systems to encourage greater harmony between human activities and nature. This framework considers technological systems ranging from individual processes to supply chains and life cycles, along with corresponding ecological systems at multiple spatial scales ranging from local to global. The demand for specific ecosystem services is determined from information about emissions and resource use, while the supply is obtained from information about the capacity of relevant ecosystems. Metrics calculate the sustainability of individual ecosystem services at multiple spatial scales and help define necessary but not sufficient conditions for local and global sustainability. Efforts to reduce ecological overshoot encourage enhancement of life cycle efficiency, development of industrial symbiosis, innovative designs and policies, and ecological restoration, thus combining the best features of many existing methods. Opportunities for theoretical and applied research to make this framework practical are also discussed.

1 Introduction

Increasing interest in sustainability has resulted in several approaches for considering the broader environmental impact of industrial processes and products [1]. These activities aim to enhance efficiency and reduce impact across the entire life cycle. Resulting methods include eco-efficiency [2], carbon [3] and water [4] footprints, life cycle assessment [5, 6], and cradle to cradle design [7], which are widely used for guiding decisions, managing supply chains, and designing products and processes. These efforts have mainly focused on resource use and emissions, and their impact

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on people and the environment. The role of ecosystems in sustaining all human activities has been mostly ignored, until recently.

Ecosystems provide goods such as grains, biomass, water, and genetic resources; regulate the climate, pests, floods, and air and water quality; support other services via photosynthesis, pollination, and biogeochemical cycles; and are of cultural, spiritual and aesthetic value. Their importance for sustainability is undeniable not just physically but also monetarily [8, 9]. The Millennium Ecosystem Assessment identified 80% of global ecosystem services as degraded [10], while Rockstrom et al. [11] claim that anthropogenic activities already exceed the "safe operating zone" in services associated with carbon and nitrogen cycles, and biodiversity loss. These studies point toward the urgent need to consider the status of ecosystem services in engineering decisions, and to devise ways of encouraging ecosystem restoration.

Almost all eco-efficiency and life cycle oriented methods ignore the essential role of ecosystems in sustaining human activities and well-being. Some methods do consider the demand of selected ecosystem services, but all ignore the capacity of ecosystems to supply individual services. LCA accounts for the impact of human activities on some ecosystem services associated with water, soil carbon, biomass, land use, and biodiversity [12, 13], as do some thermodynamic methods [14, 15]. However, these methods only consider the demand of these services and not their locations and availability. Ecological footprint does account for biocapacity [16] but in a highly aggregated manner that is blind to individual services. As a result, decisions based on these existing methods could unintentionally increase reliance on scarce or degraded ecosystem services or destroy ecosystems entirely.

Quantifying the role of ecosystem services has received attention in the last few years, and has resulted in many models, frameworks and tools [17]. Industrial efforts have been led by organizations such as Business for Social Responsibility (BSR), World Business Council for Sustainable Development (WBCSD), and the Natural Capital Coalition (NCC). Nonprofit environmental groups have also initiated projects for assessing corporate reliance on ecosystem services [18]. Often these tools quantify nature's services in monetary terms to enable policy and corporate use. However, a gap exists between efforts and methods for assessment of ecosystem services and design of sustainable systems [19].

This paper describes a new framework for assessing and engineering interconnected technological-ecological systems by explicitly accounting for the demand that technological systems place on ecosystems and the supply of ecosystem services that nature can provide to a process or product at multiple spatial scales. We call this approach Techno-Ecological Synergy (TES) to reflect its emphasis on establishing mutually beneficial or synergistic relationships between technological and ecological systems, with the ultimate goal of achieving harmony between human activities and nature. The ecosystem services demanded by the technological system are quantified by information about resource use and emissions, while the supply is quantified by knowledge of ecosystems, their biogeochemical functioning, and the services and benefits they provide. Unlike eco-efficiency or ecosystem evaluation measures which focus on minimizing the impact of technological systems on natural ecosystems, TES metrics are developed to determine and reduce the demand overshoot for each ecosystem service with regard to available and maximum possible ecosystem service provision. This approach combines the best features of existing methods such as life cycle assessment, cradle to cradle design, and ecosystem service assessment. It encourages improving process efficiency as in traditional engineering, enhances life cycle efficiency as done by life cycle and footprint methods, encourages closing of material cycles as in industrial symbiosis and cradle-to-cradle design, and encourages ecosystem restoration as done by ecosystem service assessment methods.

In the rest of this article, the next section provides a brief overview of relevant methods, followed by two sections that define the techno-ecological system, and the methodology of techno-ecological synergy. An illustrative example follows, closing with an outlook of challenges that need to be met for this framework to be practical.

2 Background

Numerous methods and approaches have been proposed to better align engineered technological systems with environmental sustainability goals. Such efforts range from basic guidelines and checklists for "green" design [20, 21, 22, 23] to comprehensive analysis and design tools for full accounting of social, environmental, and economic impacts. The latter are reviewed in [24], and include Cradle to Cradle design [7], Design for Environment (DfE) [25], and fully integrated LCA design software [26, 27]. These and other sustainable engineering methods have paid limited attention to the dependence and impact of engineering activities on ecosystems. As reviewed in [28], methods such as water footprint [4], human appropriation of net primary productivity [29], and some aspects of LCA do consider the demand for some ecosystem services. Ecologically-based LCA (Eco-LCA) quantifies the demand for ecosystem services in physical units of mass, exergy and emergy [30], including the role of some biogeochemical cycles [31, 32]. Life cycle characterization factors are being developed to quantify the impact of land use on ecosystems [33, 34]. However, life cycle methods consider mainly the impact on ecosystems at the life cycle scale, and none of these methods consider the supply of specific ecosystem services at multiple spatial scales. Most existing methods encourage continuous improvement by doing "less bad," [35], which need not translate into keeping human activities within ecological constraints.

Ecosystem service assessment and modeling is an active area of research and includes efforts for understanding the role of ecosystems in supporting and enhancing human well-being [8, 36], developing models and software that quantify ecosystem services [37, 38], and frameworks for classifying them [10, 39, 40, 41]. There have been numerous initiatives to build links between ecosystem service evaluation at local, regional, and national levels [42, 43, 44, 45, 46, 47] along with characterizing ecosystem services as flows [48], budgets [49], and land management tools [50, 51]. These efforts have provided much clarity about the role of ecosystems for enabling human activities, and focused attention on their irreplaceable role in supporting economic and social activities.

Some work has considered supply and demand for specific ecosystem services such as water for particular scales [52] or across spatial scales [53] but these do not connect with sustainable engineering. One of the most active areas of research around ecosystem service is in assessing their value to the economy or society. Building on neo-classical natural resource economics, a number of methods have been suggested to value ecosystems using direct or indirect valuation [43, 54, 40]. However, as with sustainable engineering methods, current ecosystem service methods fall short of enabling sustainable engineering. This is due to either their narrow focus on quantification of ecosystem service supply thus ignoring the demand or consumption of such services, or their narrow focus on monetary valuation thus being unable to capture potential deficits of ecosystem service provision.

3 Methodology

The Techno-Ecological Synergy (TES) framework attempts to quantify the demand and supply for ecosystem services at multiple spatial scales, and compare alternatives based on the extent to which the demand for an ecosystem service differs from the supply. The system and flows considered in the TES approach are depicted in Figure 1. As shown, at a selected spatial scale, technological systems rely on inputs from ecosystems within and outside the selected boundary. Ecosystems may utilize some waste products from technological systems, and those that cannot be utilized appear as pollutants in the environment. For example, a forest can take up emissions such as oxides of nitrogen, sulfur, and carbon from manufacturing, while providing oxygen and biomass to the process. These flows do not necessarily traverse in pipes and conveyors, and can be augmented with "natural" transport, for example, carbon dioxide emitted into the atmosphere and carbon dioxide sequestered elsewhere from the atmosphere. TES strives toward understanding and enhancing such synergies, with the goal of closing material loops at multiple spatial scales, as described below. Such an approach explicitly accounts for whether a human

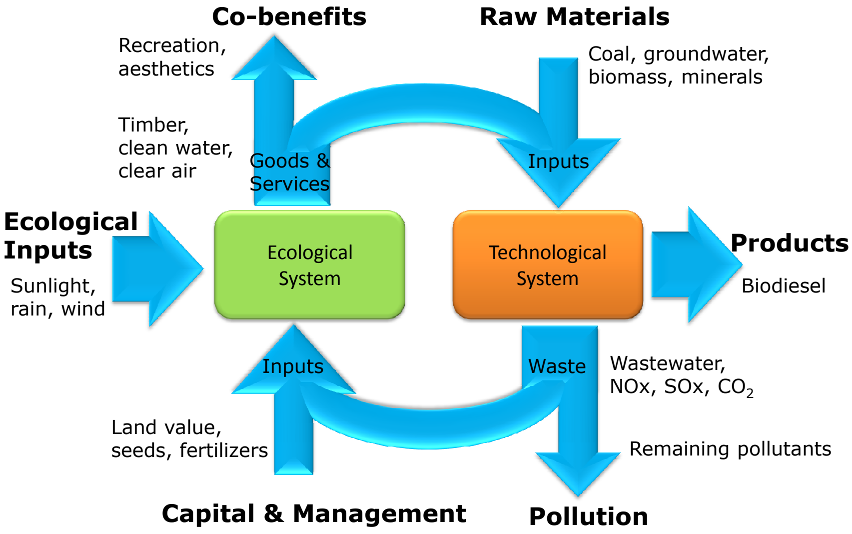


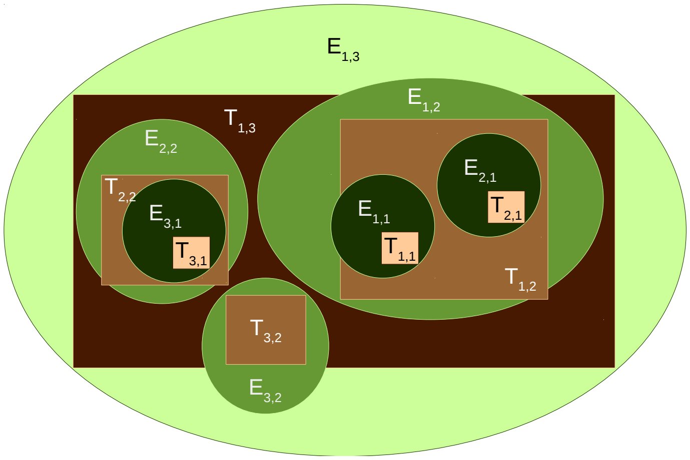
Figure 1: Flows considered in Techno-Ecological Synergy at a selected scale.

activity is within the regenerative capacity of the biosphere at the spatial scales impacted by the activity.

3.1 Defining the System

TES involves defining two types of boundaries: technological and ecological. The former involves choosing the human activities to be evaluated, which could be a single process, life cycle, or economic network, while the latter involves specifying geographical regions according to the nature of the ecosystem service being considered. For TES assessment of a specific manufacturing process, this process could represent the smallest technological scale. This could be followed by considering the supply chain and important processes in the life cycle, added as small-scale systems at the appropriate geographic location. The challenges of developing a comprehensive life cycle network model based on such process information are well-known in the LCA literature. A common way of considering a large boundary while avoiding challenges of a large and intractable network is to integrate process models with more aggregate models. In such hybrid models, each of the processes is nested within processes at larger scales, which can include their regional, national, and global economies [55, 56].

As depicted in Figure 2, technological models at each scale may be represented by $T_{i,j}$ which consists of the i-th technological process at the j-th scale. Each technological system is nested within ecosystems in its vicinity, $E_{i,j}$. Thus, if the smallest technological scale includes manufacturing processes, then the smallest ecological scale could be the plant site or the corporate campus; if the technological system is a residence, the smallest ecological scale could be the yard around the house [57]. Such a technological system could be assessed by quantifying its dependence on ecosystem services at multiple spatial scales, or by including its interaction with other technological processes in the life cycle and corresponding ecosystems. As shown, $T_{1,1}$, $T_{2,1}$, $T_{3,1}$ represent technological processes at the finest scale, $j = 1$. These could be individual production processes. Technological systems at a coarser scale, $j = 2$ are shown as $T_{1,2}$, $T_{2,2}$, and $T_{3,2}$. These could be average processes, say within a supply chain, whose information is obtained from a life cycle inventory database, as discussed in Section 3.3. Ecosystems supporting these technological systems are shown in Figure 2 as $E_{1,2}$, $E_{2,2}$ and $E_{3,2}$. A finer scale process may be nested inside a process at a coarser scale, as shown for $T_{3,1}$ and $T_{2,2}$. All of these technological systems are inside a system at the coarsest scale shown as $T_{1,3}$ in Figure 2. This could represent aggregated models such as economic sectors in an environmentally extended input-output model [58, 59]. A final, even coarser scale could represent the global economy. In a given problem,



Scale, j	Typical $T_{i,j}$	Typical $E_{i,j}$
1	Buildings	Surrounding campus
1	Manufacturing site	Surrounding land owned by the company
2	Corn production in region	Regional ecosystems
3	Economic activities in country	Ecosystems at national scale

Figure 2: Technological and Ecological Scales

technological scales are chosen based on factors such as data availability, and scales at which changes can be influenced. As depicted in the figure, each technological scale is nested within an ecosystem scale, with the global biosphere being the largest ecological scale. How these scales are defined depends on the system being studied and user preferences, as illustrated in Section 4.

The largest ecological scale that should be considered depends on the ecosystem service being analyzed. A service such as carbon sequestration is global in nature because of the global flow of CO_2, which means that for closing the carbon loop, global and smaller scales should be considered. Thus, carbon sequestration in any part of the world can be relevant to CO_2 emissions and satisfy the demand for this service anywhere on the planet. In contrast, a service such as pollination is local and determined by the range covered by pollinators. Thus, this service is not relevant at larger geographic scales. The largest scales of some ecosystem services are listed in Table 1. This is analogous to the concept of “servicesheds” in ecosystem services literature, namely the total land area that contributes service consumed or enjoyed by a particular beneficiary, be it a village or a plant. For some ecosystem services, we will need to specify the smallest and largest allowable scale to ensure proper interpretation of the TES metrics as described in Section 3.5.

Through technological means, it has become possible to expand the spatial scale or serviceshed of some ecosystem services. For example, the use of domesticated bees that are trucked to different regions expands the spatial scale at which these services are available. Such options should be considered within a design, however for the sake of consistent methodology with regards to spatial scale, TES emphasizes natural ecosystem services, so these enhancements of ecosystem services are treated as separate technological systems. Thus, for example, a dam and reservoir will be another fine scale $T_{i,j}$ system, with its direct contributing area being the associated ecological system.

3.2 Demand and Supply of Ecosystem Services

After defining the system, the demand and supply of ecosystem services must be quantified. Generally speaking, the demand for each ecosystem service may be determined by specific emissions and resource use of the relevant technological systems, while supply may be estimated from knowledge about relevant ecosystems at the selected ecological scale. As summarized in Table 1, the demand for many ecosystem services is the quantity released into or withdrawn from the environment. For example, the demand for carbon sequestration is the mass of CO_2 emitted, whereas its supply is the mass of CO_2 sequestered from the atmosphere by plants, trees, oceans etc. The demand for water provisioning is the volume of water withdrawn, while the availability

Table 1: Demand, supply and largest scale of some ecosystem services.

Ecosystem Service	Quantifying Demand	Quantifying Supply	Largest ecological scale
Carbon Sequestration	CO_2 emissions	Capacity of ecosystems to sequester carbon	Global
Pollination	Pollinators needed for full production	Pollinators available in local ecosystems	Local
Nutrient Retention	Nutrient runoff	Capacity to absorb nutrients	Watershed
Water Provisioning	Water withdrawal	Water from rain, rivers, lakes	Watershed
Air Quality Regulation	Air pollutants	Cleaning capacity of trees, wind	Regional
Water Quality Regulation	Water pollutants	Cleaning capacity of rivers, wetlands	Regional

of water provisioning depends on features in the watershed such as rivers, rate of groundwater replenishment, rain, degree of surface imperviousness, etc. For regulating services, the demand can be quantified based on the allowed or acceptable level of risk, for example the return interval of flooding events, whereas hydrological models can predict how ecosystems modify that risk. Additional exemplar ecosystem services, along with the quantification of supply and demand, are shown in Table 1

While the ecosystem services listed in Table 1 are typical for small-scale technological systems, more services need to be considered when going to larger scales. For example, at the city scale there is demand for services such as nature recreation, and at the national scale for maintaining biodiversity. The supply of these can be measured by counting visitors or monitoring species populations, or modeled using environmental and geospatial data. Even for small-scale overshoot analysis, it is important to include these services, as otherwise services that are not "material" at small scales would seem to have zero demand as discussed in Section 3.5. To ensure consideration of all relevant services, one can take advantage of initiatives such as the European Common International Classification of Ecosystem Services (CICES) framework, which produced a hierarchical classification of ecosystem services [39].

3.3 Inventory and Models

As described in Section 3.1, TES requires information at multiple spatial scales about technological systems and the ecological systems on which they depend. Information about technological systems at various scales and levels of aggregation is available from many sources. At the finest scales are engineering models or data of manufacturing processes. Such models or data can be very detailed and relatively accurate, and are commonly used in engineering design. At coarser scales, life cycle inventory data of typical processes represents average processes in a selected geographical region [60]. Such data is usually empirical, is commonly used for life cycle assessment, and is likely to be less accurate than models at the process scale. At even coarser scales is data about flows associated with economic sectors. Such data are often available from public sources and correspond to hundreds of sectors in national economies. Such data along with economic input-output models have been used for developing environmentally extended input-output models and for LCA at national [58, 59] and global [61, 62, 63] scales. These sources of life cycle inventory data usually do not contain information about ecosystems, and cannot be used directly for TES. However, such data may be combined with models and data about ecosystems at multiple scales, as described here.

To obtain information about ecosystem services at multiple scales, various models and databases are available. Models of ecosystem services at the local scale include the i-Tree suite [64] to quantify ecosystem services provided by urban trees. These include air quality regulation by taking up pollutants such as carbon monoxide, sulfur oxides, nitrogen oxides and volatile organic compounds along with modeling reduction in water run-off, etc. Models such as CENTURY, DNDC, EPIC, and APEX simulate the capacity of soil to provide various ecosystem services according to the type of land use. Models of natural and treatment wetlands are also available [65] to quantify the water quality regulation service and other ecosystem services provided by wetlands. Other models, such as SWAT and HEC can be used to model hydrological processes and associated services such as baseflow regulation and flood protection. Such models require detailed input about local ecological conditions such as species of trees, soil quality, etc.

Several efforts are developing more user-friendly models that require less information than the detailed ecological models mentioned previously. One example is Integrated Valuation of Environmental Services and Trade-Offs (InVEST) [66]. This software contains a suite of models that are less information intensive and more approximate. Such models have been used for estimating the supply of ecosystem services over large regions, and can benefit from increasing availability of data from remote sensing and geographical information systems [67]. Examples of studies about regional ecosystem services include information about water availability and demand [68], flood regulation [69], carbon sequestration capacity [70], and pollination services [71]. These models are comprehensive and easy to use, but less accurate than the models described in the previous two paragraphs.

At larger scales, ecosystem services are often represented by aggregating information from smaller scales, which is analogous to how technological data are aggregated for inclusion in life cycle inventory databases. As data and models become available to quantify the supply of ecosystem services, they should be incorporated in life cycle inventory databases and environmentally extended input-output models to permit wider and easier application of TES. Recent work has quantified the contribution of the carbon sequestration ecosystem service in the Eco-LCA model of the U.S. [31]. Other efforts include assessments of environmental damage costs resulting from a company's direct and indirect emissions to calculate the "true cost" of corporate activities in monetary terms [72]. This approach relies on conventional economic tools such as marginal damage costs, abatement costs, environmental taxes and productive losses.

3.4 Allocation

A challenge in the proposed approach, particularly at larger scales, is due to the fact that an ecosystem service available at a selected scale is likely to be demanded by many different activities. Assessing the sustainability of alternatives requires ways of determining the correct share of an ecosystem service among multiple users. If there are multiple users of water in a watershed, the water provisioning service in the watershed needs to be allocated to each user. Similarly, the carbon sequestration ecosystem service from ecosystems on public land in a city would need to be partitioned between the activities that emit CO_2.

A similar challenge arises in life cycle assessment and footprint methods when a process produces multiple products. Examples of such situations include production of stover and corn from corn farming, or desired mineral and tailings from mining operations. In such systems, if the goal is to determine the emissions or resource use for each product, then these flows need to be allocated between the products.

Two possible ways of allocating the supply of ecosystem services between users are as follows.

- *Proportional allocation.* The ecosystem service available in a region could be partitioned between users in proportion to impact or value. For example, the carbon sequestration service from vegetation on city land could be allocated in proportion to the mass of CO_2 emitted by each activity in the city, monetary value of each activity, or some other quantity. The idea underlying this approach is similar to allocation in LCA, and will face the same challenge of determining the correct basis for allocation, and the results could change with the allocation method. Such allocation could also take the form of a market for ecosystem services that functioned at the scale of service provision.

- *Avoid allocation.* This approach would not allocate ecosystem services between multiple users, but instead consider its total supply and total demand at the selected ecological spatial scale. If the total demand exceeds the total supply, then all activities that rely on this ecosystem service at that scale will be considered to be overshooting that service. This approach will require calculation of the total ecosystem service supply and demand at the selected ecological scale, and not just for the selected technological system(s).

How the allocation method can affect decisions is discussed in the next subsection.

3.5 Impact Assessment and Metrics

The basic results from TES will consist of pairs of numbers $\{D_{i,j,k}, S_{i,j,k}\}$ representing demand, D and supply, S for each techno-ecological system, $i = 1, \ldots, I$, at each ecological scale, $j = 1, \ldots, J$, for each ecosystem service, $k = 1, \ldots, K$. Note that, as discussed in Section 3.1 and shown in Table 1, the largest scale will depend on the type of ecosystem service. These demand and supply numbers may be used to define sustainability metrics to compare alternatives, and as objectives for designing sustainable systems.

Ecological sustainability. Sustainability of the i-th system at the j-th scale and for the k-th ecosystem service may be defined as,

$$V_{i,j,k} = \frac{S_{i,j,k} - D_{i,j,k}}{D_{i,j,k}} \tag{1}$$

Negative of $V_{i,j,k}$ may be interpreted as representing ecological overshoot. A necessary, but not sufficient condition for absolute sustainability may be written as,

$$V_{i,J,k} \geq 0, \ \forall i, \forall k \tag{2}$$

Thus, for each ecosystem service, the demand cannot exceed the supply at the largest scale, $j = J$. This condition is based on the common understanding that exceeding nature's carrying capacity is undesirable for sustainable development. This is a condition for absolute, as opposed to relative sustainability because it is based on comparison with an absolute quantity, the carrying capacity for the k-th ecosystem service [73]. In contrast, relative sustainability metrics involve comparison with alternatives, and not with any absolute limits. Other characteristics of these metrics are discussed near the end of this subsection.

The condition given by Equation 2 is not sufficient for sustainability since other factors such as dynamics, complexity, social, and economic aspects also matter but are not captured in the current framework. In addition, the "wicked" nature of sustainable development makes it difficult to define a necessary and sufficient condition. If demand does exceed supply, that is, if $V_{i,J,k} < 0$ then it means that the ecosystem service is being used at a rate faster than its rate of replenishment, and the human activity is exceeding nature's regenerative capacity. Such a situation usually results in symptoms such as depletion of ground water and fossil resources, accumulation of CO_2 in the atmosphere, or of nutrients in water bodies.

The criterion given by Equation 2 may also be applied at any scale. Thus, if

$$V_{i,j,k} \geq 0 \tag{3}$$

then, it means that dependence on the k-th ecosystem service is *locally* sustainable at scale j. It could happen that Equation 3 is satisfied, while Equation 2 is not. For example, a system may emit less CO_2 than can be sequestered by its surroundings to be locally sustainable, but the electricity it buys from outside its boundary may emit more CO_2 than can be sequestered by the ecosystems at the larger scale. Satisfaction of Equation 3 represents an "island of sustainability." As discussed in Section 3.6, TES metrics may encourage the development of such islands, and ultimately satisfying Equation 2.

If the available ecosystem service in a single serviceshed is allocated between multiple users in proportion to the demand created by each user for the selected service, as discussed in Section 3.4, then Equation 1 will result in identical values of $V_{i,j,k}$ for all users. If allocation is in proportion to quantities other than demand or if servicesheds overlap, then it could result in different values of $V_{i,j,k}$ at each scale, j. If allocation is avoided then the overshoot should be calculated for scales including the largest scale. In this case, if $V_{i,j,k} < 0$ then all activities that rely on this ecosystem service at this or smaller scale are considered to be globally unsustainable. Thus, according to this criterion, any activity that demands the water provisioning ecosystem service by withdrawing water from the watershed is sustainable only if the total water withdrawal by all activities in the watershed does not exceed the available renewable water.

In the proposed TES framework, it is important to prevent analyses that appear beneficial by omitting critical ecosystem services because they are beyond the scale of the technical system being considered or are not of interest to the system owner. For example, a decision about replacing a natural area such as a wetland by a parking lot will have a negative impact on ecosystem services such as flood regulation, pest regulation, or natural aesthetic beauty. However, since this technological activity does not demand these services, $D = 0$, the corresponding value of V will tend to infinity, even when the supply is reduced. This is a perverse result since the negative impact of the decision on ecosystem services at larger scales may not be detected. To prevent such outcomes, the notion of "materiality," or "materially important" ecosystem services must be included within TES.

Materiality is a foundational principle of financial accounting and recognizes that some information is important to the fair presentation of conditions and performance. Under US law, materiality is information presenting a substantial likelihood that the disclosure of the omitted fact would have been viewed by the reasonable individual as having significantly altered the "total mix" of information made available [74]. As such, the range of ecosystem services, k, that must be considered in TES should include any services that all stakeholders in an ecosystem find important and relevant. For services that are material to a TES analysis, but at scales larger than the scale of the system being assessed, this larger scale should be considered for calculation of the metrics.

Aggregate Metrics. The metrics proposed so far provide a measure of ecological sustainability for each ecosystem service at multiple scales. These metrics may be compared for multiple products and the product with larger $V_{i,j,k}$ may be preferred. However, the high dimensionality of the sustainability metrics is likely to result in conflicts between ecosystem services making it difficult to choose between alternatives. Such challenges are common in sustainability analysis, and various approaches for comparing systems in multiple dimensions have been explored such as techniques for multi-criteria decision making. Methods may also be devised to reduce dimensionality by using weights, $w_{i,j,k}$ that represent the relative importance of each ecosystem service. Then the aggregated overshoot at scale, j may be calculated as,

$$V_j = \sum_i \sum_k w_{i,j,k} F_k \left(V_{i,j,k}\right) \tag{4}$$

where, $F_k\left(V_{i,j,k}\right)$ could be $F_k\left(V_{i,j,k}\right) = V_{i,j,k}$ resulting in a linear weighted sum. Alternatively, $F_k\left(V_{i,j,k}\right) = \mathcal{H}\left(V_{i,j,k}\right)$, where $\mathcal{H}$ represents a Heaviside or step function. The latter representation could incorporate information about ecological thresholds in determining the Heaviside function. These metrics at individual scales may be further aggregated by combining metrics at all scales resulting in a single metric. Weights, $w_{i,j,k}$ may require subjective input from individuals and society at large. Many recent efforts have focused on monetary valuation of ecosystem services, and approaches to combine them into aggregated metrics, including notions such as "shadow prices" [75, 76]. These efforts may be useful for determining the proposed weights for aggregation.

Interpretation of Metrics. The proposed metrics quantify the gap between the supply and demand of selected ecosystem services. Interpretation of the metrics and further steps will be in the following two categories.

- If supply of ecosystem services is greater than its demand, $V_{i,j,k} > 0$, then the selected human activity is operating within nature's carrying capacity, and as indicated by Equation 3, the system may be considered to be sustainable at the selected scale and ecosystem services. This situation indicates strong sustainability since each ecosystem service is considered separately. If only $V_j > 0$ but some individual $V_{i,j,k} < 0$, then it indicates weak sustainability at the selected scale. In these cases, efforts may be directed at maintaining this sustainable situation. As schemes for "payment for ecosystem services" are developed, systems in this category may be able to benefit monetarily due to the "value addition" that they provide to society at large.
- If supply is less than the demand, $V_{i,j,k} < 0$ then the k-th ecosystem is unable to satisfy the demand posed by technological systems. In this case, human activities are likely to result in harm to society and the environment. This damage may be quantified with the help of methods developed for assessing the environmental and human impact of pollution and resource use by methods such as those in life cycle impact assessment [77] or for monetization of damages due to pollution [78].

Despite the popularity of such aggregation schemes for ecosystem services and the ease of making decisions with aggregate metrics, they should be used only when absolutely necessary, and certainly not in a manner that the underlying physical information is lost or ignored. This is because of known disadvantages of aggregation such as the assumption of substitutability and the resulting weak sustainability criteria [79]. Monetary valuation of ecosystem services is also not without its risks of providing perverse decisions [80]. A hierarchy of metrics may be defined to get the best of disaggregate and aggregate quantities.

3.6 Improvement and Design

TES aims to encourage engineering and human activities to be within ecological constraints. Satisfying this goal means making changes such that $V_{i,j,k} \geq 0, \forall\{i, j, k\}$. This may be achieved by enhancing technological efficiency to reduce the demand for ecosystem services, or by restoring and protecting ecological systems to increase the supply of ecosystem services. This is an important feature of TES as compared to other methods for assessing and designing sustainable systems. Since these methods do not consider the supply of ecosystem services, their improvement efforts are often limited to technological aspects. An equally important feature of TES is the explicit recognition of the inherent interdependencies between technological and ecological systems. Such recognition enables a better understanding of the resiliency of coupled techno-ecological systems during any enhancement of technological efficiency or restoration of ecological service provision.

The multiscale nature of TES presents improvement and design opportunities at each spatial scale considered. Typically, changes are likely to be easiest at the smallest scale, such as a manufacturing process. If there are emissions that cannot be absorbed or mitigated by ecosystems, then it will be impossible for $V_{i,j,k} \geq 0$ for some values of i, j, and k. Examples include processes that emit molecules that do not occur in nature such as chlorofluorocarbons, various synthetic polymers, many pharmaceutical molecules, etc. For such molecules, the only way to satisfy the TES objective of $V_{i,j,k} \geq 0$ is by technological changes. One approach is to treat such molecules as "technological nutrients" and like biological nutrients, to recycle in technological systems [35].

Nonrenewable resources will invariably result in values of $V_{i,j,k} < 0$. Therefore, seeking TES will discourage their extraction and encourage their reuse and recycling by efforts such as industrial symbiosis.

4 Illustrative Example

This section illustrates the type of results and insight that TES can provide by application to a biodiesel manufacturing process. All the data needed for the TES analysis of this process

Table 2: TES at local and regional scales for conventional biodiesel manufacturing. Note that $V_{i,j,k}$ is bounded between -1 and ∞ and larger values are more desirable.

		Without TES			With Local TES			With Local & Regional TES		
k	Ecosystem Service	Local, $V_{1,1,k}$	Regional, $V_{1,2,k}$	Global, $V_{1,3,k}$	Local, $V_{1,1,k}$	Regional, $V_{1,2,k}$	Global, $V_{1,3,k}$	Local, $V_{1,1,k}$	Regional, $V_{1,2,k}$	Global, $V_{1,3,k}$
1	Air Quality Regulation	$\ll 0$	< 0	NA	≈ 0	< 0	NA	≈ 0	≈ 0	NA
2	C sequestration	$\ll 0$	$\ll 0$	$\ll 0$	< 0	$\ll 0$	$\ll 0$	< 0	< 0	$\ll 0$
3	Water Quality Regulation	< 0	< 0	NA	≈ 0	< 0	NA	≈ 0	≈ 0	NA
4	Nonrenewable energy	-1	-1	$\ll 0$	$\ll 0$	-1	$\ll 0$	$\ll 0$	$\ll 0$	$\ll 0$

are not yet available, so this example is to illustrate some characteristics of TES and identify research needs.

The problem considered is as follows. A biodiesel manufacturer is assessing its operation, and would like to identify ways of making its manufacturing more sustainable. Existing engineering methods can help make the process more efficient, and existing sustainable engineering methods can account for broader impacts in the life cycle and help in reducing them. Such approaches rely on indicators of relative sustainability, as discussed in Section 3.5, and focus on doing "less bad."

TES considers the same technological systems, along with the role of ecosystems at multiple scales. At the smallest scale, TES considers only the biodiesel manufacturing process and its surroundings. This technological system, $T_{1,1}$ is considered to be within its immediate surroundings of the manufacturing site, $E_{1,1}$, which is within a region, $E_{1,2}$, and the planet, $E_{1,3}$. For illustration purposes, we consider the ecosystem services of air quality regulation, water quality regulation, carbon sequestration, and nonrenewable energy resources. Design alternatives are considered at local and regional scales.

Without TES, all services are likely to be unsustainable at local, regional and global scales, as indicated in the third to fifth columns of Table 2. Based on these results, the company may start with local options for enhancing its sustainability. Enhancing technological efficiency is one option to reduce the demand for ecosystem services. This "classical" solution, however, does not leverage potential benefits of supporting ecosystems. The easiest TES option is for the company to restore ecosystems on its own land and establish synergies between these ecosystems and the manufacturing activities. In this situation, the results of TES are likely to show improvement over the base case without TES, particularly at the local scale, $j = 1$, as shown in the sixth to eighth columns of the Table 2. Relevant ecosystems in this case could be trees on the corporate campus, which could take up emissions such as nitrogen and sulfur oxides, particulate matter, and reduce ground level ozone formation. These trees could also replace some of the fossil energy used in manufacturing by using wood as fuel. In addition, for water quality regulation, a treatment wetland on the manufacturing site could treat the wastewater and produce water that could be reused in the process. Also, the biomass from the wetland could be harvested and used as fuel in the plant. These local changes may enable an island of sustainability at the corporate scale but it may push impacts to larger scales.

After implementing local options, the company may consider a regional TES option, which could involve investment in a regional nutrient cap-and-trade market, reducing the levels of downstream pollutants by affecting agricultural runoff from upstream farmers. The company can also consider purchase of carbon credits from voluntary markets such as California's Carbon Market, REDD+, as carbon sequestration supply is attributed to the company's global direct impact. For other services, such as air quality, TES would encourage collaborative consideration of emission reductions within the "serviceshed," which for this example encompasses the area where air pollutants emitted to the atmosphere affect city-dwellers' health. Metrics in the last three columns indicate improvement at the regional scale. TES may be further extended to include processes in the life cycle and to a hybrid life cycle model that includes national and international flows. Encouraging such activities at multiple scales is a unique feature of TES and goes well beyond the features of existing sustainable engineered methods.

5 Outlook

The framework of techno-ecological synergy expands the reach of sustainable engineering beyond the current techno-centric approach by including the pivotal role of ecosystems. It can be applied at multiple scales ranging from an individual process to the entire life cycle, and encourages reduction of the impact of technological systems along with restoring the ability of ecosystems to provide goods and services. Practical application of this framework requires use of models and data from engineering, life cycle assessment, ecological modeling, geographical information systems, and advances in other disciplines including policy, economics, and law. This presents many opportunities for theoretical and applied research across disciplines.

Author Information

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