Techno-Ecological Synergy: A Framework for Sustainable Engineering

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Abstract

Even though there is little agreement on a definition of sustainability, defining unsustainability is much easier: it is a state where the impact of human activities exceeds nature's carrying capacity. Avoiding such a situation is even included in many definitions of sustainability. However, this carrying capacity is rarely considered in methods for sustainable engineering, including life cycle assessment, and methods for designing sustainable chemical processes. Ecological footprint does account for biocapacity, but in a highly aggregated manner that is not very useful for guiding decisions. Given the degradation of ecological processes highlighted in several studies [1, 2], accounting for the dependence and impact of human activities on ecosystems is an urgent need.

We propose a novel framework for Sustainable Engineering that explicitly accounts for the demand for ecosystem services generated by human activities, and the supply of ecosystem services available from nature at multiple spatial scales. The demand for ecosystem services is quantified by information about resource consumption and emissions. For example, the demand for the water provisioning ecosystem service is quantified by the volume of water withdrawn for an activity, while the demand for the carbon sequestration ecosystem service is quantified by the quantity of CO2 emitted. The supply of ecosystem services is determined from knowledge about available ecosystems at the selected spatial scale. Thus, forest cover and species determine the ability to regulate air quality by taking up pollutants such as nitrogen and sulfur oxides and carbon monoxide. Information about tree cover, soil quality and management, etc. can quantify the supply of the carbon sequestration ecosystem service. Models for quantifying various services are available from ecologists at multiple scales, including local, regional and global. They form the basis of the proposed framework.

In the TES framework, each technological system is represented as $T_{i,j}$ which consists of the i-th technological process at the j-th scale. These could be individual manufacturing processes or average processes obtained from a life cycle inventory database, or an economic sector in a regional or national economic input-output model. Each technological system is nested inside ecosystems in its vicinity, that is $T_{i,j} \in E_{i,j}$, where $E_{i,j}$ represents ecological systems in the vicinity of $T_{i,j}$. 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 an single-family home, the smallest ecological scale would be the yard around the house. This smallest scale is then expanded to consider regional, national, and global scales. 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 sustainability analysis, its assessment needs to be at the global and smaller scales. 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 geographical scales.

Results from a TES study consists of a pair of numbers $\{D_{i,j}, S_{i,j}\}$ representing demand and supply for each ecosystem service, $i = 1, \ldots, I$, and at each ecological scale, $j = 1, \ldots, J$.

These demand and supply numbers may be used to define sustainability metrics to compare alternatives and as objectives for designing sustainable systems. The degree of overshoot for the i-th service may be defined as,

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

A necessary, but not sufficient condition for absolute sustainability is,

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

Thus, for each ecosystem service, the demand cannot exceed the supply at the largest scale, $j = J$. This condition is not sufficient for sustainability since other factors such as dynamics and complexity also matter but are not captured in the current framework. If demand does exceed the supply, that is, if $V_{i,J} < 0$ then such a situation usually results in symptoms such as depletion of ground water, accumulation of CO_2 in the atmosphere, or of nutrients in water bodies. The criterion given by Equation 2 may also be applied at smaller scales. If

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

then, it means that dependence on the i-th ecosystem service is *locally* sustainable at scale j. It could happen that Equation 3 is satisfied, while Equation 2 is violated. For example, a process may emit less CO_2 than can be sequestered by its surroundings to be locally sustainable, but the electricity it buys from outside the process boundary may emit more CO_2 than can be sequestered by the ecosystems at the larger scale.

This framework may require allocation of a regional ecosystem services among multiple activities that demand it. Two approaches are explored: allocation based on quantities such as monetary value of the activity or its emissions, and no allocation. The first approach is analogous to what is used in LCA and is subjective. The second approach is easier to use. It implies that if at the selected scale use of an ecosystem service is unsustainable, then all activities in that region that rely on the selected service will be considered to be unsustainable. For example, because the global demand for carbon sequestration far exceeds the global supply of this service, all activities that demand this service are considered to be unsustainable at the global scale.

Some benefits of the TES framework include the following. 1) The goal of reducing ecological overshoot for individual ecosystem services at multiple scales will encourage enhancements in technological efficiency, along with ecological protection and restoration. Existing methods mainly encourage the former. 2) If human activities demand services that ecosystems simply cannot provide, then the only way to satisfy the TES goal of $V_{i,j} \geq 0$ is by technological efficiency that eliminates this demand. This will discourage use of nonrenewable resources and encourage cycling of molecules that do not occur or are rare in nature. 3) The TES approach favors systems that have a smaller overshoot with respect to ecosystems at the selected scale. This approach encourages integrated design of technological and ecological systems such as that of a building and its surrounding land [3], and of a manufacturing process and ecosystems on available land [4]. 4) If $V_{i,j} < 0$, then the impact of emissions and resource use will need to be determined by various impact assessment methods. In contrast, if $V_{i,j} \geq 0$ then the system is locally sustainable and there is no need for applying methods such as LCA. Thus, a company could focus on achieving local sustainability, and only including locally sustainable manufacturers in its life cycle. In such a situation, methods such as LCA become unnecessary. These and other characteristics of the TES framework will be demonstrated with the help of a case study.

References

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