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Synergies between industry and nature – An emergy evaluation of a biodiesel production system integrated with ecological systems

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ABSTRACT

Techno-ecological synergy (TES) is a framework that encourages integration of technological and ecological systems. Specifically, it incorporates the role of natural capital in engineering assessment and design by quantifying both demand and supply of ecosystem services. Emergy can provide valuable support to improve and interpret TES evaluation, as it is a methodology particularly useful for evaluating systems at the biosphere–technosphere interface. The present study evaluates how the TES framework based on emergy can shed new light by comparing conventional technological alternatives and ecological alternatives for meeting a particular ecosystem service demand. Both the demand and supply of ecosystem services are quantified in consistent units of emergy to obtain aggregated TES metrics. Specifically it was found that additional equipment to treat air pollutants have a higher emergy investment as compared to the forest ecosystem, while the technological unit to treat wastewater requires less emergy as compared to the horizontal subsurface flow wetland, its ecological counterpart. This new approach is tested by application to a biodiesel production plant and by calculating emergy metrics. This work shows that emergy can provide a fundamental improvement to the current TES framework, as it provides an aggregated metric for multiple ecosystem services.

1. Introduction

Several efforts are directed toward developing methods for evaluating the fundamental role of ecological systems in sustaining humanity. Among others, the first and best-known attempt was by Costanza et al. (1997), who highlighted the relevance of ecosystem services from a monetary standpoint, at a global scale. This approach has drawn attention to the value of the ecosystem services by using a language easy to understand (i.e. the economic one). The growing concern about issues such as the degradation of ecosystem services (MA, 2005), the operation of human beings beyond the so-called "safe operating space" (Rockström et al., 2009; Steffen et al., 2015) and the overexploitation of natural resources that exceeds the natural regenerative capacity of the ecosphere (Borucke et al., 2013), have made clear the necessity to include ecosystem services in sustainability assessments of human activities. This awareness has resulted in the development and implementation of tools capable of investigating and capturing the work done by Nature, both from economic and physical viewpoints. While the former is particularly useful to bring the debate around ecosystem services into mainstream economic analyses and to understand the relevance of the issue, the latter is fundamental to provide clear information about exploitation of natural capital and the services that it generates.

In recent years an input-state-output approach has been developed to show that both natural systems and human ones can be understood by this approach (Pulselli et al., 2011, 2015). This idea has a thermodynamic root and is used to show the connection between the sources of energy and matter and ecosystem services (for ecological systems) and economic output (for human ones). Emergy is the common basis with which the inputs to both types of systems can be described, since it represents the amount of solar energy directly and indirectly required to produce any output

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Abbreviations: TES, techno-ecological synergy; V, sustainability metric; D, demand of ecosystem services; S, supply of ecosystem services; CHP, combined heat and power; SCR, selective catalytic reduction; MEA, monoethanol-amine; FGD, flue gas desulfurization; ABR, anaerobic baffle reactor; Em, emergy; UEV, Unit Emergy Value; sej, solar emergy joule; R, emergy flow related to local renewable resources; N, emergy flow related to local non-renewable resources; F, emergy flow related to resources purchased outside the system; %R, fraction of emergy from renewable inputs; ELR, Environmental Loading Ratio; EIR, Emergy Investment Ratio; EYR, Emergy Yield Ratio.

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(Odum, 1996). An important difference between natural and human systems is the fact that while in the latter inputs and outputs appear to be strictly correlated (Pulselli et al., 2015), in the former it is important to have a properly organized and functioning state in order to have a higher amount of output, i.e. ecosystem services (Pulselli et al., 2011).

In the same line, the idea of developing synergies between technological and ecological systems was independently proposed by Urban et al. (2010) and then applied to a residential system (Urban and Bakshi, 2013). Schaubroeck et al. (2013) evaluated a framework that combines ecosystems and the technosphere by means of a life cycle approach. In this work ecosystems were included within the system boundaries and evaluated together with the technological compartments the system is made of. By adopting the same approach, Othoniel et al. (2016) tried to evaluate the life cycle impacts on ecosystem services, highlighting that there are several aspects that are still incomplete in such evaluations (e.g. modeling the cause-effect chains). With regard to human-environment systems, Liao et al. (2012) stressed the need of adopting thermodynamic analysis in industrial ecology to better evaluate the sustainability of such systems. However, all the above studies lack the needed supply–demand perspective of ecosystem services. Accounting for both the ecosystem service demand and supply while looking at techno-ecological systems is necessary to maintain the system within ecological limits.

In this regard, one of the most recently developed approaches that aims to physically quantify the sustainability level of systems is the techno-ecological synergy (TES) framework (Bakshi et al., 2015). This framework is an effort toward addressing "the urgent need to consider the status of ecosystem services in engineering decisions", by quantifying the demand and the supply of ecosystem services. The demand is quantified in terms of emissions and resources use, while the supply is represented by the benefits provided by nature. Specifically, the TES approach assesses and designs synergistic networks of technological and ecological systems at multiple spatial scales, from local to global. A unique feature of TES is that it quantifies the demand on ecosystem services imposed by human activities, and considers the capacity of relevant ecosystems to supply these services. This information is used to define environmental sustainability metrics based on quantifying the difference between the supply and demand. A positive value of this metric, or a state of absolute sustainability is achieved when the systems operate within the carrying capacity of ecosystems, when the demand is less than the supply for the selected ecosystem service. This approach is different from most methods used for assessing and designing technological systems, since most existing methods only aim to reduce the environmental impact or ecosystem service demand. Such methods also measure the level of sustainability of systems, relative to other similar systems, and not based on the ecosystem capacity. A practical outcome is that TES encourages reduction of impacts by modifying technologies, as done by existing methods, but also considers (and often supports) restoration and protection of ecosystems, unlike most existing methods.

The potential economic and environmental benefits of assessing and establishing techno-ecological synergies have been demonstrated through several studies. Urban and Bakshi (2013), demonstrated the benefits of including ecosystems in the design of residential systems, accounting for carbon sequestration, water provisioning service and system costs. Gopalakrishnan et al. (2016) assessed the synergies and trade-offs between industrial processes and surrounding ecosystems with the application to a biodiesel manufacturing site. This work also highlighted the practical challenges in extending this approach to the diverse array of ecosystem services. This previous work focuses on carbon sequestration, air quality regulation and water quality regulation ecosystem services. Hanes et al. (2017), used the TES concept to design a methodology for incorporating simultaneous decisions on the design of both technological and ecological systems, by considering a life cycle boundary, and the demand and supply for multiple ecosystem services. The methodology was applied to design of a renewable energy production system where multiple ecosystem services like carbon sequestration and air quality regulation were considered.

However, all the previous work considers only few of the many ecosystem services identified by the MA. Even then, there are over a half dozen emissions that need to be compared. This entails some form of aggregation if the promise of assessing and designing techno-ecological synergies is to be realized. This work uses the emergy for doing such aggregation.

Application of the TES framework by adopting the emergy perspective can help better understand the interaction between the technological approach that is usually adopted in engineering design and the alternative one that includes implementation of nature-based solutions, that are those solutions based on the work done by ecological systems. In this regard the purpose of this work is to evaluate how the TES framework can benefit by using the emergy approach, in terms of the engineering design as emergy gives useful information about natural resources consumption, and from a methodological viewpoint as it provides a common basis on which ecosystem services can be evaluated Specifically, this paper aims to, (i) compare technological and ecological solutions for achieving the same goal in an engineering process; (ii) quantify both demand and supply of ecosystem services, as proposed by the TES framework, in emergy terms to calculate aggregated metrics. The appropriateness of using emergy, which has been described as an ecocentric approach, for quantifying ecosystem services, which are described in an anthropocentric manner, is also discussed. The suggested approach is explored at the process scale, through an application to a biodiesel production plant located in the US (see Gopalakrishnan et al., 2016), where air quality regulation and carbon sequestration services provided by a forest and water purification service provided by a constructed wetland are respectively evaluated as alternative options to the technological ones that are usually adopted for treating air pollutants and wastewater. The goal of these alternatives is to go beyond regulations toward net-zero or net-positive impact.

2. Materials and methods

2.1. Techno-ecological synergy (TES)

The TES framework is based on the promise of developing mutually beneficial relationships between technological and ecological systems at multiple spatial scales. The linkage is analyzed by quantifying the demand of ecological services required by human activities and the capacity of nature to supply the same kind of services. The demand, D of ecosystem services by technological systems can be determined by estimating the amount of natural resources that are consumed and the emissions that are produced. On the other hand, the supply, S is evaluated on the basis of the beneficial effects that the provision of ecosystem services generates, by offering resources and absorbing emissions and waste flows. The comparison between the demand and the supply of ecosystem services makes it possible to define the metric, V that enables estimation of the level of sustainability characterizing the i-th system, at the j-th scale and for the k-th ecosystem service (Bakshi et al., 2015):

$$V_{i,j,k} = (S_{i,j,k} - D_{i,j,k})/D_{i,j,k} \tag{1}$$

$i = 1, \ldots, I;\ j = 1, \ldots, J;\ k = 1, \ldots, K$

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