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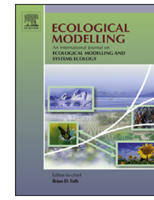

Emergy evaluation of benthic ecosystems influenced by upwelling in northern Chile: Contributions of the ecosystems to the regional economy

Fernando Berrios[a,b,*], Daniel E. Campbell[c], Marco Ortiz[b]

[a] Programa de Doctorado en Ciencias Aplicadas, mención Sistemas Marinos Costeros, Universidad de Antofagasta, PO Box 170, Antofagasta, Chile
[b] Instituto de Antofagasta (IA), Instituto de Ciencias Naturales AvH, Facultad de Ciencias del Mar y Recursos Biológicos, Universidad de Antofagasta, Chile
[c] USEPA, ORD, NHEERL, AED, Narragansett, RI, USA

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ABSTRACT

Emergy evaluations of three benthic ecosystem networks found in Mejillones, Antofagasta and Tongoy Bays, located on the coast of northern Chile, were carried out with the intent of documenting the contributions of these coastal ecosystems to the economy. The productivity of these bays is strongly influenced by the Humboldt Current System, as well as by the loss of upwelled flows that occurs during El Nino events. The results of the emergy evaluations were expressed as emdollars (EM$), a combined emergy-money measure that can be used to examine the equity of the emergy exchanges between fishermen and the buyers of the harvested algae and shellfish. In addition, an estimate of the total ecosystem services provided by these coastal ecosystems was made. The emdollar (Em$ y^{-1}) and the hypothetical monetary value (US$ y^{-1}) of the nitrate nitrogen upwelled constituted the highest inflow of emergy to all three benthic ecosystems. The empower density expressed as Em$ m^{-2} y^{-1} was highest in Mejillones Bay; however, the natural capital (biomass) of the ecological components (EM$ m^{-2}) was highest in Antofagasta Bay, where La Rinconada Marine Reserve is located. The relationship between the coastal zone system and the regional economic system was assessed using the emergy benefit after exchange, EBE, which showed that there were net gains to the overall welfare of the sellers in two regions, 3,280,000 Em$ to those in Mejillones Bay, and 34,000,000 Em$ to those in Tongoy Bay, but a net loss of 2,000,000 Em$ to the sellers of algae and shellfish harvested from Antofagasta Bay. By supplying a clearer picture of the equity of trade relationships for individual organisms, fisheries and bays, emergy evaluation can help develop and implement management strategies for the conservation and preservation of coastal ecosystems to ensure that they are sustainable in the future.

1. Introduction

Ecosystems can be characterized by the processes of transforming available energy, cycling materials, replicating information, and they self-organize into hierarchical networks. These networks support diverse ecological populations, by means of dynamic pulsing, which interacts with economic activities through pathways of power and control (Odum, 2007). Power flows in ecosystems are coupled to the economy through controlling feedbacks manifested in the monetary value assigned to the products and services provided by ecosystems. Obtaining a better understanding of the relationship between the market value of marine ecosystem products and the environmental work required for those products is essential for maintaining healthy and maximally sustainable regional systems. Whereas, a comprehensive understanding of the mechanisms of power and control between ecological and economic systems is necessary to establish efficient policies that solve problems related to the sustainable consumption of goods and services generated by ecosystems; in practice, the policies governing fisheries management and conservation of natural resources appear to be moving in the direction favoring economic interests rather than also promoting the environmental and ecological health of ecosystems (Airoldi and Beck, 2007). If the health of ecosystems suffers too much, then the overall health of the entire ecological-economic system is threatened. To counter this trend, we need to find a fair method for quantifying the exchange of real

* Corresponding author.
E-mail address: fberriosrobles@gmail.com (F. Berrios).

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wealth[1] in transactions where money is exchanged for environmental products (e.g., fish and shellfish) and for estimating the contributions of environmental goods and services that are external to markets (e.g., noncommercial species) to the economy. To address this problem, the real wealth of ecosystem goods and services (i.e., as measured by emergy) can be quantified on an equal basis with the monetary gains by expressing monetary gains in terms of the real wealth (emergy) that can be purchased on the market by the money received for the products of ecosystems.

From an economic perspective, the definition of ecosystem goods and services is related to the contributions that they make to our well-being (MEA, 2005), whereas, natural capital yields flows of valuable goods and services from the stock of environmental (land, air, water, sea, etc.) and ecological (biodiversity and ecosystem components) natural capital (Costanza and Daly, 1992; Odum, 1996). In this work, we evaluate the natural capital of the benthic ecosystems in coastal Chile in ecological terms considering the biomass (stock) of the different components that make up the benthic trophic networks and their contributions to the well-being of regional economy.

1.1. The efficacy of the emergy approach

Neoclassical economic theory does not attempt to quantify the value of all the environmental goods (biomass, food, etc.) and services (evapotranspiration, waste assimilation, etc.) of ecosystems that represent the benefits that humans derive from ecosystem functions. So, natural goods and services without commercial importance (i.e., off-market) often end up being ignored in public and private decisions, compromising the sustainability of ecosystems from a global point of view (Odum and Odum, 2000). To address this problem, various authors have used economic methods (e.g., direct and indirect market pricing, such as contingent valuation, among other methods) and non-economic methods (e.g., based in energy) for economic valuation of ecosystem functions, goods and services (Costanza et al., 1997; Straton, 2006; Costanza et al., 2014; Hutniczak, 2015).

Odum (1996, 2007) criticized the use of both money and caloric energy to evaluate the relative importance of each of the components of an ecosystem with regard to its function and value within a system. He argued that: (1) the work of nature is not paid for with money, yet it contributes to the processes valued by society; (2) energy alone does not represent the true value of the contributions of resources from the different elements of an ecosystem to an economic group, because (3) energy sources when expressed in terms of their caloric values are not equivalent in terms of their ability to do work in a system. As a consequence of these observations, he suggested that *Emergy evaluation* be used to integrate these commonly unquantified processes such as those provided by the environment (e.g., rain, wind, solar radiation) into market evaluations, (Odum, 1996).

The application of emergy evaluation, using both analysis (Odum, 1996) and synthesis perspectives (Brown et al., 2000; and subsequent Emergy Synthesis Volumes 2–9 and associated special issues of Ecological Modelling, (Franzese et al., 2014; Brown et al., 2015) has proved to be a useful tool to value the properties of ecological-economic systems at different scales (Odum and Arding, 1991; Campbell et al., 2015; Morandi et al., 2015), ecological services (Campbell and Tilley, 2014; Grönlund et al., 2015), natural and human capital (Campbell and Brown, 2012; Mellino et al., 2015) and to perform financial accounting for the environment, economy, and society (Campbell, 2013). Relevant to this analysis, Franzese et al. (2015) and Vassallo et al. (2017) have further developed and elucidated biophysical and trophodynamic accounting methods (e.g., emergy accounting) for the assessment of natural capital in marine protected areas and marine environments; thereby providing the means to quantify the contributions of ecosystem goods and services that arise from marine and estuarine natural capital storages.

1.2. Estimate of the total ecosystem services provided to the regional economy

We recognized that our analyses of the commercial and noncommercial products and services provided by the benthic ecosystem fisheries to the regional economy did not give a complete picture of all the ecosystem goods and services provided by the emergy inputs to the coastal benthic ecosystems. A literature search did not reveal any assessments that have valued the total coastal marine environmental inputs to the regional economy of northern Chile in regard to their role (i.e., the work that they are doing) in maintaining the health and integrity of the region. Therefore, we made a first order estimate of the total contributions of the environmental forcing functions of the three bays to the regional economy using the method first proposed by Pulselli et al. (2011) and applied to many countries by Coscieme et al. (2014). In this method, the Ecosystem Emergy to Money Ratio (EEMR) of Pulselli et al. (2011) defined as the geobiosphere emergy baseline divided by the global estimate of the hypothetical[2] monetary value of global ecosystem services from Costanza et al. (1997) was used to estimate the economic value of the goods and services provided by the renewable resource inflows of a region or nation of interest.

1.3. Environmental setting for the benthic ecosystem evaluations

Most of the Chilean coast (18°–56° S) is strongly influenced by the Humboldt Current System and its importance lies in being one of the most productive marine ecosystems in the world (Strub et al., 1998). In oceanographic terms, this high productivity is supported by the upwelling of sub-surface equatorial waters rich in nutrients and of low oxygen concentration (Strub et al., 1998; Escribano and Hidalgo, 2001). Several studies have analyzed the importance and influence of upwelling areas in northern Chile on the pelagic system, focusing primarily on: (1) the effects on primary and secondary production (Escribano and McLaren, 1999; Daneri et al., 2000); (2) different aspects of population dynamics (Escribano, 1998; Vega et al., 2005); (3) the effect on fisheries (Thiel et al., 2007; Montecino and Lange, 2009); and (4) the EL Nino Southern Oscillation, ENSO, variability (Laudien et al., 2007; Pacheco et al., 2012); among other topics. This area supports both important, artisanal, pelagic-benthic fisheries (i.e., for mollusks, algae, coastal and pelagic fish), as well as scallop aquaculture, with total artisanal landings of about 545,000 t per year (Servicio Nacional de Pesca y Acuicultura SERNAPESCA, 2014. Anuario Estadístico). This environmental setting has contributed to local economic growth of the artisanal fisheries sector, which is focused on benthic resources present in Mejillones, Antofagasta and Tongoy Bays with the majority of landings comprised of the brown alga, *Lessonia* spp., gastropods *Concholepas concholepas* and *Fisurella* spp., the cephalopod, *Octopus* spp., and the scallop, *Argopecten purpuratus.* (SERNAPESCA, 2014; Ortiz and Wolff, 2002; Ortiz et al., 2015).

[1] Real wealth is the work that an item or flow can do when used in a system for its intended purpose. For example, a car can be driven only so far on a liter of petroleum, regardless of the price paid at the pump. Real wealth is measured by the emergy of an item and not necessarily by its price.

[2] The amount of money estimated by Costanza et al. (1997) as the value of global ecosystem services is not really circulating in the gross world product, GWP, because these money flows were, in part, measured by contingent valuation and other methods that give hypothetical dollar values of ecosystem goods and services.