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# Emergy evaluations of the global biogeochemical cycles of six biologically active elements and two compounds

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ABSTRACT

Estimates of the emergy carried by the flows of biologically active elements (BAE) and compounds are needed to accurately evaluate the near and far-field effects of anthropogenic wastes. The transformities and specific emergies of these elements and of their different chemical species are also needed to quantify the inputs to many ecological and economic production functions. In this study, we performed emergy evaluations of the global biogeochemical cycles of the BAE, carbon, C, nitrogen, N, sulfur, S, phosphorus, P, oxygen, $O_2$ and silica, Si, as well as the global cycles of two compounds (+2), methane, $CH_4$ and water, $H_2O$. We assembled budgets for the global flows of the "BAE + 2" from the literature for the Preindustrial Era and the Industrial Age. The emergy basis for these elemental flows was obtained by documenting the global inflows of renewable and nonrenewable emergy for the Preindustrial Era (*i.e.*, *circa* 1850) and for the Industrial Age. The nonrenewable emergy inputs in the Industrial Age were documented using a variable time window corresponding to the period of observation when the different elemental budgets were evaluated. We calculated specific emergies and some transformities of the total flows of the elements and of some of their chemical species. The elemental cycles were diagrammed in Energy Systems Language (ESL) and tables of specific emergies are provided for use in subsequent emergy evaluations. The accuracy of evaluating the global cycles of the BAE + 2 at intermediate complexity was assessed by comparison to the results of an earlier detailed analysis of the global N cycle. Joint evaluation of the BAE + 2 allowed us to examine these elemental cycles with respect to commonalities and differences in their structure, function, and potential impacts of their perturbations on the global ecosystem. We characterize the coupling of the BAE in terms of a fast biogeochemical loop and a slow geochemical loop, an insight which emerged from the process of diagramming the nitrogen cycle in ESL. Finally, we compared our emergy evaluation results to other means of ranking greenhouse gases (GHGs) and other wastes and developed specific recommendations that more research and management attention should be focused on $N_2O$, S and $CH_4$, while continuing present efforts to better understand and manage $CO_2$ and reactive N.



## 1. Introduction

Human impacts on global biogeochemical cycles are now broadly recognized (Vitousek et al., 1997a,b) and observable effects such as climate change, loss and degradation of ecosystems, and declines in biodiversity are progressively becoming the focus of management efforts to prevent environmental damage by modifying human behavior that is destructive to the environment (Doney, 2010; Lehman and Geller, 2004). In addition, where environments have been damaged by the wastes from economic production processes managers seek to establish policies that require mitigation of that damage through ecosystem restoration and other palliative means (*e.g.*, http://co.humboldt.ca.us/planning/salt-river-eir.pdf; http://water.epa.gov/lawsregs/guidance/wetlands/mitbankn.cfm). An accurate evaluation of the effects of wastes on the global biogeochemical cycles of the biologically active elements (BAE) and compounds such as methane and water (+2) is a crucial aspect of understanding the current environmental crises confronting the world. One obstacle to establishing successful programs to exert socioeconomic pressure to alter human behavior or to make laws and policies that require mitigation or restoration of

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environmental damage is that a quantitative method for establishing fair equivalence between socioeconomic and environmental outcomes has not been agreed upon.

Emergy evaluation (Odum, 1996) is an objective method for establishing equivalences among economic, environmental and social outcomes based on accounting for the available energy of one kind (*i.e.*, solar joules) that is required for each of the outcomes to occur within the system under evaluation. Emergy evaluation is based on the quantification of production functions of all kinds by accounting for all of the inputs to the production process using a normalized measure of the available energy required for the product or service. So the fundamental equation of emergy analysis is:

$$\text{Emergy} = \sum_{i}^{n} \text{Available Energy}_i \times \text{Transformity}_i$$

where $n$ is the number of inputs to the production function and $i$ is an individual input. For each $i$ the quantity of available energy in joules of the input required to make the product or service must be known as well as the transformity of that input, *i.e.*, the quantity of emergy in solar emjoules required to make one unit of the input, in this case one joule of available energy of input $i$. The units of emergy are solar emjoules (semj), the units of available energy or energy with the potential to do work are joules (J), and the units of transformity are then solar emjoules per joule (semj/J). This equation can be modified to accept inputs measured in other units, but the transformity, or more broadly, the emergy per unit measure or the Unit Emergy Value (UEV) must also be modified to match the altered measure of the input. For example, if mass in grams is used to quantify the inputs to a production process, the emergy per unit factor is the specific emergy (semj/g).

Although many emergy evaluations have been performed (Odum et al., 1987; Brown and Ulgiati, 2002; Brown and Buranakarn, 2003) and many UEVs have been calculated (Odum, 1996; Buranakarn, 1998; Bastianoni et al., 2009; Campbell and Ohrt, 2009; Heberling and Hopton, 2010), the information set needed for emergy evaluations is presently incomplete, because there are still many critical values for products and services that are unknown or not well documented. For example, transformities for the BAE + 2 are needed to establish equivalences among the gaseous and other wastes produced by economic production processes in order to estimate the expected concomitant environmental damage caused by these wastes and for the development of fair trading and mitigation schemes. Since the set of possible inputs to all kinds of production functions is large, there are many additional transformities and other UEVs that are needed. However, in this paper, we focus on establishing transformity and specific emergy values for six BAE (carbon, C, nitrogen, N, sulfur, S, phosphorus, P, oxygen, $O_2$, and silica, Si) and two compounds (methane, $CH_4$ and water, $H_2O$) through performing emergy analyses of their global mass budgets. We believe that emergy evaluations of these global cycles are particularly important in understanding and prioritizing research on the effects of perturbations of these flows on the global ecosystem, because such evaluations may help in finding workable strategies that will result in the establishment of viable, *i.e.*, fair, trading systems to protect the planet. Because of the present global crises mentioned above and the needs of on-going research at the US Environmental Protection Agency (EPA) and at other institutions concerned with the environmental impact of wastes, there is an immediate need for accurate values of these elemental flows.

A few emergy evaluations of global cycles of the BAE + 2 have been carried out in the past. Odum et al. (1998) and Buenfil (2001) evaluated the global hydrological cycle obtaining transformities and specific emergy values for many global water flows and storages. Campbell (2003a) compared selected transformities for global water flows obtained from an evaluation of five global hydrological cycles and Campbell (2003b) evaluated the specific emergy of the flows of six forms of N in the prehistoric (*i.e.*, prior to the development of agriculture) N cycle based on an evaluation of a detailed global N budget. Transformities and other unit emergy values for N and P used as fertilizers were calculated by Odum (1996). Tonon and Mirandola (2003) calculated a transformity for $O_2$ and Campbell and Ohrt (2009) calculated the specific emergy of S produced as a by-product of petroleum refining using data from Bastianoni et al. (2009). Recently, Watanabe and Ortega (2011) calculated specific emergies for water and for several N and C species that are important greenhouse gases (GHGs), *e.g.*, $N_2O$, $CO_2$ and $CH_4$, with the purpose of estimating an emergy-based value for ecosystem services such as carbon sequestration, denitrification, and aquifer recharge.

One of the primary reasons for the success of industrial civilization is that mankind developed the technological capability to break the tightly controlled biogeochemical cycles of the Earth (Lovelock, 1979); thereby, extracting energy and materials for use to support human purposes, *e.g.*, economic uses (Odum, 2000; Campbell et al., 2009). However, the extraction and use of the BAE also displaced them in space and time, so that today the biogeochemical processes that had adapted over millions of years of co-evolution with life on Earth have been stretched to their limits (*e.g.*, Hughes et al., 2003; Hoegh-Guldberg and Bruno, 2010). Many of the primary materials essential for economic production are also the elements that are essential to support the structure and function of living systems, *i.e.*, the BAE, C, N, S, P, O, Si, as well as the compounds $CH_4$ and $H_2O$ (*i.e.*, BAE + 2).

There are several theoretical and practical questions that arise in considering human domination of the global biogeochemical cycles of the BAE. Campbell et al. (2009) point out that the emergy signature of the Earth changed dramatically from around 1850 to the latter half of the 20th century, *i.e.*, the emergy base for the Earth or the amount of emergy used in a year increased more than 5-fold over this time. This increase was almost entirely due to the increased use of fossil fuels and minerals to expand and develop human civilization. As a result of these activities the global fluxes of the BAE + 2 have changed to varying degrees. This implies that the specific emergies and transformities of these elements maybe different today than they were in 1850, *i.e.*, prior to the Industrial Age.

Practically, one of the unique strengths of the emergy methodology is that it provides a unified, self-consistent objective method for quantifying the relative value of material and energy flows in the economy and in the environment on equal terms; *i.e.*, solar equivalent joules. The implication is that emergy evaluations can help find fair value for the economy and for the planet to help structure market mechanisms, as well as other means, for controlling and treating the wastes of economic production processes. Human agency has played a large role in altering the global fluxes of C, N, S, P, and $CH_4$ (*e.g.*, Lal, 2008; Vitousek et al., 1997a,b; Brindlecombe et al., 1989; Kvenvolden and Rogers, 2005), thus the results of these emergy evaluations may be practically useful in establishing equivalences among these elements to support trading and other socioeconomic control mechanisms. One goal of this study was to obtain specific emergies of the global flows of six biologically active elements and two compounds for use in environmental accounting for the impact of wastes and for establishing emergy values to guide environmental management policies, *e.g.* on climate change. A second goal was to compare the specific emergies of global element flows during the Industrial Age to those in the Preindustrial Era to determine how these values have changed, and to assess the sensitivity of the global biogeochemical system to the 5-fold increase in the emergy use of the global system over the past 160 years (Campbell et al.,