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Emergy Net Primary Production (ENPP) as basis for calculation of Ecological Footprint

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A B S T R A C T

Society needs urgently good tools to understand the biosphere dynamics, become aware of Earth's biophysical limits and make appraisals of environmental performance of human dominated systems. In this context, the Ecological Footprint (EF) was suggested as one of the most important tools. But, according to calculations based on Emergy Analysis, the indicators of EF could underestimate the problem of human carrying support. EF does not consider the work of untouched nature in productivity and ecosystems services. In order to improve the EF results, the present study suggests: (a) to include the ecosystems not considered in conventional EF i.e. tundra, deserts and areas covered by ice; (b) to consider the value of Net Primary Production (NPP) in Emergy units (seJ m^{-2} $year^{-1}$) as the base for the calculation of Equivalent Factors (EQF); (c) to account for the consumption of fossil energy used in collection, treatment and distribution of water for domestic use, for this the carbon emissions data (in tonC m^{-3} of water) were used. Introducing these changes to the conventional EF calculation and considering the Peruvian economy (in 2004) as the study case, the Biocapacity obtained was 14.31 gha $capita^{-1}$ and the footprint was 6.68 gha $capita^{-1}$. These values mean that Peru can support 2.14 times its population if the current life style is maintained, as opposed to the 4.0 times ratio obtained with a conventional EF calculation.

1. Introduction

The Ecological Footprint (EF) is a tool that is being used by the world-wide scientific community, as a result of its didactic form to transmit the impact of the society on nature through easy-to-understand measurement. There are two main reasons for which the EF has become very popular: it uses a mathematical formula to consider the effect of the consumption of society (Footprint) in its natural environmental (Biocapacity); and it incorporates a vast amount of information in a simple quantitative measure to express its results (land area in global hectares). The EF calculates Biocapacity as the availability in bioproductive land area and footprint as the consumption of the evaluated system, both in global hectares. Details of the calculations can be obtained in Monfreda et al. (2004).

As with the majority of the existing methods that evaluate the sustainability of systems and processes, the EF-GAEZ (called thus because it uses the Global model Agro-Ecological Zones of FAO) has been extensively criticized. Main inadequacies of the EF-GAEZ ability to measure the level of human impact are:

(a) It considers carbon emissions as area of forest necessary to absorb CO_2, but some carbon sequestering also occurs in areas of agriculture, pasture, ocean, and so on (Venetoulis and Talberth, 2008). Even though these areas absorb CO_2 to a lesser extend than forests, they need to be accounted for. Areas considered non-productive or with low productivity (mountains, deserts, tundra, and areas covered by ice) are not considered in EF-GAEZ (Venetoulis and Talberth, 2008), but they produce environmental services that must be accounted for in the Biocapacity. Nevertheless, the EF-GAEZ makes conservative estimates when sufficient data are not available.
(b) EF-GAEZ considers each area only once, although the same area may be supplying two or more ecological services. Only the forest areas are counted two times, one as bioproductive area to supply forest products and another as available area to absorb CO_2 emissions (Monfreda et al., 2004). Even so, the

Abbreviations: BC, Biocapacity; EF, Ecological Footprint; EF-GAEZ, EF based on GAEZ suitability indices; EF-NPP, EF approach that employs Net Primary Production; EF-ENPP, EF approach that employs Net Primary Production based on Emergy; EMA, Emergy Analysis; ENPP, Emergy Net Primary Production; EQF, Equivalence Factor; YF, Yield Factor; GAEZ, Global Agricultural Ecological Zone; GAP, Global Average Productivity; GDP, Gross Domestic Product; gha, global hectare (in this work gha means Peru's hectare); Gt C, 10^9 ton of carbon; LCF, Load Capacity Factor; NPP, Net Primary Production; CGW, Continental and Glacial Water; REN, Renewability; seJ, solar emjoules (unit measure of Emergy Analysis); Tr, solar Transformity.

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forests also supplies other ecological services that are not accounted for, such as the maintenance of the hydrologic cycle, soil formation and conservation, filtering of solid, liquid and gaseous pollutants and others.

(c) In EF-GAEZ approach, the use of energy is accounted for as fossil fuel by means of carbon dioxide emissions, even though it is also possible to evaluate EF from the use of the required land area to support the biofuel production. EF-GAEZ assumes a carbon sequestration of 0.95 tC ha^{-1} $year^{-1}$ (Wackernagel et al., 2005). Thus, for each ton of emitted carbon the EF-GAEZ assumes a footprint of 1.05 ha (excluding the quantity retained by the oceans—65%). The carbon sequestration ratio is based on the forest-absorbed amount of CO_2 during the period between 1980 and 1990, disregarding the CO_2 absorbed by other ecosystems and assuming that the sequestration rate did not change with time.

(d) EF-GAEZ does not include in the calculation of Biocapacity the contribution of other important ecosystems, such as the oceans which cover 2/3 of the planet. Therefore, it underestimates the ecosystem work that has specific functions in the global and local biological cycles (Venetoulis and Talberth, 2008). For example, the EF-GAEZ does not include the open ocean, an important ecosystem that absorbs great amounts of CO_2. It also does not include non-productive areas, as deserts and ice covered lands, even though these ecosystems produce environment services which are essential to the welfare of the humanity.

(e) EF-GAEZ does not include fresh water in footprint accounting, even though this is a consumption that largely affects sustainability (Chambers et al., 2000). Collection of fresh water can be a secondary function in some places of planet, but in other places (arid regions where water is a limiting factor) the use of the water competes directly with other primary functions of the ecosystem. Moreover, currently half of the water that inflow to rivers and lakes is used in anthropic processes (Hassan et al., 2005).

(f) EF-GAEZ does not include other non-human species in the calculation of Biocapacity (Chambers et al., 2000). Biocapacity should also provide support to other species' needs.

(g) EF-GAEZ does not incorporate the work done by nature in the production of natural and human resources.

The Ecological Footprint is recognized as an important contribution to estimate the human impact on nature, but it still needs to be improved. Some papers are being published trying to clarify some basics definitions and discussing about methodological advancements on Ecological Footprint, for instance Kitzes and Wackernagel (2009) and Wackernagel (2009). We believe that introducing some concepts from Emergy[1] Analysis (Odum, 1996) into the EF calculation could be an alternative to improve the final EF indicators.

We consider that Emergy Analysis (EMA) is a more robust tool than EF because it allows to take into account other flows that influence sustainability (i.e. energy flows used to dilute internal waste, soil loss, deforestation and others). Emergy Analysis was formalized as a method of ecosystem valuation from the point of view of the biophysical economy. Its concepts are rooted on the works of Lotka (1925) and Bertalanffy (1968). Odum (1986) used the term "Emergy" (written with "m") for the first time with the meaning of EMbodied enERGY, also called EnERGY Memory (Scienceman, 1987). The aim of this methodology is to obtain a thermodynamic measurement of the Emergy previously used to produce a resource. It uses a common unit for all the resources: the equivalent solar energy Joule, or solar Emergy Joules (seJ). Solar Emergy is used to give value to natural resources that the conventional economy does not evaluate correctly (rain, raw materials from nature, water from rivers, biodiversity and others) and also to properly value the resources provided by human economy, mainly fossil fuels and their derivatives (goods and services of industrial economies). Emergy Analysis, due to this characteristic, is used to study the environmental inventory and the human impact on it (Siche et al., 2008). Even thus, EMA still has some deficiencies that must be overcome, for instance: the lack of a database with Solar Transformities[2] of good quality ("with" and "without" labor and services); to standardize the Emergy Baseline that must be used for all Emergy analysts; and to standardize the *numeraire* (exergy, energy or mass).

This work proposes a method to improve the comprehensiveness of EF-GAEZ final indicators, by redefining its equivalence factors (EQF). For this, a synergic use of Ecological Footprint and Emergy Analysis were used with some suggestions from Venetoulis and Talberth (2008). Thus, the new EQF's considers the potential of land to supply resources to humans and it also considers the work done by nature in the generation of resources.

2. Emergy Analysis: some concepts and definitions

In accordance to the second law of thermodynamics, each energy's transformation process degrades energy and decreases the available energy passed to the next transformation step. However, the "quality" of such energy increases. Any kind of energy can be converted to heat, but one form of energy cannot be substituted by another form of energy in all situations. For instance, plants cannot substitute fossil fuel for sunlight in photosynthetic production. The quality of one type of energy makes it able to be used for one type of transformation, but makes it unable for other type of transformation. According to Emergy theory, quality is related to a form of energy and to its concentration, for instance wood is more concentrated than detritus, coal more concentrated than wood, and electricity produced from coal more concentrated than coal (Ulgiati and Brown, 2009). The quality of energy is an important concept in Emergy Analysis and is represented by the Transformity value.

Emergy Analysis converts each mass and energy flow to the same value basis. It takes into account every contribution from nature and human economy in order to know the relative importance of each resource (Odum, 1988). This methodology classifies the system flows – and internally exchanged – as renewable and non-renewable flows, making it possible to calculate indices that can be useful to policy makers, especially by comparing different alternatives (Brown and McClanahan, 1996; Odum, 1996; Ulgiati et al., 1995).

Emergy Analysis consists of: (a) to drawn a systemic diagram (Fig. 1) of the system or process under analysis using the symbols proposed by Odum (1996). This step is important to understand how the system works, its dependence on external resources, the internal feed-backs of energy and mater, and the production; (b) identification of all Energy, Materials and Monetary flows that participate in the processes carried out within a system and calculation of Emergy flows through the use of appropriate conversion factors named Emergy Intensities[3]: Energy flow (in

[1] Emergy is the available energy of one kind of previously used up directly and indirectly to make a service or product. Its unit is the emjoule (Odum, 1996).

[2] Solar Transformity is the solar Emergy required to make one joule of a service or product. Its units are solar emjoules per Joule (seJ J^{-1}). A product's solar transformity is its solar Emergy divided by its energy (Odum, 1996).

[3] Emergy Intensity shows the real wealth of the product, i.e. the value that represents all emergy used to make the product. The definition of Emergy Intensity is very similar to Energy Intensity (used in Energy Assessment), but Emergy Intensity accounts for more than only market energy. Emergy Intensity is divided in: Transformity (seJ J^{-1}); Specific Emergy (seJ g^{-1}); and Emergy per Monetary Unity (seJ $\$^{-1}$), usually expressed as seJ USD^{-1}.