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Analysis

Shared wealth or nobody's land? The worth of natural capital and ecosystem services

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A B S T R A C T

The prerequisite for a sustainable and equitable use of common resources (the so-called Commons) must be the proper evaluation of their role within the complex network of relationships that ensure ecosystems functioning, resilience, and evolutionary dynamics. It is crucial to ascertain to what extent the common wealth is used for the common benefit. Money-based schemes for valuing the Commons, such as the so-called "willingness-to-pay", provide a user-side evaluation perspective based on the idea that value only stems from utilization by humans. As a complement to such a point of view, we present and discuss in this paper a donor-side evaluation method (Emergy Synthesis) based on the idea that a proper measure of value can be achieved by also accounting for the work done by the biosphere in generating services and resources. It should not be disregarded that such resources and services also provide support to other species in the web of life. Emergy, a scientific measure of such environmental support, is suggested as a tool capable to assess quantity and quality of shared resources, thus providing a basis for their environmentally sound management.

1. Introduction

Governments use money-based accounting systems of national economies to calculate macroeconomic indicators such as gross domestic product, gross national product, and per capita income, among others. In the last years, also in response to a perceived lack of comprehensiveness of such accounting systems, more attention was placed on the economic use and evaluation of the ecosystems. A recent example in this direction is the international project "The Economics of Ecosystems and Biodiversity TEEB (http://www.teebweb.org/) aimed at evaluating in money terms the contribution of ecosystems and biodiversity within the framework of productive economic systems. The term "Environmental Accounting" is most often referred to as the practice of including the indirect costs and benefits of an economic activity, for example its environmental load on health and society, along with its direct costs, when making business decisions.

Considering the almost complete decoupling of the economy and the environment that characterized the so-called mainstream (or neoclassical) economics by far, the recent recognition that human economies rely on natural resource storages and ecosystem services must be considered an important step ahead, very likely one of the most important achievement of Ecological Economics, a modern branch of the Economic theory (Georgescu-Roegen, 1975; Costanza, 1989; Martinez-Alier, 1990; Patterson, 1998; Daly and Farley, 2004; Faber, 2008).

Point is now: What is the value of natural capital and ecosystem services? How can such a value be measured? Value for whom? No doubt that within the framework of Neoclassical Economics the value of an environmental resource is very small when the resource is abundant and starts to increase when it approaches scarcity. Several resources were not assigned any value in the past due to their relative abundance (land, pasture, fresh water) compared to demand by a smaller population. They remained as no-value "Commons" until growing population and increased use made their economic value to grow. Some "Commons", such as clean air and rain water, are not (yet) marketed and therefore they are considered worthless: as a consequence, they are considered nobody's resources and degraded by improper use (e.g. polluted by chemical emissions). Other resources such as land, forests and fresh water storages can more easily be limited and marketed, so that they are being assigned monetary values. Worth mentioning as a typical case of misused commons, the trend towards privatization of water and improper use has been clearly indicated as unacceptable practice by the United Nations in its 64th General Assembly on 28 July 2010, declaring access to clean drinking water and sanitation as a human right (UNO, 2010).

A large number of studies have already warned about the turndown ahead, suggesting models, policy tools, limits to growth, and alternative lifestyles (Hubbert, 1949; Meadows et al., 1972; Capra, 1982; Tainter, 1988; Odum and Odum, 2001; Heinberg, 2009). Moreover, while the present resource exploitation mostly supports the welfare of a minority of wealthy people in developed countries, the environmental degradation related to such welfare affects the majority of world population, left without the primary resources and services necessary to secure their present and future well being. Hardin (1968) referred to the degradation of common resources as to

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an inexorable "tragedy of Commons". Barnes (2006) claims that there is no reason for which the "Commons are inexorably "*fated to self-destruct*" and suggests Commons – the inheritance received by nature and by previous generations – to be maintained over time by revising the dynamics of global markets. He suggests new actors (independent Trusts) to operate in favor of the other species, the global environment and future generations. Barnes identifies "three forks" of the Commons river, i.e. the main pathways for the formation of Commons: Nature, Community and Culture (Fig. 1). According to such an identification, Barnes listed a large number of products, services and infrastructures that are generated by Nature or by the common effort of entire societies and that in turn become a source of additional value and wealth. Internet and the stock market are two examples of infrastructures that generate value (the existence of which allows actions that support economic and cultural processes and generate income). Creation of wealth by using the Commons is, in Barnes' opinion, something that involves property rights of all species and the unborn as well. All individuals are entitled to ownership rights by birth and should receive dividends of the wealth created.

The problem with the sustainable use of the Commons is that it is not easy to establish an agreed upon measure of value as the basis of economic, normative and conservation actions. Energy taxes, carbon taxes, and even the Kyoto protocol share the difficulty of identifying a measure of value that can be used as the basis of a "policy for the Commons".

In spite of the efforts done by several Governments and the scientific community, the anthropocentric framework that still characterizes most of the economic approaches mainly focuses on and assigns value to those services that are of interest and benefit to humans, in so disregarding the fact that nature provides services to countless species different than human beings. Odum (1988, 1996) identified the work of biosphere driven by solar, gravitational and geothermal energies as the source of environmental goods and services. He provided a common measure for such sources, namely the solar equivalent energy (emergy), pointing out that it can be used as the basis for sustainability assessments and natural capital evaluations (Odum, 1994a). Other authors developed emergy-based studies on sustainable economic development (Ulgiati and Brown, 1998), ecosystem value (Brown and Bardi, 2001), carrying capacity (Brown and Ulgiati, 2001), taxation and incentive schemes (Bimonte and Ulgiati, 2002), landscape development intensity (Brown and Vivas, 2005), environmental debt (Campbell, 2005), among others, all relying on the idea that the emergy content of a flow or storage is a measure of (not only economic) value, quality and wealth. The focus of the emergy accounting method is placed on the overall functioning of the geobiosphere with all its components and processes, within which human societies are embedded. Since shared resources belong to all species on Earth and to the future generations as well, processes and systems which receive the largest benefits from their appropriation of the Commons (storages of minerals, fuels, standing biomass, fresh water, clean air, culture, information, biodiversity) should provide a proportional feedback to reinforce the resource basis. This is needed in order to prevent natural capital degradation and to ensure the resource throughput (empower) being maximized through all levels of world ecosystems and societies.

2. The Emergy Synthesis Method. Concepts and Definitions

Pointing out that human societies feed on natural capital withdrawal and use different kinds of ecosystem services, Odum (1988, 1996) identified natural capital and ecosystem services as the real source of wealth, in spite of the common belief that only labor and economic capital were such a source. Emergy, the total amount of solar equivalent energy that is invested by the environment in support of a given process, is suggested as a scientific measure of the direct and indirect work performed by the biosphere. Within such a "donor-side" perspective, the value of a resource relies on the effort that is needed for its production and delivery over a "trial and error" process that ensures optimization of resource use.

The emergy synthesis method (Odum, 1996) is a technique of quantitative evaluation that determines the environmental value of non-marketed and marketed resources, services, commodities and storages in common units of solar equivalent energy required to make a given product or service. The method is based on principles of energetics (Lotka, 1922), systems theory (von Bertalanffy, 1968) and systems ecology (Odum, 1994b). It allows to quantify the amount of environmental work supporting each flow or storage, thus valuing each resource based on a supply-side effort, not just on human preferences and market contingency. In short, emergy is defined as the total available energy of one kind (usually of the solar type) directly and indirectly required to support a process and generate an output product or service. All renewable and nonrenewable, local and imported input flows to a process (matter, energy, labor, money and information) are listed in an inventory and converted to emergy units by means of emergy intensity coefficients named Unit Emergy Values (UEV; also named transformities when the flow is measured in energy units). All the emergy input flows resulting from the procedure are added into a total and several performance indicators are then calculated. Flows that are not directly of solar origin are converted to solar equivalents by means of suitable conversion coefficients. As a consequence, emergy is measured in unit of solar equivalent joule (seJ).

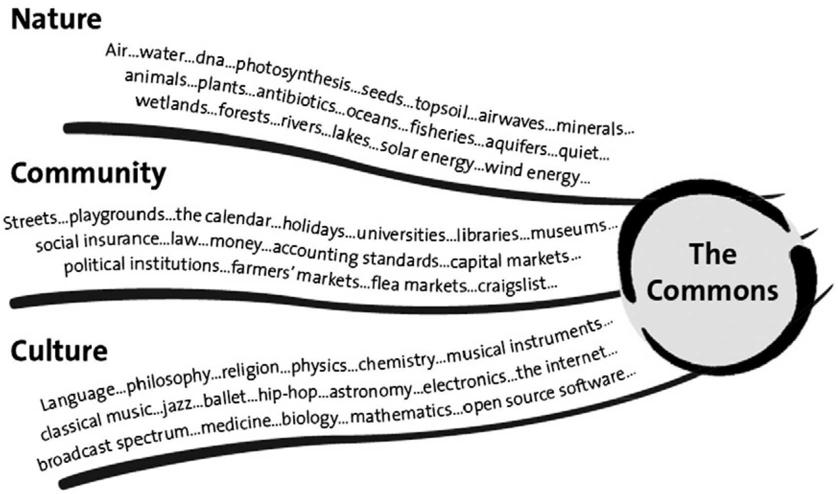

Fig. 1. The three forks of the Commons river (Barnes, 2006).

In evaluating economies, the link between emergy supply and economic performance is provided by the ratio of total emergy used to GDP (Gross Domestic Product), measured as seJ/currency unit. It indicates the emergy investment needed to create a unit of monetary wealth. The emergy to money ratio is used in the emergy calculation procedures to convert into emergy units the money inputs associated to labor and services. Further details on the method cannot be given here, but can be found in Brown and Ulgiati (2004, 2010a).

3. What Should Environmental Accounting Account For?

Solar radiation, gravitational potential and deep earth heat are the driving forces that keep the biosphere able to develop and operate, by supporting matter and information cycles. It is through cycling that systems maintain themselves far from thermodynamic equilibrium, adaptive and vital. Cycling allows for the continuous convergence and divergence of energy, materials and information as well as for interaction of concentrated forms of energy with lower quality resources in amplifier actions (Brown and Ulgiati, 1999). Processes of convergence build order, adding structure, reassembling materials, upgrading energy and creating new information. Processes of divergence degrade structures and disperse materials and information, for new cycles to occur.

By concentrating minerals in the earth crust, and by circulating air, water, and nutrients, the environmental flows of solar radiation, gravitational potential and deep heat generate and keep operating the life support system within which organisms, species, populations and entire communities interact and develop over time. The systems diagram of Fig. 2 clarifies the patterns through which such a dynamics occurs. Ecosystems supported by the main environmental driving forces provide direct services to all species, and also contribute to build resource storages for future use: a) slow-renewable storages such as ground water, topsoil, standing biomass and biodiversity; b) non-renewable storages such as fossil fuels and minerals (the terms slow-renewable and non-renewable are relative to the lifespan of human societies).

Each species receives from the surrounding ecosystem a series of free services (ecosystem services) and in turn supports the life of other organisms by contributing free services to them. Sustainability is guaranteed when organisms feed on flows directly available and only withdraw every year fractions of the stored resources that are smaller than or equal to the amount that is generated yearly by the

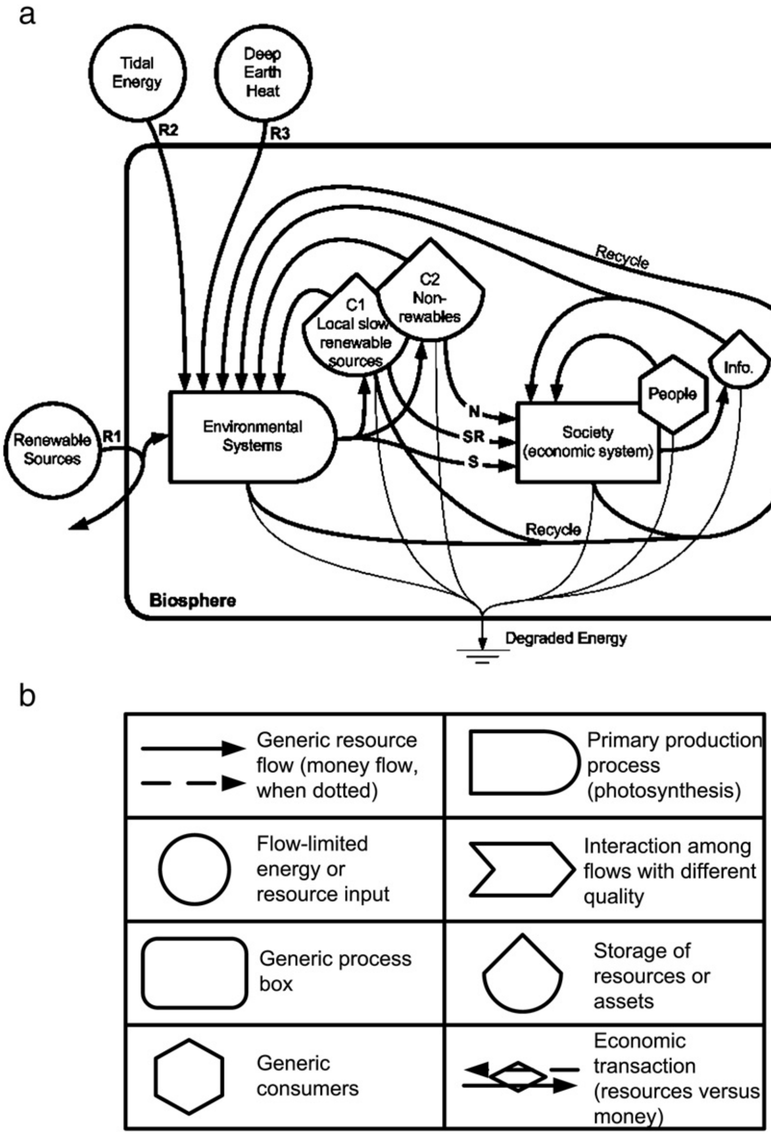

Fig. 2. a. Systems diagram of the biosphere showing the inflow of renewable driving energies (R1, R2 and R3), ecosystem services (S), slow-renewable and non-renewable resource flows (SR and N), storages of slow-renewable and non-renewable sources (C1 and C2), societal assets and people, generation of information, recycle of materials and feedback of human labor and information to lower hierarchical levels in order to reinforce the resource basis and maximize power (Brown and Ulgiati, 1999). b. Legend of systems symbols used in Fig. 2-a and following figures, from Odum, 1996.

ecosystem. This way stored resources are not depleted over time but act as buffers for increased stability.

Recent results from the Millennium Ecosystems Assessment (MEA, 2005) pointed out the role of ecosystems services to the stability of human societies and human-well being. Although such a point of view is mainly focused on human values and preferences (the user-side point of view), yet the set of ecosystems services pointed out by MEA researchers provides an important starting point for further assessments of the interplay of man and biosphere, and well-balanced interactions among all its components. MEA documents list four kinds of ecosystem services:

a) Supporting services (services necessary for the production of all other ecosystem services): soil formation, nutrient cycling, primary production via photosynthesis;
b) Provisioning services (products obtained from ecosystems): food, fresh water, fuel wood, fiber, biochemicals, genetic resources;
c) Regulating services (benefits obtained from regulation of ecosystem processes): climate regulation, disease regulation, water regulation, water purification;
d) Cultural services (non-material benefits obtained from ecosystems): spiritual and religious, recreation and ecotourism, aesthetic, inspirational, educational, sense of place, cultural heritage.

The MEA effort, although certainly valuable and timely, does not provide any evaluation of the "production cost" of such services from the point of view of the biosphere. Instead, it would be very interesting and important to test innovative frameworks and accounting methods to assess how much of the environmental work goes into providing each typology of services. Such an assessment would provide an understanding of how much is lost if the environmental service is discontinued and how much is gained if it is kept healthy and vital (Allen et al., 2003). Disregarding these aspects would dismiss the "supply-side quality" of resources, similarly to what most energy analysts do when adding joules of different nature (from fossil fuels, nuclear, sun, wood, wind, etc.), by assuming that all joules are alike and ignoring the work done by the biosphere to provide different energy sources.

4. Human-Made Capital and the Economic System

Fig. 3 highlights the dynamics of economic systems within the larger framework of the biosphere. The main environmental driving forces support the work of nature for cycling and concentrating resources (soil, wood, fresh water, minerals). The economic system invests energy, goods, labor and services in order to exploit such resources provided for free by nature. In so doing, economic activities and sectors (mining, industry, agriculture, fishery, forestry, education, health services, transportation, etc.) in turn provide products and services to the market. Exploitation of free environmental resources cannot be unlimited, in a physically-limited word. If withdrawal is faster than turnover time, the resources are depleted and used up. In order to prevent or delay depletion, investments from economy should not only support withdrawal, but also provide a reinforcing feedback to ensure the stability of the resource basis (e.g.: plant new trees after wood harvest; rotate crops in order to stabilize the content of soil organic matter and nutrients; recycle reusable materials) according to Lotka–Odum's Maximum Empower Principle (Lotka, 1922; Odum, 1996).

Economic activities release new flows and develop new storages. Oil is converted into electricity and transportation services; minerals are converted into infrastructures and machinery; electricity, machinery and infrastructures are in turn converted into educational, health and recreational services. In so doing, new storages of information are created (universities, libraries, arts and museums, know how, and, over longer time frames entire cultures, religions, languages) that in turn become the basis for further development of societal system and, at the same time, feedback to the lower hierarchical levels to expand or stabilize the resource basis.

A further and practical example of the role of natural capital and ecosystem services in economic processes is provided by Brown and Ulgiati (2002) who calculate the environmental support to electricity production by means of Odum's Emergy approach. The systems diagram of the thermal power plant in Fig. 4 shows how the latter is linked to the environment as both a source and a sink. The authors demonstrate that the operation of the plant is not only driven by the fuel used, but also relies on the possibility to dilute the chemicals and the heat released to the atmosphere and to the water bodies. The environment as a sink must be therefore considered an important driving force in itself, without which a sustainable operation cannot be implemented. As a consequence, the Commons (atmosphere, rivers and sea) are used and filled up to generate wealth in favor of the plant owner, without any additional advantage to the "owners" of the Commons, who pay for the electricity or may have never used electricity in their life.

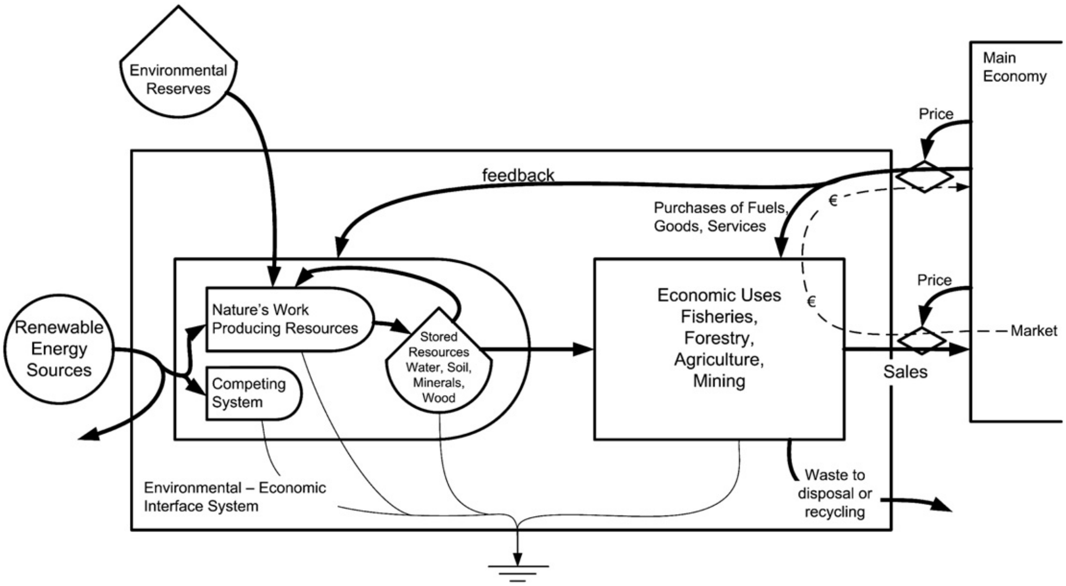

Fig. 3. Systems diagram of an economic systems within the framework of biosphere activity, showing supporting flows of resources and the reinforcing feedback from higher to lower levels of the hierarchy (Odum, 1996; systems symbols from Fig. 2).

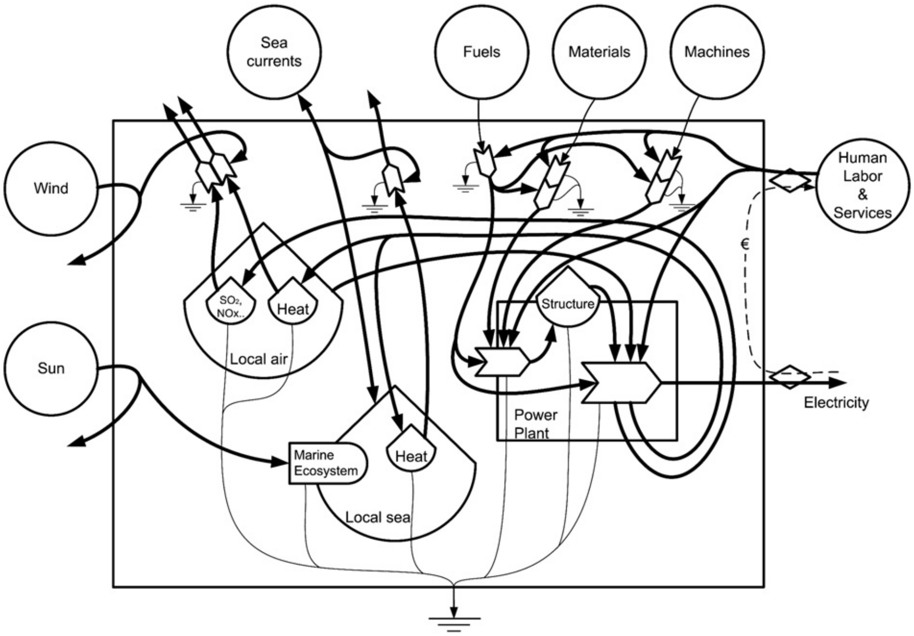

Fig. 4. Systems diagram of a thermal power plant and its surrounding environment. The plant does not only use fuels and machinery, but it also needs to release heat and chemicals (SO_2, NO_x, etc.) to the environment (Brown and Ulgiati, 2002; systems symbols from Fig. 2).

Barnes (2001) calculated as an example the potential dividends from the use of a selection of common resources in the USA such as the sky for dilution of pollutants and broadcasting. He also included in the accounting some "new" Commons, that were not considered earlier as economic resources, due to the fact that their scarcity is a recent event (e.g. societal assets, biodiversity, quietude, and financial liquidity). These new resources are most often an important basis for business; just think of liquidity, i.e. the possibility to sell stocks guaranteed by the existence and operating of a Stock Market infrastructure regulated by the Law and by public institutions (which also are a new category of Commons themselves). According to Barnes, liquidity adds up to 30% of total value of a company, which means that the company benefits from the existence of common infrastructures and controls. Barnes maintains that the wealth generated by the use of common resources (flows and stocks of resources and infrastructures) should be accompanied by a return of wealth to all the "stakeholders", i.e. the large number of owners by birth rights. He foresees a "cap and trade" system strengthened by the distribution of dividends to the stakeholders or to their representatives. Such dividends could be converted into feedback actions to increase well-being (education, health services, retirement) or to further preserve and reinforce the resource basis exploited. The exploitation of the Commons would become more expensive for the production and business sectors, thus pushing towards wiser use and increased efficiency, while the distribution of dividends would make the residual exploitation more equitable and the stakeholders more aware of the need for preserving their shared "property".

Similarly to the authors of the Millennium Ecosystem Assessment, Barnes faces the problem of how assigning the "right" value – if any – or at least an operational one to each flow or stock, by relying on something different than just human preferences (the market value). Although the idea of rewarding all stakeholders by returning them a fraction of the wealth created on their ownership is certainly fascinating and in principle applicable within the current free market system (as Barnes claims), its application is made in practice uneasy by the lack of a standard method for assigning value to each resource flow or stock. Such a method should be scientifically sound, applicable to all kinds of flows and stocks, independent of human preferences, and finally related to sustainability issues and environmental integrity (so that its application would improve the overall stability of the biosphere). Barnes refers to the need for a new market operating system that he names "Capitalism 3.0", the introduction of which is foreseen in the years to come.

5. Emergy Value of Flows and Storages

As an application of the emergy concept, Brown and Ulgiati (1999) evaluated the emergy value of the global flows and storages (ecosystem services and natural capital) driving the biosphere with reference to the year 1995, highlighting the possibility to quantify on a common basis the amount of resource on Earth, be they characterized by short or long turnover time. They also pointed out that:

a) storages: the fraction of existing renewable and slow-renewable resource storages in the year 1995 was about 3.5 times larger than the fraction of nonrenewable ones;
b) flows: the annual flow of nonrenewable emergy used by society was about 2.2 times the renewable and slow-renewable flows.

We updated Brown and Ulgiati's data with reference to the year 2006 in order to ascertain if any changes occurred to such a picture in the last decade (Tables 1 and 2). Data confirm both the 1995 findings about resource stocks and annual flows used. Results suggest that renewable and slow-renewable resources could contribute a very large support if societies were purposefully designed to feed on them instead of non-renewables. Instead, modern industrialized societies rely on a much smaller resource basis, the characteristic of which is that resources can be released at higher power. They apparently show a "preference" (or rather a need, due to resource-intensive life styles) for the use of resources that can be released faster, even if they are the less abundant.

The about 20% increase of the annual emergy flow in the year 2006 compared to 1995 can be at least partially attributed to the additional one billion new inhabitants of the planet in the last decade and its impact on the available stocks was compensated by a small increase of known or economically recoverable reserves. The annual emergy flow of non-renewable resources is now about 1.5% of the total known resource storages, while it was 1.2% in 1995. The meaning of this last finding is self-evident, placing a large concern on the sustainability of a societal pattern based on resources that may be no longer available within a time frame of 100 years or less.

Table 1
Renewable, slow-renewable and non-renewable emergy storages of Earth natural capital (years 2005–2006).

#	Item	Unit	Amount (unit/yr)	Solar emergy intensity (seJ/unit)[a]	Solar emergy (seJ)
Renewable or slow-renewable storages					
1	Fresh water	J	1.64E+23	3.06E+04	5.01E+27
2	Soil organic matter	J	3.10E+22	1.24E+05	3.85E+27
3	Plant biomass	J	4.16E+22	1.68E+04	6.99E+26
4	Animal biomass	J	4.55E+19	1.68E+06	7.64E+25
Subtotal R and SR storages[b]					9.64E+27
Nonrenewable storages					
5	Coal	J	1.73E+22	6.72E+04	1.16E+27
6	Crude oil	J	7.15E+21	9.07E+04	6.49E+26
7	Natural Gas	J	6.98E+21	8.06E+04	5.63E+26
8	Metals (Al, Cu, Pb, Fe, Zn)	G	1.74E+17	1.68E+09	2.92E+26
9	Uranium ore	J	1.68E+21	3.01E+03	5.05E+24
10	Phosphate rock	G	1.10E+16	5.19E+09	5.71E+25
Subtotal NR storages2					2.73E+27
TOTAL STORAGE OF NATURAL CAPITAL					1.24E+28

1. ***Fresh water:*** Total freshwater including ice caps = 33.28E6 km^3 (Wetzel, 1975). Gibbs free energy of water = 4.94E6 Jm^{-3} (Odum, 1996). Available energy of water = (33.28E15 m^3)(4.94E6 Jm^{-3}) = 1.64E23 J.
2. ***Soil organic matter:*** 11.05E9 ha in woodland, crops, pasture, grassland (World Resources Institute, 1996). Assume: 1 m deep, 1% organic content, 5.4 kcal g^{-1}. Available energy of organic matter in soil = (9.32E13 m^2)(1 m)(1E6 cm^{3}m^{-3})(1.47 g cm^{-3})(1%)(5.4 kcal g^{-1})(4186 J kcal^{-1}).
3. ***Plant biomass:*** Total biomass = 1.84E12 t dry wt (Whittaker and Likens, 1975). Available energy of biomass = (1.84E12 t) (1E6 g t^{-1}) (5.4 kcal g^{-1}) (4186 J kcal^{-1}) = 4.16E22 J.
4. ***Animal biomass:*** Total biomass = 2.013E9 t dry wt (Whittaker and Likens, 1975), out of which 1.015E9 t on land, 0.998E9 t in oceans. Available energy of biomass = (2.013E9 t) (1E6 g t^{-1})(5.4 kcal g^{-1}) (4186 J kcal^{-1}) = 4.55E19 J.
5. ***Coal:*** Proven reserves = 8.26E11 t (hard coal 4.13E11; soft coal 4.13E11) (British Petroleum, 2009). Available energy of coal = (4.13E11 t)(27.9E9 J t^{-1}) (4.13E11 t) (13.9E9 J t^{-1}) = 1.73E22 J$_{coal}$. Proven reserves have been steadily decreasing since 1995 (1.03E12 t$_{coal}$) up- to-date.
6. ***Crude oil:*** Proven reserves = 1.71E11 t (British Petroleum, 2009). Available energy of crude oil = (1.71E11 t)(4.186E10 J t^{-1}$_{oil\ eq.}$) = 7.15E21 J$_{oil}$. Proven reserves have been steadily increasing since 1981 (9.26E10 t$_{oil\ eq.}$) up-to-date.
7. ***Natural gas:*** Proven reserves = 1.85E14 m^3 (British Petroleum, 2009). Available energy of natural gas = (1.85E20 m^3)(37.7E6 J m^{-3}) = 6.98E21 J$_{nat.gas.}$ Proven reserves have been steadily increasing since 1981 (8.24E13 m^3) up-to-date.
8. ***Selected metals (Al, Cu, Pb, Fe, Zn):*** Total recoverable reserves = 1.73E11 t (World Resources Institute, 1996) = 1.73E17 g.
9. ***Uranium:*** Recoverable reserves at present market price (<130 $ kg^{-1}) = 3.01E6 t (European Nuclear Society, 2008). Available energy of Uranium = (3.01E6 t)(1.00E6 g t^{-1}) (0.007) (7.95E10 J g^{-1}) = 1.68E21 J$_U$.
10. ***Phosphate:*** Recoverable reserves = 11.0E9 t (USDI, 1996). = 11.0E15 g.

[a] Emergy Intensities from literature (Odum, 1996; Brown and Ulgiati, 2004; www.emergysystems.org).
[b] Largest flow among items 1 to 4, according to the emergy algebra.

6. Criticisms to the Emergy Approach

Crucial to the emergy synthesis method, as with most other biophysical accounting methods, is the accurateness of the inventory and the reliability of the UEVs, that have been criticized under the ecological economics, thermodynamic, and uncertainty points of view (Mansson and McGlade, 1993, Hau and Bakshi, 2004, Cleveland, 2008, Ingwersen, 2010). Some criticisms have been already addressed and answered in the last decade, also thanks to the huge debate originated in the ongoing series of biennial emergy conferences (www.emergysystems.org). Yet, some of the raised questions were and still are appropriate and call for further refining of the approach. In order to clarify at least the most important issues, we will shortly refer to Hau and Bakshi (2004), who provide a very comprehensive evaluation of pros and cons that includes most of the recent and less recent criticisms, and also suggest improvement patterns. The latter are not an easy task, since as Hau and Bakshi clearly point out criticisms pertaining to uncertainty, sensitivity, and quantification apply to most methods that focus on a holistic view of production activities (life cycle assessment, material flow analysis, and exergy analysis) and require a joint effort to be displayed.

First of all, the emergy theory has been criticized under the assumption that it fosters an energy theory of value to replace other theories of value. In particular, the concept of transformity, a measure of production cost and at the same time a measure of value within the hierarchy of biosphere processes, was criticized for not incorporating human preferences and market dynamics. This criticism may miss the fact that the goal of emergy evaluations is to provide an “ecocentric” value of systems' processes and products as opposed to the anthropocentric values of economics. Thus it does not purport to replace economic values but to provide additional information, from a very different point of view, with which public policy might benefit.

A second aspect, the thermodynamic one, relates to the basic definition of emergy, namely the relation of emergy to other thermodynamic quantities (energy, exergy, Gibbs energy, etc). Odum (1996) clearly defined emergy in terms of available energy used up (or exergy, Table 1.1 page 13 of his book Environmental Accounting). In so doing he linked all calculated quantities to a second law concept, namely the available energy, that implicitly takes time and entropy into account. Most criticisms in this regard are correct, in that a large number of emergy analysts do not respect this basic definition and use energy (heat) as basic numeraire. In order to clarify and solve the issue, Brown and Ulgiati (2010) recently recalculated the total emergy driving the biosphere, based on updated estimates of the global flows of solar radiation, deep heat and gravitational potential, and using available energy (exergy) as the basic numeraire, confirming the previous findings about the total emergy driving the biosphere and also providing updated values for the transformities of the global flows. Their work also deals with a third crucial aspect in the emergy theory, uncertainty and lack of sufficient statistical treatment of emergy data. Linking large scale, environmental flows to local scale, technological and economic processes necessarily brings into the assessment the large uncertainty inherent in the quantification of energy and matter cycles at large time and spatial scales, that in turn affects the calculated transformities and UEVs. Ulgiati et al. (in press), Ingwersen (2010) and Brown and Ulgiati (2010) developed concepts of quality assessment of UEVs, source of uncertainty and statistical treatment tools and procedures (distribution of UEVs, weighted averages, Monte Carlo simulations, etc).

Table 2
Annual renewable, slow-renewable and non-renewable emergy flows driving the Earth global processes and human economies (years 2005–2006).

#	Flow	Unit	Amount (unit/yr)	Solar emergy intensity (seJ/unit)[a]	Solar emergy (seJ/J)
Renewable flows					
1	Solar radiation	J/yr	3.94E+24	1	3.94E+24
2	Earth cycle (thermal energy)	J/yr	6.72E+20	11981	8.05E+24
3	Tides (geopotential energy)	J/yr	5.20E+19	73923	3.84E+24
Subtotal renewables					1.58E+25
Slow-renewable flows					
4	Wood	J/yr	5.86E+19	1.85E+04	1.08E+24
5	Soil	J/yr	1.38E+19	1.24E+05	1.71E+24
Subtotal-slow renewables					2.80E+24
Non-renewable flows (from storages)					
6	Oil	J/yr	1.64E+20	9.07E+04	1.49E+25
7	Natural gas	J/yr	1.16E+20	8.06E+04	9.35E+24
8	Coal	J/yr	1.39E+20	6.72E+04	9.34E+24
9	Nuclear electricity	J/yr	9.86E+18	3.00E+05	2.96E+24
10	Phosphate	J/yr	5.43E+16	1.29E+07	7.00E+23
11	Lime	J/yr	1.73E+17	2.72E+06	4.71E+23
12	Selected metals (Al, Cu, Pb, Fe, Zn)	g/yr	1.59E+15	1.68E+09	2.67E+24
Subtotal nonrenewables					4.04E+25

1. ***Sunlight:*** Solar constant, 2 cal cm^{-2} min^{-1}, 70% absorbed. (Von der Haar and Suomi, 1969). Earth cross section facing the sun = 1.278E14 m^2. Available energy of solar radiation = (2 cal cm^2 min yr^{-1})(1.278E18 cm^2)(5.256E5 min yr^{-1})(4.186 J cal^{-1})(0.7) = 3.936E24 J yr^{-1}.
2. ***Deep earth heat:*** Heat released by crustal radioactivity and other deep earth phenomena = 1.98E20 J yr^{-1} (Sclater et al., 1980). Heat flowing up from the mantle = 4.74E20 J yr^{-1}. Available energy of deep heat = 6.72E20 J yr^{-1}.
3. ***Gravitational energy:*** Available energy released through tide dynamics = 2.7E19 erg s^{-1} (Munk and Mc Donald, 1960). Available energy of tides = (2.7E19 erg s^{-1})(3.153E7 s yr^{-1})/(1E7 erg J^{-1}) = 8.513E19 J yr^{-1}.
4. ***Wood:*** Annual net forest area loss = 11.27E6 ha yr^{-1} (Brown et al., 1997). Biomass= 40 kg m^{-2}(30% moisture). Available energy of wood = (11.27E6 ha yr^{-1})(1E4 m^2 ha^{-1})(40 kg m^{-2})(1.3E7 J kg^{-1})(0.7) = 5.86E19 J yr^{-1}.
5. ***Soil erosion:*** Total soil erosion = 6.1E10 t yr^{-1} (Oldeman, 1994). Assume soil loss of 10 t ha^{-1} yr^{-1}, 1.0% organic matter in soil (5.4 kcal g^{-1}) and 6.1E9 ha agricultural land = 6.1E16 g yr^{-1}. Available energy of organic matter = (6.1E16 g)(0.01)(5.4 kcal g^{-1})(4186 J $kcal^{-1}$) = 1.38E19 J yr^{-1}.
6. ***Oil:*** Total production 2008 = 3.93E9 $t_{oil\ eq}$ yr^{-1} (British Petroleum, 2009). Available energy of oil = (3.93E9 $t_{oil\ eq.}$)(4.186E10 J $t^{-1}{}_{oil\ eq.}$) = 1.64E20 J yr^{-1}.
7. ***Natural gas:*** Total production 2008 = 2.77E9 $t_{oil\ equiv}$ (British Petroleum, 2009). Available energy of natural gas = (2.77E9 $t_{oil\ eq.}$)(4.186E10 J $t^{-1}{}_{oil\ eq.}$) = 1.16E20 J yr^{-1}.
8. ***Coal:*** Total production 2008 = 3.32E9 $t_{oil\ eq.}$ (British Petroleum, 2009). Available energy of coal = (3.32E9 $t_{oil\ eq.}$)(4.186E10 J $t^{-1}{}_{oil\ eq.}$) = 1.39E20 J yr^{-1}.
9. ***Nuclear energy:*** Total electric production 2008 = 9.86E18 J_{el} (British Petroleum, 2009).
10. ***Phosphate:*** Total production 2006 = 1.56E8 t y^{-1}(http://www.indexmundi.com). Gibbs free energy of phosphate rock = 3.48E2 J g^{-1}. Energy Flux = (1.56E14 g)(3.48E2 J g^{-1}) = 5.43E16 J yr^{-1}.
11. ***Limestone:*** Total production 2006 = 2.83E8 t y^{-1}(http://www.indexmundi.com). Gibbs free energy of limestone = 611 J g^{-1}. Available energy of limestone = (2.83E14 g)(611 J g^{-1}) = 1.73E17 J yr^{-1}.
12. ***Selected metals (Al, Cu, Pb, Fe, Zn):*** Total global production 2006 = 1.59E9 t y^{-1} (http://www.indexmundi.com) = 1.59E15 g yr^{-1}.

[a] Emergy Intensities from literature (Odum, 1996; Brown and Ulgiati, 2004; www.emergysystems.org).

Other criticisms related to calculation techniques (average of different cases, allocation procedures, etc) were also raised and call for increased attention. For example, Cleveland's (2008) criticism about the use of single transformities for fossil fuels (namely for coal) was recently addressed by Brown et al. (2011) who calculate a set of distinct transformities for oil, coal and natural gas originated in different locations and geologic eras worldwide, also addressing the uncertainty of such estimates.

It is not possible here to go deeper into the individual issues raised by Hau and Bakshi, Cleveland, and other authors, nor to present the most recent results and patterns developed by the emergy community and ISAER (International Society for the Advancement of Emergy Research) to further improve the approach and remove weaknesses and internal inconsistencies, because it would require an entire new paper. Efforts toward improvement and synergic interaction of approaches are in progress (Ulgiati, 2000; Sciubba and Ulgiati, 2005; Franzese et al., 2009; among others).

7. Emergy-Based Evaluation of Selected Uses of Common Resources

The complex questions concerning the fit of humanity in the biosphere require that we look at things from a different perspective. Until the beginning of the industrialization, the emergies released by humans were small, compared with the renewable driving emergy. Instead, now-a-days human societies release about twice the emergy in slow-renewable and non-renewable resources than flows into the biosphere from renewable sources. How best to fit humans and environment together? Decisions at the scale of biosphere and society require a valuation system free of human bias. It is not surprising that development of resources, exploitation of global fisheries and forests continue unimpeded when evaluated using economic value systems based on willingness-to-pay. Neoclassical economic valuation cannot overcome the fact that its main underlying principle is that value stems from utilization by humans and utility is measured in terms of benefit to human being.

Let's therefore explore to what extent the emergy method can be used to complement and integrate the pictures provided by the MEA list of ecosystem services as well as by the claim for an economic benefit to all the stakeholders for the use of “their” share of Commons, as foreseen by Barnes. Both pictures provide very interesting points of view, but their useful application to policy making requires that they are integrated by means of a method capable to assess the quantity and the environmental quality of the Commons. We provide in the following paragraphs a survey of selected applications of the Emergy evaluation method to assess quantity and quality of natural capital and ecosystem services, in order to provide a basis for sustainable resource management policies.

7.1. Emergy and Equitable Trade

It is nothing new that very few wealthy countries have access to (and actually use) the largest share of the world energy and material resources. The generation of environmental and social instability in several areas of the planet can be discussed in relation to the existence of such an imbalance. Conventional economic approaches quantify traded flows in terms of the amounts of goods traded and the money paid for them, once again without any quality assessment of the traded resources. The economic assessment of trade very often only focuses on money balance and does not take into proper account the real quality of (= what it takes to make) the traded resources as well as the related environmental problems, both from the point of view of the depletion of resources and of the pollution generated in the exporting country. Resources are very often mined and partially processed in the exporting country, then refined and used in the importing developed countries. The price of exported resources is very often inadequate to compensate for the depletion of local storages and the environmental burden generated by resource extraction and primary processing. Instead, resources drive significant economic and environmental benefits in technologically and economically developed countries.

The unbalance of resource trade among countries is of paramount importance to environmental and political stability, as clearly pointed out by H.T. Odum (1994c): "*Trade and projects that unbalance local economies […] they leave major sectors of the world's population in poverty, essentially outside the world economy. This pattern wastes resources into luxury and excess of the developed countries, diverting resources that used to go directly to population support (without payments). This pattern is not sustainable, does not maximize world wealth and emergy, does not reinforce world production, and will not last. These patterns will become discredited as world opinion changes, as revolutions occur, and worldwide resource depletion soon cuts off the largesse of the overdeveloped countries.*"

Odum (1996) and Brown (2003) clearly identified the "advantage to the buyer" in the relations between industrialized countries and countries the economies of which are mainly based on exports of primary resources. This happens in spite of an apparent balance of money flows between trading countries (economic "terms of trade"). The situation appears even worse when the environmental burden associated to the traded resources is also taken into account and its geographical distribution is carefully investigated. It clearly appears that environmental and development problems cannot be solved by "free market" economy alone. The latter lacks the conceptual framework and the scientific tools needed to deal with the complexity of self-organizing systems, which operate on multiple scales and hierarchical levels. An emergy-based alternative definition of "terms of trade" can be provided whereby the emergy associated to the traded resource is compared to the emergy associated to the money received (Fig. 5). By means of such a procedure, each traded product is multiplied by a suitable emergy intensity factor (transformity, seJ/J, or specific emergy, seJ/g), so that the emergy released for its production is calculated. The total emergy associated to the money paid for is then calculated by multiplying such a money flow by the emergy supporting a unit of GDP in the importing country, in so determining the total emergy that can be purchased in that country thanks to the money received. The differences between the economic and emergy-based "terms of trade" accounting procedures are discussed in detail by Ulgiati and Cialani (2005), who maintain, building on Odum's emergy method, that the fairness of trade and resource exchange among developed and developing countries is hardly expressed by monetary indicators as well as by the conventional terms of trade. This is because money value underestimates a large set of free environmental services and natural capital uses, which are embodied in the traded goods.

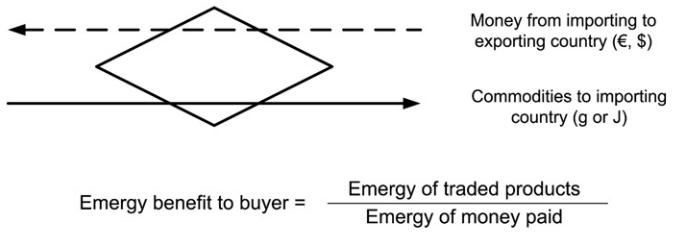

Fig. 5. Definition of trade in emergy terms (Odum, 1996).

7.2. Emergy and Environmental Taxation Schemes (Envitax)

Bimonte and Ulgiati (2002) pointed out the existence of a "new scarcity", i.e. the increasing unavailability of important components of the life support system. The ability of the environment to act as both a source of primary resources and as a sink for waste is not unlimited as it was in the past. If resource exploitation is carried out without any concern about its consequences on environmental integrity, degraded ecosystems become increasingly unable to provide basic ecological services (water cycling, photosynthesis, support to biodiversity, among others) and resources (wood, food, fresh water). As a consequence, these authors (Bimonte and Ulgiati, 2002) suggested a taxation tool based on Odum's emergy method, pointing out that, in general, environmental policies and taxation schemes only focus on a particular goal and do not take a general and global view of the environment's contribution. For example, the aim of the carbon tax is to reduce carbon dioxide emissions and prevent global warming, although atmospheric temperature is not the only parameter that requires control or feedback from the economic system. The integrity of the environment as a whole is of fundamental importance and taxation schemes or financial instruments must evolve in line with these objectives. According to Bimonte and Ulgiati (2002), the emergy approach offers a way to look at the quality of a production process, namely at its ability to reinforce the productive basis and avoid the waste of resources. Bimonte and Ulgiati also point out that environmental integrity and at the same time the reinforcement of the productive basis cannot be obtained by simply restricting the use of a given resource. As clearly underlined by Odum (1996): "*whereas energy conservation in the sense of increasing efficiency of use has net benefits, an economy that conserves in the sense of restricting fuel use tends to reduce … its ability to compete economically. Taxing fuels is sometimes offered as an incentive for energy conservation, but reducing fuel has a negative amplifier effect on the economy that may be greater than the increases in efficiency. If the tax reduces luxury and waste, the effect is beneficial*". To be effective towards environmental integrity, a taxation policy should therefore focus on the quality of production and use processes, i.e. the quality of resources used and the performance of the process as a whole, not just on the use of a single resource or the respect of a single parameter. Bimonte and Ulgiati therefore suggest a taxation scheme based on the Emergy Sustainability Index, ESI (Ulgiati and Brown, 1998), an aggregated measure that takes into account both economic advantages (return on emergy investment, measured by an Emergy Yield Ratio, EYR) and environmental loading (measured by an Environmental Loading Ratio, ELR). The ESI (calculated as the ratio of the EYR to ELR) is sensitive to both resource alternatives "renewable, non-renewable" and "local, imported". Its inverse tends to zero the more a process is sustainable and could be used to develop an environmental taxation strategy where taxes are proportional to a decreasing value of the index. Such a tax would be a way to penalize processes which use less environmentally sound technologies and less renewable resources. Of course, the inverse would be true for environmental incentives. According to the authors, the Envitax scheme also suggests using the tax revenues to restore the natural capital stressed by the human activity. If the environment is considered a fund instead of a stock, and if there is agreement that such a fund should remain unchanged by restoring its ability to sustain a certain process, using Envitax revenues to restore the natural capital would have multiple effects: a) slow down the appropriation and depreciation of the fund, b) restore the fund at the expenses of the polluters, c) implement an environmental policy based on both a comprehensive and global evaluation of biosphere work and the environmental quality of each input.

7.3. Environmental Debt

An interesting point of view, rich with development and application perspectives, is also provided by the concept of emergy, based environmental debt accounting, developed by Campbell (2005). This author defines the concept of environmental liability and provides the conceptual basis for its operation in the form of an energy systems model. The concept of environmental debt is based on the recognition that economies receive work contributions from the environment (services, resources, natural capital depleted or degraded, etc.) without providing sufficient payment in the form of reinforcing feedback. In order to solve such an important lack of proper accounting of the environmental services and capital, a Double Entry Bookkeeping was suggested, similar to the traditional methods used in financial accounting, where emergy is used to document environmental liabilities and to construct a balance sheet that accounts for all economic and environmental work contributions to economic production. According to Campbell, "*once all empower credits and debits in the environmental and economic system are known, recorded and analyzed, the political process can be used to address questions of the appropriate debtload to be carried by society, and the schedule for repaying existing debts*".

7.4. Quality Adjusted Shannon Diversity

Brown et al. (2006) identified a lack of system view in the conventional Shannon diversity indices used in Ecology. According to these authors, there are two conceptual problems with the standard use of the Shannon equation: first, it uses stocks instead of flows, and second one cannot compute whole system diversity since it ignores the hierarchical organization of ecosystems (the equation is maximized when the probability of observing each component is equal). To overcome these limitations, they have proposed a quality adjusted Shannon diversity index, where importance value is the relative contribution of each component species to the total emergy flow through all biotic components computed by summing net production multiplied by transformity over all components. In so doing, physical flows are adjusted for quality factor and biodiversity is maximized when the emergy on each pathway is equal, as also postulated by Odum (1996).

The four cases presented (trade, envitax, environmental debt, and adjusted Shannon diversity) share two common characteristics:

a) all of them include in the assessment the donor-side point of view and patterns of quality assessment. Resources (flows and storages) are not valued based on human preferences, but are valued according to their demand for environmental support over time and space. The larger the time and spatial scales involved, the longer the turnover time and the more difficult is to replace a resource when used up. Some resources less "priced" by market dynamics or not marketed at all, might well appear crucial and very valuable based on a biosphere system of value.
b) For all of them the concept of feedback reinforcement is crucial, be it a fair reward for a traded resource, the restoration of natural capital by reinvesting environmental taxation revenues, a schedule for repaying the environmental debts or finally a feedback control from higher to lower levels of the metabolic chain. Again, the appropriate intensity of such a feedback is something that is hardly evaluated or not considered at all within the conventional market dynamics.

The use of the Emergy evaluation method allows the identification of a "biosphere value" for resources and commodities that could profitably complement monetary evaluations. As a consequence, the efforts of ecological economists and concerned policy makers towards a proper management of natural capital and ecosystem services would be reinforced by the new framework available.

Emergy-based tools provide an answer to the unsolved questions raised by the Millennium Ecosystem Assessment findings as well as by the "cap & trade & dividends" strategies designed by Barnes. The Emergy method appears to be a powerful way to value and categorize the use of resources as well as to implement management policies capable of integrating the human preferences at local scale with biosphere support at the larger scale. In other words, all the MEA services listed above and the Commons identified in Fig. 1 can be accounted for and valued in emergy units, thus contributing to improve and integrate quantity and quality factors, economic tools, interspecies and intergenerational equity, and finally proper environmental conservation and management strategies.

8. Summary and Concluding Remarks

Natural capital, the common heritage that we received from past Nature's work and the integrity of which was preserved by the careful use of the previous generations, is now at risk. Its exploitation in support of unsustainable economic growth driven by global markets generates a fragile wealth in favor of a minority of the world population. Authoritative studies warn about the crucial role of natural capital and ecosystem services that must be preserved for the well being of the whole planet and passed to the next generations. Regulatory policies and taxation schemes have been suggested and the debate about the most convenient strategies is still in progress. Environmental and social aspects are strictly intertwined so that decision making is even more difficult and choices questionable. What is absolutely needed is a procedure to quantitatively account for natural capital without only relying on financial tools based on human preferences and fluctuating market dynamics.

The use of emergy synthesis method to evaluate natural capital and ecosystem services provides a stronger basis to management policies as it ensures that the global dynamics of the biosphere (and therefore the interest of all species and future generation) is taken into proper account from a donor-side perspective. The emergy method is capable to generate a bold set of data and scenarios related to the present and future use of natural capital, the state and trend of world storages (water, biomass, biodiversity, minerals), and a clear assessment of the reliance of monetary wealth on natural capital appropriation. In so doing, it would also be possible to assess how fair is such an appropriation and how benefits are shared among world population.

However, a huge effort is still urgently needed in order to:

- Update the emergy evaluation of each country's economy and assess their reliance on natural capital. Investigate processes that use the Commons and those economic sectors that heavily rely on their depletion.
- Quantify the value of local Commons (minerals, forests, biodiversity, clean air, surface and ground water, topsoil, land, fisheries, wetlands, etc.) and show their variations over time in emergy terms.
- Identify the endangered storages (for instance water and soil erosion) and explore feedback actions to prevent degradation and favor restoration. Investigate tools to optimize the use of the Commons.
- Identify and investigate the new Commons, such as infrastructures, culture, education, services, that are supported by natural capital and contribute to the creation of wealth.
- Overcome the still existing weaknesses of the emergy method in what relates to computational procedures, number of published case studies, treatment of uncertainty, and finally
- Implement better links of emergy to other approaches (economic, thermodynamic and social) in order to achieve synergic results, away from unidimensional evaluation methods.

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