Article

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Emergy Evaluation of the Biosphere and Natural Capital

The measure of value called emergy is used to evaluate the flows of energy and resources that sustain the biosphere including the economy of humans. A donor system of value based on solar emergy required to produce things is suggested as the only means of reversing the logic trap inherent in economic valuation, which suggests that value stems only from utilization by humans. The stocks of natural capital and flows of environmental resources are evaluated in emergy and related to Global World Product. Several emergy indices are introduced as a means of evaluating sustainability of economies and processes. The total emergy flux of the biosphere is composed of 32% renewable flows of sunlight, tidal momentum and deep heat (it was 68% in 1950), and 68% slowly-renewable and nonrenewable flows. An index of environmental loading on the biosphere is shown to have increased about 4 times since 1950, while an index of global sustainability suggests that overall, sustainability of the global economy has precipitously declined.

INTRODUCTION

Geologic processes, atmospheric systems, ecosystems, and societies are interconnected through a series of infinitely different and changing relationships... each receiving energy and materials from the other, returning same, and acting through feedback mechanisms to self-organize the whole in a grand interplay of space, time, energy, and information. Processes of energy transformation throughout the biosphere build order, degrade energy in the process, and cycle information in a network of hierarchically organized systems of ever-increasing spatial and temporal scales.

Understanding the relationships between energy and the cycles of materials and information may provide insight into the complex interrelationships between society and the biosphere. Society uses environmental energies directly and indirectly from both renewable energy fluxes and from storages of materials and energies that resulted from past biosphere production. The actions of society, its use of resources and the load this resource use places on the biosphere are of great concern. Clearly it is imperative that perspective be gained concerning the interplay of society and environment to help direct planning and policy for the next millennium.

In this paper, emergy (1) is used to value flows of energy and materials, within the biosphere, including systems of humanity. When expressed in units of the same form of energy, systems of varying scales and organization can be compared and indices of performance can be calculated. Insight into the general behavior of systems may be gained through cross-scale comparison.

Flows of Energy Maintain Order

Systems of the biosphere are maintained by flows of energy that cycle materials and information. Without continual flows of input energy that build order, systems degrade away. It is through cycling that systems remain adaptive and vital. Materials or information sequestered in unreachable or unusable storages are of no value and often soon lose their importance or relevance. Cycling allows for the continuous convergence and divergence of energy, materials and information. Processes of convergence build order, adding structure, reassembling materials, upgrading energy and creating new information. Processes of divergence disorder structure and disperse materials and information and allow concentrated energy to interact in amplifier actions with lower quality energies to maximize power flows.

The biosphere (Fig. 1) is driven by the flux of renewable energies in sunlight, tidal momentum, and deep earth heat. Human society draws energy directly from the environment, from short-term storages (from 10–1000 year turnover times) like wood, soils, and ground-water, and from long-term storages of fossil fuels and minerals. These energies and materials cycle through society's economy powering productive processes and building physical structure and storages of information. Feedback pathways exist throughout as do pathways of recycle, each diverging in reinforcement actions that carry materials and information back to sites of production and transformation.

In most systems, a significant portion of inflowing energy is degraded, with smaller amounts transformed into higher quality energies. Materials, on the other hand are mostly transformed and upgraded, only to recycle after their use, back through the environment. Information is created and recreated with each cycle in systems, driven by sources of energy and facilitated by material structure. In each cycle, through the process of convergence and divergence, information is validated for it is only through use that information can be maintained.

Environmental Resources and Natural Capital

Human society draws resources, and services from the environment. The resources are easily understood as things like fossil fuels, wood, water, fruit, animals, and so forth. Less easily understood and relatively difficult to quantify are environmental services such as waste assimilation, flood protection, or aesthetic qualities.

There is confusion in the literature concerning what is an environmental service, an environmental good, natural capital, or human released energy (2–5). The systems diagram in Figure 1 clarifies our meanings. Environmental services are represented by the flow labeled S from environmental systems to human society (6). The flows of environmental resources are labeled SR and N for Slowly Renewable and Nonrenewable, respectively. Renewability is a relative concept, since it depends on how quickly a material or energy is used compared to the speed at which it is generated. Wood, for instance, can be a renewable resource, if the rate of harvesting is matched with the regeneration rate. Fossil fuels and most mineral resources on the other hand are not renewable, even though they are being constantly regenerated, because their rate of use is much faster than the regeneration rate.

In this paper, we refer to energies as renewable or nonrenewable. Renewable energies to the biosphere are: sunlight (R_1), tidal energy (R_2), and deep earth heat (R_3). Renewable materials and energies used directly by society (renewable environmental resources) are those flows from storages of materials and energies that are used at rates slower than their generation rate (SR). Nonrenewable materials and energies used by society (nonrenewable environmental resources) are those flows from

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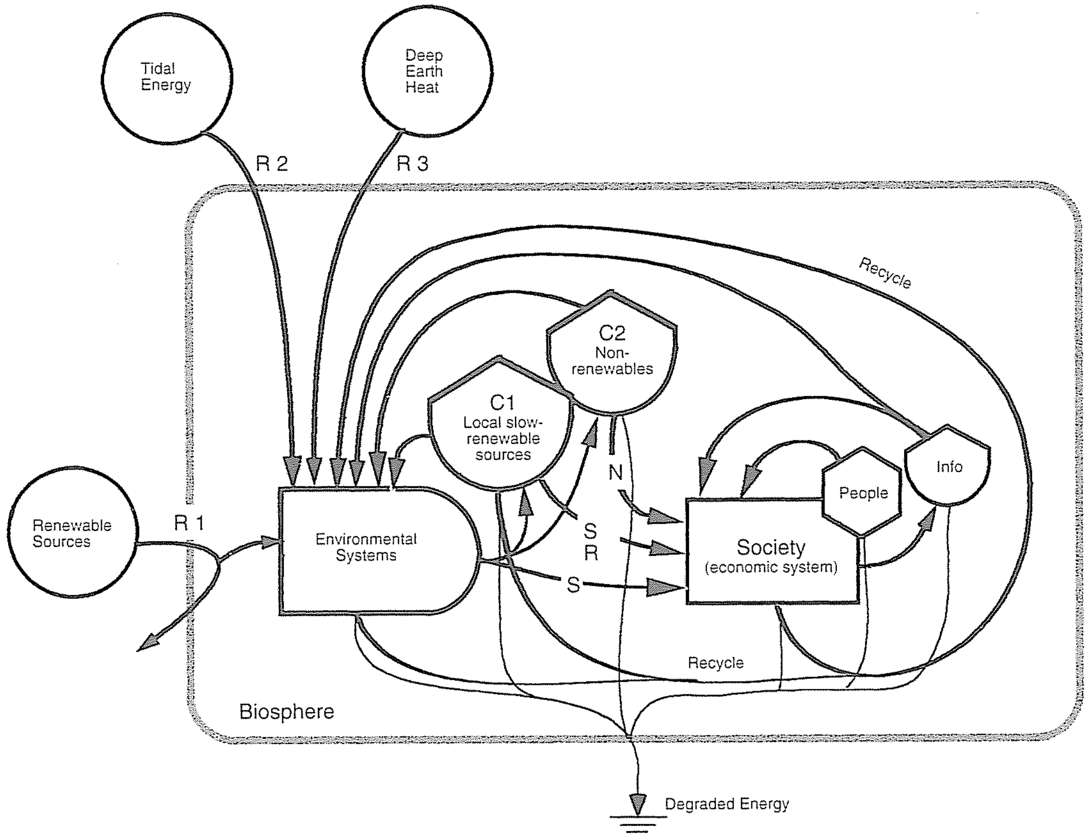


Figure 1. Systems diagram of the biosphere showing the inflow of renewable energies (R1, R2, and R3) environmental services (S), slow-renewable resource flows (SR), nonrenewable resource flows (N), the recycle of materials, and feed back of human energy and information. Info = information.

storages that are used at rates faster than their regeneration (N). We refer to them as "society released" materials and energies from storages of natural capital. The distinction between society released energy and environmental resources is difficult to make, since all flows used by humans are released by humans.

Natural capital is the storage of materials and energy from which environmental resources are drawn. In Figure 1, natural capital has been divided into two storages (C_1 and C_2). The first is the storage of plant biomass, soil organic matter, animals and water that is slowly renewable (C_1). The second is the storage of fossil fuels and minerals that are nonrenewable (C_2). We believe it important to maintain a difference between a storage as capital and a flow that is a flux of material or energy.

ENERGY AND EMERGY

Energy has been defined as the ability to do work, based on the physical principle that work requires energy input. Energy is measured in units of heat, or molecular motion... the degree of motion resulting in expansion and quantified in calories or joules (7).

Heat energy is a good measure of the ability to raise water temperature. However, it is not a good measure of more complex work processes. Processes outside of the window defined by heat engine technology, do not use energies that lend themselves to thermodynamic heat transfers. As a result, converting all energies of the biosphere to their heat equivalents reduces all work processes of the biosphere to heat engines. Human beings, then, become heat engines and the value of their services and information would be nothing more than a few thousand calories per day. Obviously, not all energies are the same and methods of analysis need reflect this fact.

Different forms of energy have different abilities to do work, and it is necessary to account for these different abilities if energies are to be evaluated correctly. A joule of sunlight is not the same as a joule of fossil fuel, or a joule of food, unless it is being used to power a steam engine. A system organized to use concentrated energies like fossil fuels cannot process a more dilute energy form like sunlight. Evaluation of energy sources is system dependent. The processes of the biosphere are infinitely varied and are more than just thermodynamic heat engines. As a result, the use of heat measures of energy that can only recognize one aspect of energy, its ability to raise the temperature of things, cannot adequately quantify the work potential of energies used in more complex processes of the biosphere. As in thermodynamic systems where energies are converted to heat to express their relative values, in the larger biosphere system as a whole, energies should be converted to units that span this greater realm, accounting for multiple levels of system processes, ranging from the smallest scale to the largest scales of the biosphere, and accounting for processes other than heat engine technology.

Most valuation systems are based on utility, or what is received from an energy transformation process. Thus, fossil fuels are evaluated based on the heat that will be received when they are burned. Economic evaluation is based on the willingness to pay for perceived utility. An opposite view of value in the biosphere could be based on what is put into something rather than what is received. In other words, the more energy, time, and materials that are "invested" in something, the greater its value. This might be called a donor system of value, while heat evaluation, and economic valuation are receiver systems of value (8). A similar statement, i.e. that which is invested in something determines its value, is shared by Jørgensen (9), and recently by Svirezhev (10) using exergy accounting of ecosystems.

Emergy Basis of Value

A relatively new method of valuation, called Emergy Accounting (1) uses the thermodynamic basis of all forms of energy and materials, but converts them into equivalents of one form of energy, usually sunlight. Emergy is the amount of energy that is required to make something. It is the "memory of energy" (11) that was degraded in a transformation process. The units of emergy are emjoules, to distinguish them from joules. Most often emergy of fuels, materials, services etc. is expressed in solar emjoules (abbreviated sej). Emergy then, is a measure of the global processes required to produce something expressed in units of the same energy form. The more work done to produce something, that is the more energy transformed, the higher the emergy content of that which is produced.

To derive solar emergy of a resource or commodity, it is necessary to trace back through all the resources and energy that are used to produce it and express each in the amount of solar energy that went into their production. This has been done for a wide variety of resources and commodities and the renewable energies driving the biogeochemical process of the earth (12). When expressed as a ratio of the total emergy used to the energy of the product, a transformation coefficient results (called transformity whose dimensions are sej J^{-1}). As its name implies, the transformity can be used to "transform" a given energy into emergy, by multiplying the energy by the transformity. For convenience, in order not to have to calculate the emergy in resources and commodities every time a process is evaluated, previously calculated transformities are used.

There is no single transformity for most products, but a range. There is probably a lower limit, below which the product cannot be made, and there is some upper limit, although in theory, one could invest an infinite amount of fuel in a process and thus have an infinitely high transformity. Average transformities are used whenever the exact origin of a resource or commodity is not known or when not calculated separately. (Definitions of terms used in Emergy Accounting can be found in Appendix A).

Emergy measures value of both energy and material resources within a common framework. Transformities provide a quality factor as they account for convergence of biosphere processes required to produce something. Embodied in the emergy value are the services provided by the environment which are free and outside the monied economy. By accounting for quality and free environmental services, resources are not valued by their money cost or society's willingness to pay, which are often very misleading.

Emergy and Maximum Empower

Emergy accounting is a technique of quantitative analysis which determines the values of nonmonied and monied resources, services, and commodities in common units of the solar energy it took to make them (called solar emergy). The technique is based on the principles of energetics (13), system theory (14) and systems ecology (15). One of its fundamental organizing principles is the maximum empower principle (empower is emergy/time).Stated as simply as possible the maximum empower principle is as follows:

Maximum Empower Principle: Systems that self-organize to develop the most useful work with inflowing emergy sources, by reinforcing productive processes and overcoming limitations through system organization, will prevail in competition with others.

It is important that the term "useful" is used here. Useful work means using inflowing emergy in reinforcement actions that ensure and, if possible, increase inflowing emergy. Energy dissipation without useful contribution to increasing inflowing emergy is not reinforcing, and thus cannot compete with systems that use inflowing emergy in self-reinforcing ways. For example, drilling oil wells and then burning off the oil may use oil faster (in the short run) than refining and using it to run machines, but it will not compete, in the long run, with a system that uses oil to develop and run machines that increase drilling capacity and ultimately the rate at which oil can be supplied.

Table 1. Flux of renewable and nonrenewable energies driving global processes, 1995.

Note	Source	Energy Flux (J yr^{-1})	Transformity* (sej J^{-1})	Solar Emergy Flux (E24 sej yr^{-1})	Emdollars# (E12 Em$)
Global Renewable Energies					
1	Solar insolation	3.94 E24	1	3.94	3.57
2	Deep earth heat	6.72 E20	6055	4.07	3.69
3	Tidal energy	8.52 E19	16842	1.43	1.30
			Subtotal	9.44	8.56
Society Released Energies (nonrenewables)					
4	Oil	1.38 E20	5.40 E04	7.45	6.75
5	Natural gas	7.89 E19	4.80 E04	3.79	3.43
6	Coal	1.09 E20	4.00 E04	4.36	3.95
7	Nuclear energy	8.60 E18	2.00 E05	1.72	1.56
8	Wood	5.86 E19	1.10 E04	0.64	0.58
9	Soils	1.38 E19	7.40 E04	1.02	0.93
10	Phosphate	4.77 E16	7.70 E06	0.37	0.33
11	Limestone	7.33 E16	1.62 E06	0.12	0.11
12	Metals	992.9 E12 g	1.0 E09 sej g^{-1}	0.99	0.90
		Subtotal		20.46	18.54
		TOTAL		29.91	27.10

* Transformities from Odum (1)
\# Emdollars obtained by dividing Emergy in column 5 by 1.1 E12 sej $^{-1}$ (Table 4).

1	Sunlight	Solar constant, 2 cal cm^{-2} min^{-1} 70% absorbed Earth cross section facing the sun = 1.278 E14 m^{2} Energy Flux = (2 cal cm^{2} min yr^{-1})(1.278 E18 cm^{2}) (5.256 E5 min yr^{-1})(4.186 J cal^{-1}) (0.7) = 3.936 E24 J yr^{-1}	(31)
2	Deep earth heat	Heat released by crustal radioactivity = 1.98 E20 J yr^{-1} Heat flowing up from the mantle = 4.74 E20 J yr^{-1} Energy Flux = 6.72 E 20 J yr^{-1}	(32) (32)
3	Tidal energy	Energy received by the earth = 2.7 E19 erg sec^{-1} Energy Flux = (2.7 E19 erg sec^{-1})(3.153 E7 sec yr^{-1}) / (1 E7 erg J^{-1}) = 8.513 E19 J yr^{-1}	(33)
4	Oil	Total production = 3.3 E9 Mt oil equivalent Energy Flux = (3.3 E9 t oil eq.) x (4.186 E10 J t^{-1} oil eq.) =1.38 E20 J yr^{-1} oil equivalent	(34)
5	Natural gas	Total production = 2.093 E9 m^{3} Energy Flux = (2.093 E12 m^{3}) x (3.77 E7 J m^{3}) =7.89 E19 J yr^{-1}	(34)
6	Coal	Total production (soft) = 1.224 E9 t yr^{-1} Total production (hard) = 3.297 E9 t yr^{-1} Energy Flux = (1.224 E9 t yr^{-1}) (13.9 E9J t^{-1}) + (3.297 E9 t yr^{-1}) (27.9 E9 J t^{-1}) =1.09 E20 J yr^{-1}	(34) (34)
7	Nuclear energy	Total production = 2.39 E12 kwh yr^{-1} Energy Flux = (2.39 E12 kwh yr^{-1}) (3.6 E6 J kwh^{-1}) = 8.60 E18 J/yr elec. equivalent	(34)
8	Wood	Annual net forest area loss = 11.27E6 ha yr^{-1} Biomass = 40 kg m^{2}; 30% moisture Energy Flux = (11.27 E6 ha yr^{-1}) (1 E4 m^{2} ha^{-1})(40 kg m^{2}) (1.3 E7 J kg^{-1})(0.7) = 5.86 E 19 J yr^{-1}	(18) (35)
9	Soil erosion	Total soil erosion = 6.1 E10 t yr^{-1} Assume soil loss estimate of10 t ha^{-1} yr^{-1} and 6.1 E9 ha agricultural land = 6.1 E16 g^{-1} yr^{-1} (assume 1.0% organic matter), 5.4 kcal g^{-1} Energy Flux = (6.1 E16 g) (.01) (5.4 kcal g^{-1})(4186 J kcal^{-1}) =1.38 E19 J yr^{-1}	(16, 17)
10	Phosphate	– Total global production = 137 E6 t yr^{-1} Gibbs free energy phosphate rock = 3.48 E2 J g^{-1} Energy Flux = (137 E12 g) (3.48 E2 J g^{-1}) = 4.77 E16 J yr^{-1}	(36) (1; p125)
11	Limestone	– Total production = 120 E6 t yr^{-1} Gibbs free energy phosphate rock = 611 J g^{-1} Energy Flux = (120 E12 g) (6.11 E2 J g^{-1}) = 7.33 E16 J yr^{-1}	(36) (1; p47)
12	Metals	– Total global production of Al, Cu, Pb, Fe, Zn (1994) = 992.9 E6 t yr^{-1} = 992.9 E12 g yr^{-1}	(37)

BALANCING HUMANITY AND NATURE

The biosphere is driven by renewable inputs of solar energy, tidal momentum, and deep heat each contributing to geologic, climatic, oceanic, and ecologic processes that are interconnected with flows of energy and materials and nonrenewable energies contained in vast storages that are exploited and released by society (Fig. 1). Within the last several hundred years, the total inputs of energy released by society to the biosphere, from slowly renewable storages and nonrenewable storages, have grown to exceed the renewable ones. Table 1 lists the overall emergy values of the flows of emergy driving the biosphere, including those released by society. The energies released by society power machines and productive processes, creating structure and information that is fed back in autocatalytic pumping actions to increase power flows. Included in these flows are energies like wood and soils. Wood is sometimes considered a renewable energy input, however rates of deforestation and cutting exceed regrowth. The net loss of wood biomass is included in Table 1. Soil erosion has become a serious global problem. It is estimated that over 1/3 of all agricultural land is suffering erosional losses that threaten productive capacity (16, 17). Eroded soil is included as a slowly-renewable energy "released" by society, since it is lost to agricultural production in the future.

Total emergy driving the biosphere, including human society, in 1995 was 29.91 E24 sej, composed of 9.44 E24 sej from renewable inputs and 20.46 E24 sej from slowly- renewable and nonrenewable sources. Of the total emergy inputs to the global "economy", 68% are from slowly- and nonrenewable sources, while 32% are renewable. By far, the flows of nonrenewable fossil energies, including nuclear, dominate, comprising nearly 85% of the total released by society. Figure 2 is a graph of the changes in total global emergy flows since 1950, showing the steady yearly flux of renewable energies, and the increases in nonrenewables over the time period.

Figure 2. Emergy flows and Gross World Product (GWP) for the period 1950–1995, showing the increase in nonrenewable energy use and the constant renewable inflow. Estimated from energy data in Brown et al. (18) and calculated according to the methodology used in this paper.

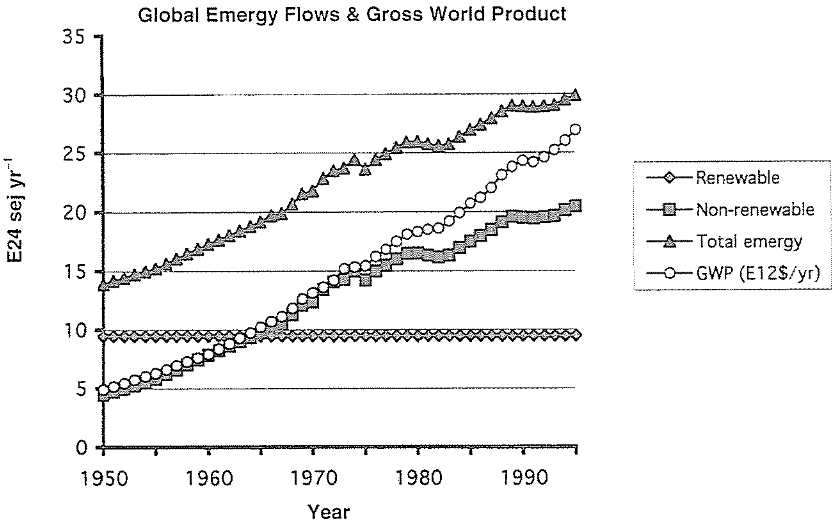
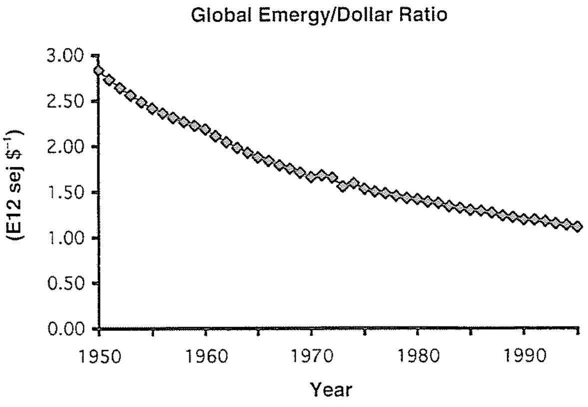


Figure 3. Global emergy dollar ratio for the period 1950–1995, showing the decline in purchasing power of money, even though the GWP has been corrected for constant 1995 dollars. Data from Figure 2.



Emergy and the Global Economy

The global economy is driven by the interplay of both renewable and nonrenewable energy flows. Money circulating in the world economy is driven by emergy flows and can be related to emergy flux. By dividing the annual flux of emergy driving the world economy by the annual Gross World Product (GWP) a ratio of money circulating to emergy flux is calculated. GWP, measured in 1995 USD ($), for the years 1950, 1975, and 1995 was 4.9, 15.4, and 26.9 trillion dollars, respectively (18). Total emergy driving the world economy in those same years was 13.9 E24, 23.2 E24, and 29.9 E24 solar emjoules, respectively (Fig. 2). Thus, the emergy money ratio for those years was 2.8 E12 sej $\$^{-1}$, 1.5 E12 sej $\$^{-1}$, and 1.1 E12 sej $\$^{-1}$, respectively.

The ratio of emergy to money is, in essence, the fraction of total emergy required to circulate 1 dollar of GWP, with the assumption that the economy and biosphere are an integrated system. In 1995 the emergy per dollar ratio was 1.1 E12 sej $\$^{-1}$. This means that, on the average, 1.1 E12 sej were required inputs to the global economy for each dollar of GWP. The emergy per money ratio can be used to express emergy flows in equivalent monetary flows which we call emdollars (Em$). If a given emergy flow is divided by the emergy per money ratio the resulting quotient is emdollars, or the amount of GWP that results from the emergy flow (19). The emergy per money ratio can be calculated for any currency and for any transaction. For instance, we calculate emergy per money ratios for national economies and compare relative buying power (20), or for individual products and compare emergy advantage to the buyer (1), or for human services to evaluate emergy that supports service inputs to products and resources.

Figure 3 is a graph of the ratio of emergy to GWP (in constant 1995 USD) for the 45 years from 1950 to 1995. Using constant 1995 dollars reduces the effect of global inflation, yet there is still a declining trend in the emergy dollar ratio in Figure 3. The trend results from increasing participation of humans and their economies in the emergy flows of the biosphere. The decline in the emergy per dollar ratio of about 3% per year (equal to the growth of nonrenewable inputs to the global economy) represents a loss of buying power, since with each passing year, the amount of emergy that flows for each dollar of GWP is less. One might be tempted to suggest that a decline in emergy use per dollar of GWP means that the world economy is more efficient because less emergy is used for each dollar of GWP. On the other hand, we believe that it may mean that economic measures of inflation used to establish constant dollars, do not adequately account for inflation, and that a better measure might be the ratio of total emergy use to GWP (or in the case of a national economy, emergy use to GDP).

Emergy Values of Natural Capital

An emergy evaluation of global natural capital is summarized in Table 2. The natural capital accounted for in this paper is the main storages of resources within the global system. To some (3, 21, 22) the storages of "environmental resources" (rows 1–4 in Table 2) are considered natural capital; storages that we consider slowly-renewable. We also consider the nonrenewable, fossil fuel resources, metals, and phosphorus as natural capital and these are given in the Table for comparison. Total emergy value of natural capital is 739.8 E25 sej, or about 6.85 quadrillion Em$. The largest storage of natural capital is freshwater that includes the polar ice caps (about 92%) groundwater (7.5%) and lakes, rivers, soil moisture, etc. (0.5%). Soil organic matter was the next largest storage of natural capital (2.1 quadrillion Em$). Plant biomass is valued at about Em$ 335 trillion, and animal biomass about Em$ 37 trillion. The storage of non renewables (based on estimated recoverable reserves as of 1996) is valued at about 1/4 that of the total storages or about Em$ 1.53 quadrillion. The storage of environmental resources (natural capital) from which environmental services are drawn is valued at about 600 times the flow. The storages of nonrenewable energies are about 360 times the present flows.

Emergy Based Indices of Sustainability

A definition of sustainability must include time. What is sustainable in one time period (during growth, for instance) may not be sustainable in the long run. The graph in Figure 4 illustrates different phases of growth and decline of a system. It could represent a human economy where there is growth, transition and decline of driving energy sources. Practices and processes that are characteristic during the growth phase may not be sustainable during transition or decline because they rely on nonrenewable energies that are diminishing. On the other hand practices that are sustainable during decline, because they have no reliance on nonrenewables, are probably not competitive with the dog-eat-dog competition that is characteristic of fast growing systems. Criteria for success in all systems (ecosystems with and without humans) during growth periods may be less based on efficiency and quality and more on speed. During times of transition and decline criteria for judging sustainability need to include several factors: *i)* the net yield of the process; *ii)* its environmental load, *iii)* its use of nonrenewables.

Several emergy indices have been defined and discussed elsewhere to illuminate these different aspects of sustainability (1, 20, 23–25). Using Figure 5 as a guide, several of these indices are defined as follows:

Percent Renewable (%Ren): The percent of the total energy driving a process that is derived from renewable sources (R/(R+SR+N)). In the long run, only processes with high %Ren are sustainable.

Emergy Yield Ratio (EYR): At the scale of the biosphere, the EYR is the ratio of the emergy of the output (Y = R + SR + N) divided by the emergy of nonrenewable inputs (N) that are used.

Environmental Loading Ratio (ELR): At the scale of the biosphere, it is the ratio of nonrenewable (N) and slowly-renewable emergy (SR) to renewable emergy (R) ((N + SR)/R). The ELR is an indicator of the load on the environment and might be considered a measure of stress due to economic activity.

Emergy Sustainability Index (ESI): An index that accounts for yield, renewability, and environmental load. It is the incremental emergy yield compared to the environmental load and is calculated as the ratio of emergy yield to environmental load (EYR/ELR).

An Aggregate Measure of Yield and Sustainability

Maximum performance from human/biosphere interfaces and economic activities is facilitated when these processes yield net emergy and minimize their "load" on the environment. Load is used here as a general term to mean use or consumption, examples include use of land for agriculture, consumption of biological resources (wood), or waste assimilation by waterbodies. The greater the use of the environmental resources of an area the greater the load on the environment. If the load on the environment by human use is too great, reduced performance or even severe declines in function can occur (23).

The Emergy Sustainability Index (ESI) is a function of yield, renewability, and load on the environment (25). If a process has a negative net yield, by definition, it is not sustainable without continuing flows of invested emergy. At the same time, if a process depends entirely on nonrenewable resources, it is not sustainable; and finally, if a process places extreme load on the environment, it may cause damage that threatens long-term sustainability. Clearly an index that incorporates these aspects would shed light on sustainability issues and the fit of human economies with that of the biosphere.

Emergy Indices of Global, Regional, and Local Processes

Fitting the technological economy of humans to the global environmental self design is increasingly important as the flows of emergy released by humans dominate the global system. Ta-

Table 2. Global storages of natural capital, 1995.

Note	Name (joules)	Energy (sej J^{-1})	Transformity* (E25 sej)	Emergy (E12 Em$, US)	Emdollars#
1	Fresh water	1.64 E23	1.82 E04	299.2	2770.4
2	Soil organic matter	3.10 E22	7.40 E04	229.4	2124.1
3	Plant biomass	4.16 E22	1.00 E04	41.6	385.2
4	Animal biomass	4.55 E19	1.00 E06	4.6	42.1
	Subtotal			574.8	5321.8
5	Coal	2.16 E22	4.00 E04	86.4	800.0
6	Crude oil	5.82 E21	5.40 E04	31.4	291.0
7	Natural Gas	5.28 E21	4.80 E04	25.3	234.7
8	Metals	1.74 E17g	1.0 E09 sej g^{-1}	17.4	161.1
9	Uranium	8.35 E20	1.79 E03	0.15	1.4
11	Phosphate rock	11.0 E15g	3.9 E09 sej g^{-1}	4.3	39.7
	Subtotal			165.0	1527.9
	TOTAL			739.8	6849.7

* Transformities from Odum (1).
\# Emdollars obtained by dividing Emergy in column 5 by 1.10 E12 sej $\$^{-1}$ (Table 3).

1	Fresh water	Total freshwater including ice caps = 33.28 E6 km^3 Gibbs free energy of water = 4.94 E6 J m^3 Energy = (33.28 E15 m^3)(4.94 E6 J m^3) = 1.644 E23 J	(38) (1; p. 295)
2	Soil organic matter	11.05 E9 ha in woodland, crops, pasture, grassland Assume: 1 m deep, 1% organic content, 5.4 kcal g^{-1} Energy = (9.32E13 m^2) (1m) (1E6cm^3 m^3) (1.47g cm^3) (.01org) (5.4kcal g^{-1}) (4186J $kcal^{-1}$) = 3.1 E22 J	(37)
3	Plant biomass	Total biomass = 1.841 E12 t dry wt. Energy = (1.841E12t) (1 E6g t^{-1}) (5.4 kcal g^{-1}) (4186 J $kcal^{-1}$) = 4.16 E22 J	(39)
4	Animal biomass	Total biomass = 2.013 E9 t dry wt. (1.015 E9 t on land, 0.998 E9 t in ocean) Energy = (2.013 E9t) (1E6g t^{-1}) (5.4 kcal g^{-1}) (4186 J $kcal^{-1}$) = 4.55 E19 J	(39)
5	Coal	Recoverable reserves = 5.19 E11 t coal eq. (hard coal) 5.12 E11 t coal eq (soft coal) Energy = (5.19 E11t) (27.9 E9 J t^{-1}) ÷ (5.12 E11t) (13.9 E9 J t^{-1}) = 2.16 E22 J_{coal}	(34) (34)
6	Crude oil	Recoverable reserves = 1.39 E11 t oil Energy = (1.39 E11 t oil eq.) x (4.186 E10 J t^{-1} oil eq.) = 5.82 E21 J_{oil}	(34)
7	Natural gas	Recoverable reserves = 1.4 E14 m^3 Energy = (1.4 E14 m^3) (37.7 E6 J m^3) = 5.28 E21 $J_{nat.gas}$	(34)
8	Metals (Al,Cu,Pb,Fe,Zn)	Total recoverable reserves = 1.735 E11 t = 1.735 E17 g	(37)
9	Uranium	Recoverable reserve = 1.5 E6 t Energy = 1.5 E6 t) (1 E6 g t^{-1}) (0.007) (7.95 E10J g^{-1}) = 8.35 E20 J_U	(37)
10	Phosphate	Recoverable reserves = 11.0 E9 t = 11.0 E15 g	(36)

ble 3 summarizes the emergy indices for the biosphere in 1995, based on the data from Table 1. Figure 6 shows the change in these indices since 1950. The percent of total emergy flux in the biosphere that is renewable has declined from 68% in 1950 to 32% renewable today. The global ELR increased from 0.47 to 2.17, an increase in environmental stress of over 350%. Due to the simultaneous decline in the global emergy yield ratio, the global sustainability index has declined nearly 910% from 7.82 to 0.73.

Table 4 gives comparative indices for the globe and seven countries (Ecuador, Thailand, Chile, Mexico, USA, Italy, and Taiwan). Here, the Emergy Yield Ratio is more an index of "locally sustainable production", than a yield ratio. When the flows of the global or a national economy are used, the EYR divides total production by the emergy flux from nonrenewable resources and therefore expresses production per unit of nonrenewable investment.

The Emergy Sustainability index given in the last column of Table 4 is a measure of an economy's long-term global position relative to others. Low ESIs (USA, Taiwan, Italy) are indicative of economies that import a large fraction of their total emergy use and consume a relatively large percentage of total emergy in the form of nonrenewable emergy. Sustainability of an economy is a function of renewable emergy flows, the extent to which it depends on imports, and its load on the local environment. While reliance on renewable resources and minimization of imports are important measures of sustainability, when they are combined with an index of environmental stress the aggregate measure, ESI, provides a multi-dimensional measure of long-term sustainability. The higher this index the more an economy relies on locally renewable energy sources *and* minimizes imports and environmental load. Sustainability can be measured at the global level, the regional or national level, or at the scale of individual economic activities (25).

Table 3. Global emergy indices (1995).

Name of Index	Definition (Fig. 4)	Index value[a]
Environmental Loading Ratio (ELR)	(SR + N)/R	2.17
Percent Renewable (%Renew)	R/(R + SR + N)	0.32
Emergy Yield Ratio (EYR)	(R + SR + N)/ N	1.59
Sustainability Index (SI)	(EYR) / (ELR)	0.73
Emergy Dollar Ratio (E12 sej $$^{-1}$)	(R + SR + N)/ GWP[b]	1.10

a. Data from Table 1
b. GWP = Gross World Product = 27.1 E12 $US (18)

EMERGY AND PUBLIC POLICY DECISION MAKING

The complex questions concerning the fit of humanity in the biosphere require that we look at things from a different perspective. Until very recently, the emergies released by humans were small, compared with the renewable driving emergy. Not so today. At the present time society releases about twice the emergy in slowly-renewable and nonrenewable resources than flows into the biosphere from renewable sources. Questions arise like: How best to fit humans and environment together? How do we develop an understanding of the workings of the biosphere with humans in it? How do we make decisions concerning the allocation and use of environmental services and natural capital? These are difficult questions and will require our concerted efforts. One thing is for sure, it cannot be done within a system paradigm that only recognizes/uses human-centered systems of valuation. When neoclassical economics is used to answer questions concerning fit, the answers inevitably are in favor of more development, greater use of resources, further exploitation of the environment. It may be time to question the reality created by humans that results from their utility theory of value.

Decisions at the scale of biosphere and society require a valu-

Figure 4. Growth phases of an economic system showing early fast growth phase, a transition phase, and a phase of decline. Criteria for sustainability may differ depending on phase.

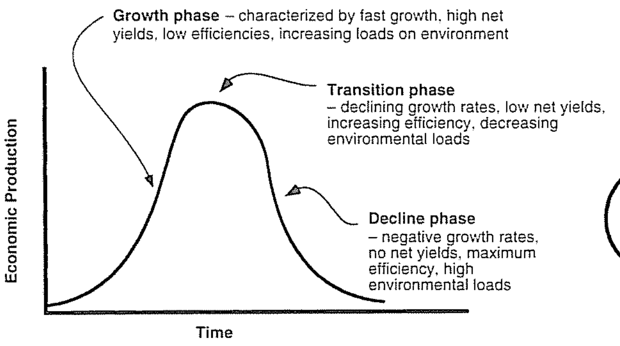


Figure 5. Simplified systems diagram of the biosphere showing the calculation of various emergy indices of sustainability.

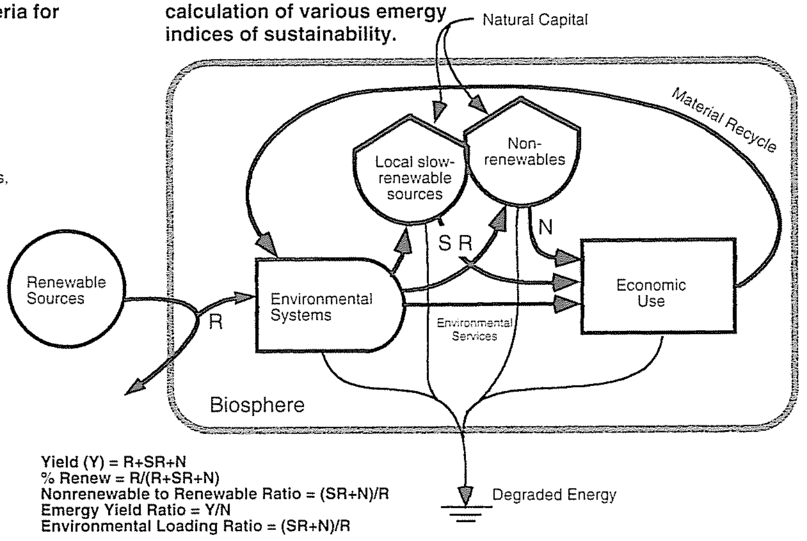


Figure 6. Graphs of the emergy indices of the biosphere for the years 1950, 1975, and 1995.

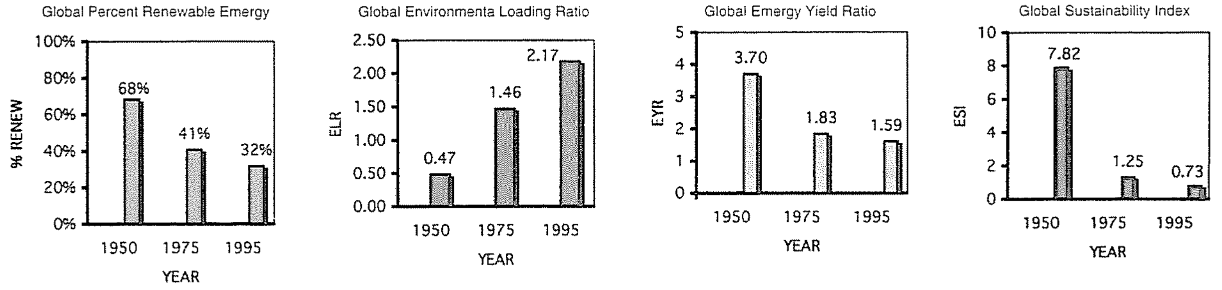


Table 4. Emergy indices of national economies and the world economy (25).

Ref	Country	Total Emergy (sej yr^{-1})	Emergy Flow (sej yr^{-1}) Renewable (R)	Slo-renewable (SR)	Nonrenewable (N)	%Renew[a]	Emergy Indices EYR[b]	ELR[c]	ESI[d]
1	Ecuador (1986)	9.64 E22	4.81 E22	4.21 E22	6.20 E21	50%	15.5	1.0	15.48
2	Thailand (1984)	1.52 E23	7.60 E22	2.70 E22	4.85 E22	50%	3.1	1.0	3.14
3	Chile (1994)	1.95 E23	6.81 E22	6.92 E22	5.78 E22	35%	3.4	1.9	1.81
4	Mexico (1989)	6.12 E23	1.39 E23	3.66 E23	1.08 E23	23%	5.7	3.4	1.66
5	WORLD (1995)	2.99 E25	9.44 E24	1.66 E24	1.88 E25	32%	1.6	2.2	0.73
6	USA (1983)	7.91 E24	8.24 E23	5.18 E24	1.90 E24	10%	4.2	8.6	0.48
7	Italy (1989)	1.27 E24	1.21 E23	3.57 E23	7.89 E23	10%	1.6	9.5	0.17
8	Taiwan (1990)	2.14 E23	2.13 E22	4.02 E22	1.52 E23	10%	1.4	9.0	0.16

Notes:
a. Percent Renewable = R/(R÷SR÷N)
b. Emergy Yield Ratio = (R÷SR÷N)/N
c. Environmental Loading Ratio = (SR÷N)/R
d. Sustainability Index = EYR/ELR

References: 1. (40), 2. (24), 3. (41), 4. (42), 5. This study, 6. (1),7. (43), 8. (44).

ation system free of human bias. It is not surprising that development of resources, exploitation of global fisheries, and forests continues unimpeded when evaluated using economic value systems based on willingness-to-pay. The only things given value are those things that humans decide are valuable. The only values given things are human values. Neoclassical economic valuation cannot overcome the fact that its main underlying principle is that value is derived from utility and that utility is measured in human terms. Thus things must be useful to humans for them to have value. Recently, there has been much activity in the economic literature, especially in the "ecological economics" literature, concerning alternative methods of assigning economic values. Most of this activity is aimed at finding some way to "fix" economic theory to accommodate nonmarket goods. Unfortunately, economic values grounded in the neoclassical paradigm are based on human centered values, whether they be willingness-to-pay, contingency valuation, replacement cost measures, or other similar approaches (2, 3, 26–28). Money and the system of prices derived from economic theory have difficulty valuing environmental resources or natural capital correctly, and to make up markets or develop "pseudo-market based" measures by asking citizens what they are willing to pay, or what they are willing to accept, is not science, it is public opinion. Using "hedonic property price procedures" (3, 29) to value global ecosystems is tantamount to saying that because humans prefer to live on the southern coast of California, USA (based on property values), the marine ecosystems of southern California are more valuable to biosphere processes than other ecosystems where property values are lower. How is it possible that human preferences for a nice view and romantic sunsets has anything to do with ecological processes of the biosphere?

In another recent approach, Pimentel et. al. (5) have tried to evaluate total economic benefits of biodiversity in the USA and worldwide by pricing soil formation, waste disposal, pollination, ecotourism, and other items. The evaluation depends on prices derived from market values of equivalent services. For example, they value the environmental service of waste disposal (organic matter recycled by decomposers) based on the USD costs of collecting and disposing of organic wastes in USA cities. While they use biophysical data for their assessment of environmental services, the evaluation still relies indirectly on willingness-to-pay since economic price derived from market prices of equivalent services is a direct reflection of human value.

A biosphere perspective, one that seeks to balance humanity and environment, needs a valuation system free of human bias. We are not suggesting that humans are unimportant, instead we are saying that neoclassical economics (and its reliance on human utility values) has no place in the policy debates surrounding resource allocation and preservation of the biosphere. No amount of tinkering with the present economic paradigm can al-

Box
Definitions

Further discussion and definitions can be found in Odum (1); Brown and Ulgiati (25); Ulgiati et al. (23).

Energy: Sometimes referred to as the ability to do work. Energy is a property of all things which can be turned into heat and is measured in heat units (BTUs, calories, or joules).

Emdollar (or EM$): A measure of the money that circulates in an economy as the result of some process. In practice, to obtain the emdollar value of an emergy flow or storage, the emergy is multiplied by the ratio of total emergy to Gross National Product for the national economy.

Emergy: An expression of all the energy used in the work processes that generate a product or service in units of one type of energy. Solar emergy of a product is the emergy of the product expressed in equivalent solar energy required to generate it. Sometimes its convenient to think of emergy as energy memory.

Emjoule: The unit of measure of emergy, "emergy joule." It is expressed in the units of energy previously used to generate the product; for instance the solar emergy of wood is expressed as joules of solar energy that were required to produce the wood.

Nonrenewable Emergy: The emergy of energy and material storages like fossil fuels, mineral ores, and soils that are consumed at rates that far exceed the rates at which they are produced by geologic processes.

Production: Production measured in emergy is the sum of all emergy inputs to a process.

Renewable Emergy: The emergy of energy flows of the biosphere that are more or less constant and reoccurring, and that ultimately drive the biological and chemical processes of the earth and contribute to geologic processes.

Transformity: The ratio obtained by dividing the total emergy that was used in a process by the energy yielded by the process. Transformities have the dimensions of emergy/energy (sej J^{-1}). A transformity for a product is calculated by summing all of the emergy inflows to the process and dividing by the energy of the product. Transformities are used to convert energies of different forms to emergy of the same form.

ter the logic trap of willingness-to-pay. Human preference cannot value ecological processes or environmental resources since these processes are outside the so called economic sphere.

Outlined in this paper is a method of valuation that is based on the principle that value is derived from what goes into something rather than on what one gets out of it. We have little difficulty in recognizing that the more effort we put into something, the more valuable it is. However, this is counter to the way most humans think about goods and services, and as a result difficult at first to accept. The question always arises, how can you say something has this or that value… what if it's not used… what if I don't want it… does it still have that value? Yes. Emergy is a biosphere value, it is the energy the biosphere invests in its goods and services (including the goods and services of society). The more that is invested, the greater the value (30).

The fact that humans now release more emergy than is inflowing from the renewable driving emergies, suggests that we, now more than ever, need to be good stewards of the biosphere. Our relationship to the biosphere changed in 1962 when the emergy released by humans equaled and began to exceed the renewable driving emergies (Fig. 2). Our awareness began to shift as we began to see the effects of our numbers. Now as our nonrenewable energy supplies dwindle, our awareness must shift again. How do we live in a lower energy world? What is the economic paradigm that will help humanity to develop necessary symbiotic interfaces with the biosphere? We believe that it is not a human-centered valuing paradigm based on the flows of money, but is a biophysical paradigm, based on the flows of energy that drive and sustain all biosphere processes.

Emergy indicators show cause for alarm. Things are not getting better from a global perspective, they are getting worse. What is required is a concerted effort to understand society's place in the biosphere. Important to this undertaking are methods of analysis that produce synthesis and comprehension of wholeness. The biosphere is one system, that includes humans. We should use methods for quantification and valuing that recognize the whole, not just one end of the hierarchy, the human end. It may be time for a paradigm shift.

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