ELSEVIER

Ecological Engineering 9 (1997) 51-69

ECOLOGICAL ENGINEERING

Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation

M.T. Brown [a,*], S. Ulgiati [b]

[a] *Department of Environmental Engineering Sciences and Center for Wetlands, University of Florida, Gainesville, FL 32611, USA*

[b] *Department of Chemistry, University of Siena, Pian dei Mantellini 44, 53100, Siena, Italy*

Received 20 July 1996; received in revised form 28 June 1997; accepted 7 July 1997

Abstract

This paper provides a reference set of indices based on emergy, for the evaluation of ecotechnological processes and whole economies. Indices of emergy yield ratio (EYR), environmental loading ratio (ELR), and emergy investment ratio (EIR), among others, are stressed, and a new index the emergy sustainability index (ESI) is defined. The emergy indices for a given system are shown to be functions of renewable, nonrenewable and purchased emergy inflows. Indices are given for several ecological engineering activities including oil spill restoration, land reclamation and wastewater recycle through wetlands, several production systems, and several national economies to demonstrate their usefulness. Ecological engineering involves both natural and engineered systems and the flows of renewable and nonrenewable energy, the appropriate amounts of which are important to determine if they are to result in sustainable use of resources. The sustainability index can be used to evaluate appropriate nonrenewable investments in eco-technology to maximize their performance. Sustainability of economies is shown to be a function of the net yield of the economy and its 'load' on the environment. The trends of these indices can be monitored over time and provide useful information about the dynamics of economic systems within the carrying capacity of the environment in which they develop. When a particular sector or production process is focused on, instead of a national economy, emergy based indices can provide

---

* Corresponding author.

PII S0925-8574(97)00033-5

insights into the thermodynamic efficiency of the process, the quality of its output, and the interaction between the process and its surrounding environment.

Keywords: Emergy; Sustainability; Emergy yield; Environmental loading; Ecological engineering

---

1. Introduction

A main problem in evaluating sustainability of activities and potential energy sources is the interplay between environmental impacts and net contributions to economic processes. It is quite clear that without a net contribution, an energy source cannot provide energy in excess of what it costs to provide it. On the other hand, if an energy source has a high net yield, but causes environmental impacts larger than its contribution, it too cannot provide energy for increases in order or even maintaining existing order, for it costs society more in maintenance and repair than it provides in new order. In a recent contribution (Ulgiati et al., 1995) an index of net contribution to society, called end use net emergy was proposed. In the present contribution we review several emergy based indices used to evaluate process and systems and propose an index of sustainability that considers both a resource's contribution and its environmental impact.

2. Sustainability and steady state paradigms

Steady state and no-growth paradigms have been proposed in the last two decades; many scientists and policy makers believed that human societies can grow to a special state, where resource supply and use are balanced. This should be considered a sustainable steady state (Goldsmith et al., 1972; Daly, 1977). After the balance point has been reached, only refinement of societies (better use of available resources) instead of growth (size and consumption increase due to a larger supply of resources) should be pursued (Daly, 1977). More recently, Daly (1990) has proposed a 'quasi-sustainable use of nonrenewables, by limiting their rate of depletion to the rate of creation of renewable substitutes.'

The impossibility, not just of growth, but also of a steady state economy has been stated by Georgescu-Roegen (1976), who claimed that a finite amount of available resources could only support a population for a limited time, after which the human species would have to disappear. The only possible trend for humankind is a steady declining state.

It seems that these authors did not take into consideration that the whole planet is a self-organizing system, where storages of resources are continuously depleted and replaced, at different rates, and matter is recycled and organized within a self-organization activity driven by solar, geothermal and gravitational energy. A clear assessment of this behavior has been recently provided by Odum (1994a,b): 'The real world is observed to pulse and oscillate. There are oscillating steady states. In most systems, including those which people are part of, storages are observed to fill and discharge as part of oscillations...If the oscillating pattern is the normal one, then sustainability concerns managing, and adapting to the frequencies of oscillation of natural capital that perform best. Sustainability may not be the level 'steady-state' of the classical sigmoid curve but the process of adapting to oscillation. The human economic society may be constrained by the thermodynamics that is appropriate for each stage of the global oscillation.'

An 'optimum performance' in resource uptake and use results from a self-organization process in Odum's statements (Odum, 1987, 1988) of Lotka's Maximum Power Principle (Lotka, 1922). According to this principle, 'natural selection tends to make the energy flux through the system a maximum, so far as compatible with the constraints to which the system is subject' (Lotka, 1922). Systems self-organize for survival and under competitive conditions, systems prevail when they develop designs that allow for maximum flow of available energy. Systems reinforce, through feedbacks, such energy flow and structure which promotes these kinds of feedbacks. Very often 'living and also man-made processes do not operate at the highest efficiencies that might be expected of them...In natural systems, there is a general tendency to sacrifice efficiency for more power output....' (Odum and Pinkerton, 1955). Optimum efficiency and thus optimum self-organization cannot be obtained forever. As environmental conditions change, also the response of the system will adapt, so that maximum power output can be maintained. In this way systems tune their thermodynamic performance according to the changing environment.

In this paper we suggest that maximum performance from ecological engineering activities, economic activities and potential energy sources is obtained 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. The greater the use of the environmental resources, 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. Additionally, we suggest that the ratio between yield of processes (or economies) and their load on the environment can be used as an index of sustainability.

3. Environmental accounting based on emergy

Emergy theory has developed over the last three decades (Odum, 1996) as a tool for environmental policy and to evaluate quality of resources in the dynamics of complex systems. A complete assessment of the methodology cannot be provided here, but for which the reader may like to refer to published reports (Odum, 1988; Ulgiati et al., 1994a; Brown and McClanahan, 1996; Brown and Herendeen, 1996; Odum, 1996).

In short, emergy is defined as the sum of all inputs of energy directly or indirectly required by a process to provide a given product when the inputs are expressed in the same form (or type) of energy, usually solar energy. Most often, inputs to a process are the result of another process (or a chain of processes), in which energy has been concentrated and upgraded. Thus emergy is derived by summing all inputs (expressed in equivalent energy of a single form; such as solar energy) used in the chain of processes that yielded the output in question. On a unit basis, one joule or gram of a given output is produced by dissipating a given amount of solar equivalent energy. The amount of input emergy (expressed as solar emergy) per unit output energy is termed, *solar transformity*. The solar transformity gives a measure of the concentration of solar emergy through a hierarchy of processes or levels; it can therefore be considered a quality factor, a measure of the global process supporting the item under study. Once transformities are known for classes of items, the total emergy of an item can be expressed as:

$$\text{Emergy} = \text{available energy of item} \times \text{transformity}$$

Solar emergy is usually measured in solar emergy joules (sej), while solar transformity is expressed as solar emergy joules per joule of product (sej/J). When an item is expressed in units different than joules, for instance as grams, the quality factor is emergy/mass (sej/g).

4. Transformity, renewability, and environmental load

Renewable energy sources are the constant and reoccurring energy flows of the biosphere that ultimately drive the biological and chemical processes of the earth and contribute to geologic processes. Sometimes resources that result from these energy sources (i.e. wood or biomass) are considered renewable resources. In this case, to be renewable their replacement time must be at least as fast as their use rate, otherwise, it is considered a nonrenewable resource if use rate exceeds replacement rate. As transformity is a measure of the convergence of emergy flows to provide a given result, it is an indirect measure of the renewability of a final product. The more energy that is converged to produce a resource, the longer the replacement time (Doherty, 1995) and the higher its transformity.

Transformity is also an indirect measure of how much activity of the environment, either directly or indirectly, has been required to manufacture a given product. In essence, the higher the transformity of a resource or energy the greater the environmental activity necessary to produce it. In like manner, the use of high transformity materials and energy requires large flows of environmental energy for matching. So transformity is an indicator of past environmental contributions to a resource and future load on environmental systems that will result from its use.

5. 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 Fig. 1 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. Decisions regarding processes under human control, where a sustainable pattern is not guaranteed and choices have to be supported by careful consideration of many different patterns, require that criteria for judging sustaibability need to include several factors: 1) the net yield of the process, 2) its environmental load, 3) its use of nonrenewables.

Several emergy indices have been defined and discussed elsewhere to illuminate these different aspects of sustainability (Odum and Odum, 1983; Doherty et al., 1992; Odum et al., 1993; Ulgiati et al., 1994a; Brown and McClanahan, 1996; Odum, 1996). Using Fig. 2, several of these indices are defined as follows:

1. Percent renewable (%Renew) is the percent of the total energy driving a process that is derived from renewable sources ($R/(R+N+M)$). In the long run, only processes with high %Renew are sustainable.

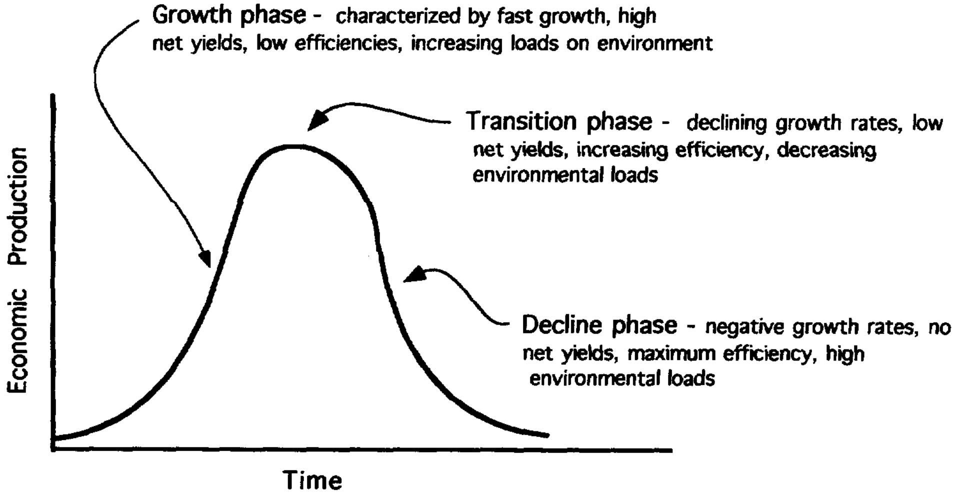
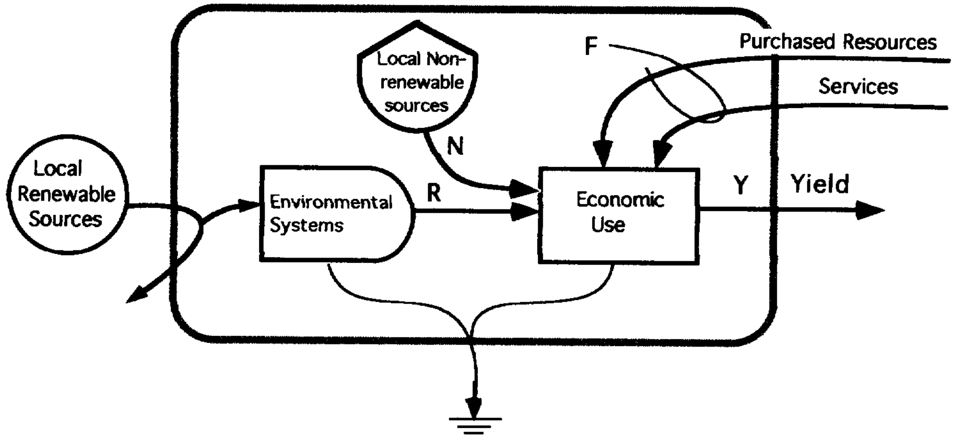


Fig. 1. Growth phases of an economic system showing early fast growth phase, a transition phase, and a phase of decline. Criteria for sustainability may differ depending on phase.



Yield (Y) = R+N+F
%Renew = R/(R+N+F)
Nonrenewable to Renewable Ratio = (N+F)/R
Emergy Yield Ratio = Y/F
Emergy Investment Ratio = F/(R+N)
Environmental Loading Ratio = (F+N)/R

Fig. 2. Emergy based indices, accounting for local renewable emergy inputs (R), local nonrenewable inputs (N), and purchased inputs from outside the system (F).

2. The nonrenewable to renewable ratio (NRR) is the ratio of nonrenewable energy contribution ($F+N$) to a process to the renewable contribution (R). High ratios indicate processes that match large amounts of nonrenewables to relatively small renewable flows of emergy.
3. The emergy yield ratio (EYR) is the ratio of the emergy of the output Y divided by the emergy of those inputs F to the process that are fed back from outside the system under study. It is an indicator of the yield compared to inputs other than local and gives a measure of the ability of the process to exploit local resources.
4. The environmental loading ratio (ELR) is the ratio of purchased F and nonrenewable indigenous emergy N to free environmental emergy R. It is an indicator of the pressure of the process on the local ecosystem and can be considered a measure of the ecosystem stress due to production activity.
5. The emergy investment ratio (EIR) is the ratio of emergy F fed back from outside the system to the indigenous emergy inputs ($N+R$). It gives an evaluation if the process is a good user of the emergy that is invested, in comparison with alternatives. It is not an independent index, but it is linked to the above EYR.

6. An aggregate measure of yield and sustainability

Sustainability is a function of yield, renewability, and load on the environment. 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 damages that threaten long term sustainability. Clearly an index that incorporates these aspects would shed light on sustainability issues. To develop the index we first give formulae for the emergy yield ratio, and environmental loading ratio using Fig. 2 as a guide for lettered pathways.

The emergy yield ratio can be written as:

$$\begin{aligned}
\mathrm{EYR} &= Y/F = (F+R+N)/F \\
&(\sum_i F_i \mathrm{Tr}_i + \sum_k R_k \mathrm{Tr}_k + \sum_j N_j \mathrm{Tr}_j)/\sum_i F_i \mathrm{Tr}_i \\
&= 1 + \sum_k R_k \mathrm{Tr}_k / \sum_i F_i \mathrm{Tr}_i + \sum_j N_j \mathrm{Tr}_j / \sum_i F_i \mathrm{Tr}_i \\
&= 1 + \eta + \vartheta \qquad (1)
\end{aligned}$$

where: F = purchased inputs, R = renewable inputs, N = nonrenewable inputs, Tr = transformity

In Eq. (1) η and ϑ are respectively the ratios of the local renewable and nonrenewable emergy inputs to the purchased inputs. The inputs to the system (R_k, N_j and F_i), are measured by their Gibbs free energy content [= (mass in grams) × (Gibbs free energy per gram)], then multiplied by their respective transformities (Tr). When EYR = 1, then both $\eta = 0$ and $\vartheta = 0$, i.e. the process is not exploiting any local resource R_k or N_j . On the other hand, when EYR > 1 it follows that $\eta + \vartheta > 0$. The larger the amount of local resource exploited in the process, the higher η or ϑ, and consequently the higher the Emergy Yield Ratio. Thus EYR is a measure of the actual exploitation of local resources, renewable or not. Of course, the same value of the Emergy Yield Ratio can result from high η and low ϑ or vice-versa.

The Environmental Loading Ratio ELR can provide additional information to EYR. We may write:

$$\begin{aligned}
\mathrm{ELR} &= (F+N)/R \\
&= \sum_i F_i \mathrm{Tr}_i / \sum_k R_k \mathrm{Tr}_k + \sum_j N_j \mathrm{Tr}_j / \sum_k R_k \mathrm{Tr}_k \\
&= 1/\eta + \vartheta/\eta \\
&= (1+\vartheta)/\eta \qquad (2)
\end{aligned}$$

When EYR is high due to a high value of η, then ELR is small, thus indicating a small environmental stress. On the contrary, when a high value of ϑ is contributing to EYR, then ELR increases, thus meaning a larger environmental stress. Therefore, a simultaneous increase of both EYR and ELR, indicates that a larger stress is being caused to the environment; on the contrary, when EYR increases and ELR decreases, the process is less of a load on the surrounding environment. In general, even when EYR is large, ELR can be large or small, depending upon the reciprocal relationship between η and ϑ. ELR may also be very large when $\eta \ll 1$, no matter the value of ϑ. A possible meaning of this behavior could be that processes that do not run on renewable resources are by definition a source of stress for the environment, as they ultimately are not sustainable patterns of matter organization (Murota, 1987; Tsuchida and Murota, 1987).

Finally, as we are interested in getting the highest yield ratio versus the lowest environmental loading, a measure of this ability can be provided by the ratio EYR/ELR:

$$S(\eta, \vartheta) = \mathrm{EYR}/\mathrm{ELR} = (1 + \eta + \vartheta)\eta/(1 + \vartheta) =$$
$$= \eta + \eta^2/(1 + \vartheta) \qquad (3)$$

which becomes an aggregate measure of yield and environmental loading, i.e. a sustainability function for a given process (or economy) under study. $S(\eta, \vartheta)$ is graphed in Fig. 3 as a function of both variables (ranging from 0 to ∞), and shows a different sensitivity to variations of the components of the emergy inputs. $S(\eta, \vartheta)$ clearly decreases when ϑ is increasing. An increase of the function is shown for increasing values of η, with a parabolic trend at low ϑ values, tending to a linear one when ϑ becomes very large. It is important to keep in mind that η and ϑ are ratios of local renewable and nonrenewable inputs to feedbacks from outside: the number of variables are three, not just two. This means that sustainability is not just provided by a low requirement of feedbacks, but by a large renewable input in comparison with the feedback itself, that may also be large. Therefore, a large input from outside the process can also be useful and sustainable, provided that it allows the exploitation of a large amount of emergy from renewable sources. As shown in the following sections, we apply the index $S(\eta, \vartheta)$ to agriculture, biofuels production, other processes, and national economies obtaining a hierarchy of the different outputs, scaled by a decreasing value of $S(\eta, \vartheta)$.

Finally, the Emergy Investment Ratio is defined as:

$$\mathrm{EIR} = F/(R + N) = 1/(\eta + \vartheta)$$

It follows that:

$$\mathrm{EYR} = (N + R + F)/F = 1 + (N + R)/F = 1 + 1/\mathrm{EIR} \qquad (4)$$

linking EYR and EIR, as already noted. Therefore, it is not always required to calculate both indices. When a process is considered and the emergy of the final product is easily calculated, the EYR may be used to assess the ‘efficiency’ of the system in local resources processing. However, when a regional economy is studied, it is conceptually difficult to evaluate an EYR for the system, since economies by definition do not have a yield to a next larger economy. In such circumstances, the

EYR is more an index of total production divided by imported emergy. Once an EYR is calculated, the sustainability index can be used to compare regional or national economies.

7. Application of emergy indices of sustainability

Ecological engineering activities involve the effective use of renewable and nonrenewable emergy contributions in processes that should provide a net benefit to society and have low environment load. In this way they may be more sustainable than conventionally engineered technological systems. Table 1 gives results of emergy analysis of several ecological engineering activities from the restoration of impacted lands to wastewater recycle through natural and constructed wetlands. For comparative purposes, results are given for Italian agriculture and a conventional, advanced wastewater treatment (AWT) plant.

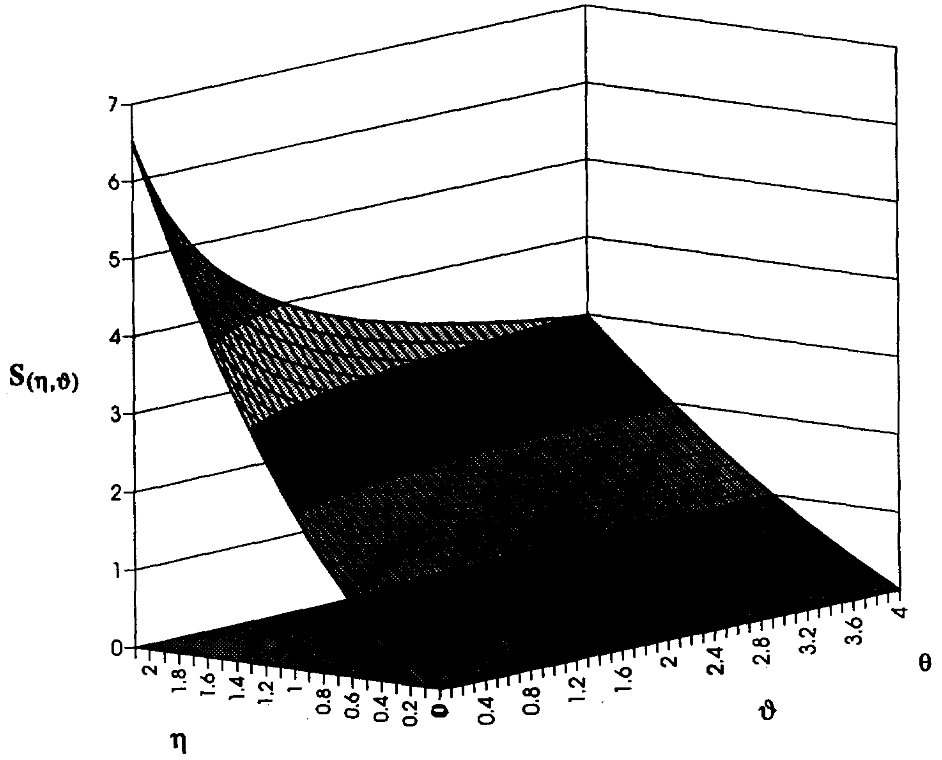


Fig. 3. Simulation of the behavior of the emergy sustainability index (Eq. (3)) versus increasing amounts of renewable and nonrenewable locally exploited resources per unit investment. η is the ratio of renewable inputs to purchased inputs and ϑ is the ratio of nonrenewable inputs to purchased inputs. $S(\eta, \vartheta) = \eta + \eta^2/(1 + \vartheta)$.

Table 1
Emergy indices of ecological engineering activities

Activity	Empower density	Emergy flow (sej/year)			Emergy indices					
		Renewable (R)	Nonrenewable (N)	Purchased (F)	%Renew[a]	NRR[b]	EIR[c]	EYR[d]	ELR[c]	SI[f]
Oil spill reclaimation (Alaska)[g]	5.6	2.15E+21	2.83E+19	1.54E+21	58	0.01	0.70	2.4	0.7	3.33
Phosphate reclaimation (FL, USA)[h]	3.9	4.38E+15	2.85E+13	3.52E+15	55	0.01	0.80	2.3	0.8	2.78
Natural wastewater wetland (SC, USA)[i]	12.7	3.76E+17	3.08E+18	1.93E+17	10	8.19	0.06	18.9	8.7	2.17
Oil spill reclamation (Venezuela)[j]	2.1	1.02E+18	6.47E+17	1.13E+18	37	0.63	0.68	2.5	1.7	1.43
Agriculture (cropland, Italy, 1989)[k]	5.0	2.40E+22	1.33E+21	5.93E+22	28	0.06	2.35	1.4	2.5	0.56
Constructed wastewater wetland (FL, USA)[l]	179.0	2.63E+18	8.45E+19	1.27E+18	3	32.18	0.01	69.6	32.7	2.13
Convetional AWT plant (FL, USA)[m]	22502.5	9.11E+16	6.19E+18	3.62E+18	1	67.94	0.58	2.7	107.7	0.03

[a] Percent renewable = $R/(R+N+F)$.

[b] Norenewable to renewable ratio = N/R.

[c] Emergy investment ratio = $F/(R+N)$.

[d] Emergy yield ratio = $(F+R+N)/F$.

[e] Environmental loading ratio = $(F+N)R$.

[f] Sustainability index = EYR/ELR.

[g] Alaskan oil spill reclamation (data from Brown et al., 1993). Area = 6.7E9 m^2, Renewable emergy inflow = sum of chemical potential of freshwater inflow and tidal currents in area of oil spill multiplied by three year recovery time. Nonrenewable emergy inflow = volume of spilled oil divided by 3 year recovery time. Purchased emergy inflow = sum of human services and fuel used in clean up divided by 3 year recovery time

[h] Reclamation of phosphate mined land in Florida (Brown, 1996. Emergy evaluation of phosphate mining in central Florida, unpublished data). Area = 1E4 m^2. Renewable emergy inflow = chemical potential energy of rainfall multiplied by 25 year recovery time. Nonrenewable emergy flow = soil loss estimated as 2 g/m^2 multiplied by half recovery time. Purchased emergy inflow = human services used in reclamation ($55 000 per arce) divided by 25 years.

[i] Wastewater wetland treatment system using natural wetland (data from US Environmental Protection Agency, 1993). Area = 2.87E6 m^2. Renewable emergy inflow = chemical potential energy of rainfall. Nonrenewable emergy flow = emergy value of wastewater and constituents. Purchased emergy inflow = human services, structures, yearly O&M.

[j] Venezuelan oil spill reclamation (data from Prado-Jatar and Brown, 1997). Area = 8.9E5 m^2. Renewable emergy inflow = chemical potential of rainfall multiplied by 15-year recovery time. Nonrenewable emergy inflow = volume of spilled oil divided by 15 year recovery time. Purchased emergy inflow = human services used in clean up operation divided by 15-year recovery time.

[k] Italian agriculture (data from Ulgiati et al., 1993). Area = 1.69E11 m^2.

[l] Wastewater wetland treatment system using constructed wetland (data from Ramakrishna, 1994). Area = 4.94E6 m^2. Renewable emergy inflow = chemical potential energy of rainfall. Nonrenewable emergy flow = emergy value of wastewater and constituents. Purchased emergy inflow = human services, berms, structures, planting materials yearly O&M.

[m] Conventional advanced wastewater treatment system (data from Nelson, 1996). Area = 0.44E4 m^2. Renewable emergy inflow = chemical potential energy of rainfall. Nonrenewable emergy flow = emergy value of wastewater and constituents. Purchased emergy inflow = human services, plant structure, chemicals, yearly O&M.

Table 2
Emergy indices of products

Product	Transformity (sej/unit)	Energy flow (sej/year)			Emergy indices					
		Renewable (R)	Nonrenewable (N)	Purchased (F)	%Renew[a]	NRR[b]	EIR[c]	EYR[d]	ELR[e]	SI[f]
Hydroelectric plant (Thialand)[g]	1.5E5	1.30E+21	3.80E+21	5.00E+20	23	2.92	0.10	11.2	3.3	3.39
Corn (1 ha Italy)[h]	5.3E4	1.42E+15	7.80E+13	4.20E+15	25	0.06	2.80	1.4	3.0	0.45
Cultivated shrimp (1 ha-Ecuador)[i]	13.0E6	4.90E+20	0	1.69E+21	22	NA	3.45	1.3	3.4	0.37
Bio-ethanol (1 ha-Brazil)[j]	2.3E5	1.52E+15	5.08E+15	6.57E+15	12	3.34	1.00	2.0	7.7	0.26
Cement (1 kg-USA)[k]	6.3E8	2.00E+11	1.90E+12	1.00E+12	6	9.5	0.48	3.1	14.5	0.21
Fruit (1 ha-Italy)[l]	2.2E5	1.42E+15	7.80E+13	1.32E+16	10	0.06	8.82	1.1	9.4	0.12
Crude oil (Alaska)	5.3E4	8.50E+19	1.13E+23	8.16E+21	0	1333.3	0.07	14.9	1429.3	0.01

[a] Percent renewable = $R/(R+N+F)$.
[b] Nonrenewable to renewable ratio = N/R.
[c] Emergy investment ratio = $F/(R+N)$.
[d] Emergy yield ratio = $(F+R+N)/F$.
[e] Environmental loading ratio = $(F+N)R$.
[f] Sustainability index = EYR/ELR.
[g] Brown and McClanahan, 1996.
[h] Ulgiati et al., 1993.
[i] Odum and Arding, 1991.
[j] Ulgiati (unpublished manuscript) from data in De Carvalho Machedo, 1992.
[k] Brown and McClanahan, 1992.
[l] Ulgiati et al., 1993.

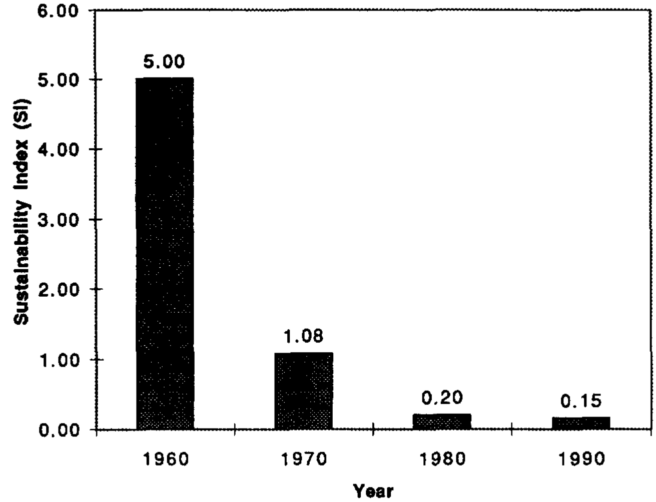


Fig. 4. Changes in the emergy sustainability index for Taiwan in the years 1960 through 1990. (data are from Huang and Shih, 1992)

These processes represent various cases where flows of purchased emergies are combined with renewable flows to increase self-organizational processes. In reclamation activities, purchased emergy is directed to increase the rate of repair and re-organization after significant environmental impacts at rates faster than would otherwise occur. In a previous paper (Prado-Jatar and Brown, 1997), it was suggested that net benefit from investment in reclamation should be evaluated based on the net difference between re-organization with and without purchased inputs. That is, for reclamation activities to be beneficial, they should result in increased self-organization greater than the emergy costs of reclamation. Here we suggest a second way to evaluate reclamation activities: by their emergy yield ratio and the intensity of the reclamation activity (ELR) combined in the emergy sustainability index (hereafter, ESI).

The recycle of wastewater through wetlands represents a special case where purchased emergy is combined with renewable emergy flows in processes where predominately natural systems perform 'waste treatment services'. The ESI relates the yield to the emergy intensity of the activity. While the ultimate goal of such systems is to process wastes in a manner that minimizes their negative impacts on environmental systems, if the intensity of the activity is too high, they begin to more resemble technological engineering solutions instead of eco-technological processes and their long term sustainability is questionable.

Table 2 gives the results of emergy analysis of various outputs for processes ranging from agricultural production to hydro-electric production of electricity. The products are ordered according to their ESI (last column). For the land-based systems (agriculture and shrimp) the data in the 4th, 5th, and 6th columns are yearly emergy flows based on 1 ha of production. The emergy flows for the hydro-electric dam in Thailand are total flows per year where the purchased

Table 3
Emergy indices of national economies

Country	Total emergy (sej/year)	Emergy flow (sej/year)			Emergy indices					
		Renewable (R)	Nonrenewable (N)	Purchased (F)	%renew[a]	NNR[b]	EIR[c]	EYR[d]	ELR[e]	SI[f]
Papua New Guinea (1987)[g]	12.1E23	1.05E+23	1.06E+22	5.30E+21	87	0.10	0.05	22.8	0.2	15.64
Ecuador (1986)[h]	9.6E22	4.81E+22	4.21E+22	6.20E+21	50	0.88	0.07	15.5	1.0	15.48
Thialand (1984)[i]	15.2E22	7.60E+22	2.70E+22	4.85E+22	50	0.36	0.47	3.1	1.0	3.14
Mexico (1989)[j]	61.2E22	1.39E+23	3.66E+23	1.08E+23	23	2.64	0.21	5.7	3.4	1.66
USA (1983)[k]	790.5E22	8.24E+23	5.18E+24	1.90E+24	10	6.28	0.32	4.2	8.6	0.48
Italy (1989)[l]	126.5E22	1.21E+23	3.57E+23	7.89E+23	10	2.96	1.65	1.6	9.5	0.17
Taiwan (1990)[m]	21.4E22	2.13E+22	4.02E+22	1.52E+22	10	1.89	2.48	1.4	9.0	0.16

[a] Percent renewable $= R/(R+N+F)$.

[b] Nonrenewable to renewable ratio $= N/R$.

[c] Emergy investment ratio $= F/(R+N)$.

[d] Emergy yield ratio $= (F+R+N)/F$.

[e] Environmental loading ratio $= (F+N)R$.

[f] Sustainability index = EYR/ELR.

[g] Doherty et al., 1992.

[h] Odum and Arding, 1991.

[i] Brown and McClanahan, 1996.

[j] Brown and McClanahan, 1992.

[k] Odum, 1996.

[l] Ulgiati et al., 1994b.

[m] Huang and Shih, 1992.

energies have been amortized over the 50 year life expectancy of the dam. The flows for cement are those necessary to produce 1 kg of product.

Results given in the last three columns are comparable between a wide range of production processes since the indices are dimensionless ratios. Production of energy sources (hydro-power and Alaskan oil) have high emergy yield ratios. Most production processes that yield products have low emergy yield ratios because they are transformation processes that provide goods, rather than processes that yield energy sources. Load on the environment depends on the scale of the process and the extent to which the process uses nonrenewable and purchased emergy. The highest load by far was Alaskan oil production from north slope oil fields.

The highest ESI for the processes given in Table 2 was for production of electricity in a hydro-electric plant in Thailand. Hydro production of electricity is typically dominated by the flows of renewable energy sources. In locations where purchased inputs can be relatively small because of the geologic structure, the EYR can be relatively high. In this example, even with the large sediment loads that will be trapped behind the dam and will therefore not contribute to down stream productivity, the environmental loading ratio is relatively low, and the ESI indicates a moderately sustainable process. The lowest ESI for the processes given is for the north slope oil fields of Alaska. Its ELR was quite high because of exploitation of nonrenewable sources and environmental impacts. As a result the sustainability index indicates a process that has a very low, long term sustainability (the life of the oil field was estimated at about 30 years in the early 1970s).

Fitting the technological economy of humans to the global environmental self design is the largest ecological engineering scale. Table 3 gives comparative indices for seven countries (Papua New Guinea, Ecuador, Thailand, 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 a national economy are used, the EYR divides total production by imported emergy and therefore expresses production per unit of imports.

Despite its relatively low development status and small economy, Papua New Guinea is a country rich in natural resources and renewable emergy flows. Its EYR is one of the highest we have evaluated, and its relatively low economic development status produces an extremely low ELR. The country has the highest ESI of countries evaluated. On the other hand, countries such as Italy and Taiwan, that use large amounts of nonrenewable emergies and import a large fraction of total emergy use, have low EYRs and high ELRs.

The Emergy Sustainability index given in the last column of Table 3 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.

If historical data are available, the sustainability index calculated for different years may show important trends. The graph in Fig. 4 shows ESI for four different time periods in Taiwan's recent past based on the data of Huang and Shih (1992).

The index has declined rapidly over the last decades as Taiwan's economy has depended on larger flows of nonrenewable emergy and has increased imports of purchased energy and materials.

8. Conclusions

There are no clear trends in the relationship between EYR and ELR (Tables 1–3). It appears that high ELRs result from process with both high and low EYRs. Combined as a single ratio these two ratios provide an aggregate measure of economic (large yield) and environmental (low stress) compatibility. The higher the ESI, the higher the yield per unit environmental stress provided. This index might be used in two ways:

1. To compare different processes yielding the same product. The higher the ESI the larger the global (economic and ecological) compatibility of the process in comparison with alternatives for the same product;
2. To evaluate technical and technological innovation. A process could be modified by introducing new patterns or technologies, towards a larger yield per unit environmental stress. This can be achieved by increasing the ability of the process to exploit locally renewable sources, or by decreasing the need of nonrenewable inputs from outside. The trend of an increasing ESI thus shows progress towards a more environmentally sound pattern of production for a given process.

When economies are evaluated as with the national economies given in Table 3, the EYR takes on a different meaning, although still a measure of net contribution of emergy to society. 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 renewable energy sources and minimizes imports and environmental load. The ESI can be used in two ways to evaluate regional economies:

1. To compare different economies in order to evaluate their relative long term global sustainability. Long term economic well-being may be better achieved by fostering the use of renewable emergy flows, protecting one's environment, and minimizing dependence on purchased emergy from abroad.
2. To follow trends in a single economy over time. Changes in the index suggest that global sustainability of an economy is increasing or decreasing depending on the direction of change of the index.

Of the countries evaluated (Table 3), Papua New Guinea (PNG) had the highest ESI, while the USA, Italy and Taiwan, the lowest. Some may argue that the 'quality-of-life' in these last two countries is much better than their comparison with PNG would suggest. While there is no doubt their citizens 'enjoy' far more consumer items than do citizens of PNG, we suggest that the level of consumerism in the USA, Italy and Taiwan as measured by the low ESI is indicative of high use of nonrenewable energy, large imports of purchased energy and materials, and large environmental stress. The population in PNG is not necessarily 'better off' than Americans, Italians or the Taiwanese in the short run, but their economy is probably more sustainable in the long run. In essence the ESI is inversely proportional to 'economic development status'.

In this paper, we have suggested the use of several indices based on emergy evaluations of processes and economies to evaluate their net contributions and their relative sustainability for the future. Like any index these are relative measures that require comparison between differing situations and processes so that perspective is gained.

From past experience, we believe that EYRs of less than about five are indicative of secondary energy sources and primary materials like cement and steel. Primary energy sources usually have EYRs greater than five. Further, processes that yield products with EYRs less than two probably do not contribute enough to be considered an energy source, and act more as consumer products than energy sources.

We are just beginning to explore the relative scale of ELR. Again from past experience, it appears that low ratios (around two) are indicative of relatively low environmental impacts (or processes that use large area of a local environment to 'dilute impacts'). ELRs greater than ten are indicative of relatively concentrated environmental impact, and those between three and ten might be considered moderate. Extremely high ELRs, like that of the AWT plant (Table 1) or Alaskan north slope oil (Table 2) result from the very large flows of concentrated fossil energies in a relatively small local environment.

The proposed emergy sustainability index (ESI) is quite new. We have not evaluated many more systems and processes than are presented in this paper, thus we are inexperienced in the implications of its scale. As a relative measure, ESIs of less than one appear to be indicative of consumer products or processes, and those greater than one indicative of products that have net contributions to society. As it relates to economies, a low ESI (less than one) is indicative of highly developed 'consumer' oriented economies, and high ESI (greater than ten) is indicative of economies that have been termed 'undeveloped'. ESI ratios between one and ten are indicative of what have been termed 'developing economies'.

The use of these indices may help to increase understanding of the relative contributions of various alternative means of production and consumption. Ecological engineering activities may benefit from this approach because appropriate investments in ecologically engineered projects should result in sustainable systems that provide a net contribution to society. This approach may also shed new light on the sustainability of national economies, a question of concern to all citizens. We suggest that those economies that have the lowest sustainability ratios have the most to lose, in the long run, as the availability of nonrenewable energy and materials declines in the future. As always, the implications for policy decisions rests on the willingness of the apparatus to make decisions for the long run, in the short run. Maybe these emergy indices will help the decision process by providing quantifiable sustainability targets.

Acknowledgements

Partial support for this research activity (Ulgiati's contribution) has been provided by the Italian Ministry of University, within the program Chemistry-60%-1995. We would also like to acknowledge previous support to Brown by the Cousteau Society for evaluations of Thailand, Papua New Guinea and Mexico.

References

Brown, M.T., Herendeen, R.A., 1996. Embodied energy analysis and emergy analysis: a comparative view. Ecol. Econ. 19, 219–235.

Brown, M.T., McClanahan, T., 1992. Emergy Analysis Perspectives of Thailand and Mekong River Dam Proposals. A Research Report to the Cousteau Society. Center for Wetlands, University of Florida, Gainesville, FL, 63 pp.

Brown, M.T., McClanahan, T., 1996. Emergy analysis perspectives of Thailand and Mekong River dam proposals. Ecol. Modeling 91, 105–130.

Brown, M.T., Woithe, R.D., Odum, H.T., Montague, C.L., Odum E.C., 1993. Emergy Analysis Perspectives of the EXXon Valdez Oil Spill in Prince William Sound, Alaska. A Research Report to the Cousteau Society. Center for Wetlands, University of Florida, Gainesville. 122 pp.

Daly, H.E., 1977. Steady State Economics: the economics of biophysical equilibrium and moral growth. W.H. Freeman, New York.

Daly, H.E., 1990. Toward some operational principles of sustainable development. Ecol. Econ. 2, 1–6.

De Carvalho Machedo, I., 1992. The sugarcane agroindustry: its contribution to reducing CO_2 emissions in Brazil. Biomass Bioenergy 3 (2), 77–80.

Doherty, S.J., 1995. Emergy Evaluations of and Limits to Forest Production. Ph.D Dissertation, Department of Environmental Engineering Sciences, University of Florida, 115 pp.

Doherty, S.J., Brown, M.T., Murphy, R.C., 1992. Emergy analysis and public policy perspectives for Papua New Guinea. A Research Report to the Cousteau Society. Center for Wetlands, University of Florida, Gainesville, FL.

Georgescu-Roegen N., 1976. Energy and Economic Myths. Pergamon Press, New York.

Goldsmith, E., Allen, R., Allaby, M., Davoll, J., Lawrence, S., 1972. A blueprint for survival. The Ecologist 2 (1), 1–43.

Huang, S.-L., and T.-H. Shih. 1992. The evolution and prospects of Taiwan's ecological economic system. Proceedings: The Second Summer Institute of the Pacific Regional Science Conference Organization. Chinese Regional Science Assoc. Taipei, Taiwan.

Lotka, A.J., 1922. Contribution to the energetics of evolution. Proc. Nat. Acad. Sci. U.S.A. 8, 147–150.

Murota, T., 1987. Environmental economics of the water planet earth. In: Pillet, G., Murota, T. (Eds.), Environmental Economics. Leimgruber, Geneva, Switzerland, pp. 185-199.

Nelson, M., 1996. Emergy Analysis of the University of Florida Sewage Treatment Facility. Class project, EES 5306. Department of Environmental Engineering Sciences, University of Florida, Gainesville.

Odum, H.T., 1987. Living with complexity. In: Crafoord Prize in the Biosciences, Crafoord Lectures. Royal Swedish Academy of Sciences, Stockholm, pp. 19–85.

Odum, H.T., 1988. Self organization, transformity and information. Science 242, 1132–1139.

Odum, H.T., 1994a. The emergy of natural capital. In: Jansson, A.M., Hammer, M., Folke, C., Costanza, R. (Eds.), Investing in Natural Capital. Island Press, Covelo, CA, pp. 200–212.

Odum, H.T., 1994b. Emergy and Policy, vol. 1. Environmental Engineering Sciences, University of Florida, Gainesville, FL, pp. 25–29.

Odum, H.T., 1996. Environmental Accounting. Emergy and Environmental Decision Making. John Wiley and Sons, New York.

Odum, H.T., Arding, J.E., 1991. Emergy analysis of shrimp mariculture in Ecuador. Working Paper. Report to the Coastal Resources Center, University of Rhode Island, Narragansett, RI. Department of Environmental Engineering Sciences and Center for Wetlands, University of Florida. p. 114.

Odum, H.T., Pinkerton, R.C., 1955. Time's speed regulator: the optimum efficiency for maximum power output in physical and biological systems. Am. Sci. 43, 331–343.

Odum, H.T., Odum E.C., 1983. Energy Analysis Overview of Nations. WP-83-82; International Institute for Applied Systems Analysis, Laxenburg, Austria.

Odum, H.T., Odum, E.C., Brown, M.T., 1993. Environment and Society in Florida. Department of Environmental Engineering Science, University of Florida, Gainesville, FL.

Prado-Jatar, A., Brown, M.T., 1997. Interface ecosystems with an oil spill in a Venezuelan tropical savanna. Ecol. Eng. 8, 49–78.

Ramakrishna, H., 1994, Emergy and economic analysis of two constructed wastewater wetlands in Florida. Terminal masters project. Department of Environmental Engineering Sciences, University of Florida. Gainesville, FL.

Tsuchida, A., Murota, T., 1987. Fundamentals in the entropy theory of ecocycle and human economy. In: Pillet, G., Murota, T., Environmental Economics. Leimgruber, Geneva, Switzerland, pp. 11–35.

Ulgiati, S., Odum, H.T., Bastianoni, S., 1993. Emergy analysis of Italian agricultural system: the role of energy quality and environmental inputs. In: Bonati, L. Cosentino, U. Lasagni, M. Moro, G. Pitea D. Schiraldi, A. (Eds.), Trends in Ecological Physical Chemistry. Elsevier, Amsterdam, pp. 187–215.

Ulgiati, S., Odum, H.T., Bastianoni, S., 1994a. Emergy use, environmental loading and sustainability: an emergy analysis of Italy. Ecol. Modelling 73, 215–268.

Ulgiati, S., Bastianoni, S., Nobili, L., Tiezzi, E., 1994b. A thermodynamic assessment of biodiesel production from oil seed crops: energy analysis and environmental loading. In: Proceedings of the 27th ISATA Conference on Electric, Hybrid and Alternative Fuel Vehicles and Supercars (Advanced Ultralight Hybrids); ENEA, pp. 477–489.

Ulgiati, S., Brown, M.T., Bastianoni, S., Marchettini, N., 1995. Emergy based indices and ratios to evaluate the sustainable use of resources. Ecol. Eng. 5 (4), 519–531.

US Environmental Protection Agency, 1993. Carolina Bays: a natural wastewater treatment program. Pub. # EPA832-R-93-005a. Washington D.C.