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Monitoring patterns of sustainability in natural and man-made ecosystems

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Abstract

By means of a systemic analysis of the relationships among components of a system's web, the flows of energy and other resources converging to produce the output (biomass, biodiversity, assets, industrial products) can be evaluated on a common basis, i.e. the content of solar equivalent energy (hereafter, emergy; Odum, H.T., 1996. Environmental Accounting. Emergy and Environmental Decision-Making. Wiley, New York). Indices and ratios based on emergy flows can be calculated and used to evaluate the behavior of the whole system. Their dependence upon the fraction of renewable and nonrenewable inputs as well as locally available versus purchased inputs from outside is stressed. A new index of sustainability is also defined and applied to case studies. The trends of these indices 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 provide insights into the thermodynamic efficiency of the process, the quality of its output, and the interaction between the process and its surrounding environment.

Keywords: Indicators; Emergy; Energy; Sustainability

1. Introduction

Sustainability is the new fundamental issue of the 90's. Attempts were made to define this elusive concept in a clear and universally valid way, but the results of this effort have been many different and sometimes contrasting definitions. Sustainability has been found linked with: (a) availability of resources and carrying capacity; (b) efficiency in resources use; (c) equity in resources share; (d) intergenerational equity; (e) environmental dynamics and constraints. The existing different approaches to this concept very often underline only one side of many, so that an economic sustainability could be defined in a different way than an

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environmental sustainability or an intergenerational sustainability, and so on.

Many scientists and policy makers believed that human societies can grow to a special state, where resource supply and use are balanced suggesting this should be considered a sustainable steady state. On the contrary, Odum (1994) observed 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. Odum (1994) has recently provided a clear assessment of this behavior:

> The real world is observed to pulse and oscillate. There are oscillating steady states… 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.

According to Odum's statement, natural and man-made processes grow and decline by using up nonrenewable storages together with other renewable resources. As a consequence of this new paradigm of oscillating steady-states, sustainability cannot be assessed simply as yes or no: it needs be assessed as a continuum range of possible oscillating values, from 0 (a theoretical system only using nonrenewables) to $+\infty$ (a theoretical system only using renewables). Therefore, the first characteristic of a measurement approach to sustainability should be its ability to account for oscillating patterns.

This paper focuses on two aspects of sustainability. To be sustainable: (1) every process must be environmentally sound (ecological compatibility); (2) every process must provide a suitable yield to the society (economic compatibility). We believe that if a process produces stress on the environment, this will sooner or later affect the availability of important natural resources, as well as the life of future generations. On the other hand, if there is no yield, the process does not contribute to support the quality of life of human societies, which are likely to turn to other, maybe less safe, processes. Exploitation rate, efficient use, production of wastes, and pollutants, are all different components of these two aspects of sustainability. All of them partially contribute to the global sustainability of a process. The indicators that are introduced in this paper will be checked for their ability to account for both ecological and economic compatibility, provided that sustainability is defined according to Odum's statement as opposite to the idea of a steady level, lasting forever.

2. Environmental accounting based on emergy

Emergy accounting methodology 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., 1994; Brown and McClanahan, 1996; Odum, 1996; Brown and Herendeen, 1997).

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, the total emergy input 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, dissipating a given amount of solar equivalent energy produces 1 J or 1 g of a given output. 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. Transformity can be considered a quality indicator, according to Lotka-Odum's maximum power principle (Odum and Pinkerton, 1955; Odum, 1996). Self-organizing systems develop towards an optimum performance for maximum output. In order to maximize the power output, an optimum efficiency is often achieved by natural systems, which is not the highest theoretical efficiency that can be expected. Thus, the transformity of the output flow or product is the optimum transformity from a self-organizing process selected by a long trial-and-error performance. It can be considered a measure of quality, in the sense that the system operating at the optimum transformity is the best fitted to the present environmental conditions, i.e. is the one showing the optimum thermodynamic efficiency for maximum power output. Systems under human control usually did not have a long selection process, so that their efficiency and transformity may still be far from an optimum performance. The increase in efficiency of human controlled systems may be measured by changing transformities, towards the optimum value for maximum power output. According to changing environmental conditions and availability of (sometimes declining) resources, the optimum will change and consequently transformities are likely to oscillate over time. An average value among available transformities is very often the best choice.

The total solar emergy of an item can be calculated as the product of its available energy content by its solar transformity. It 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).

Once the total number of input flows has been identified and the total emergy driving a process has been evaluated, a set of indices and ratios can be calculated. These indices have been shown to be particularly useful when studying and comparing processes under human control, where a sustainable pattern is not guaranteed and choices have to be supported by careful consideration of many different parameters. Some of these indices and ratios have been defined and discussed elsewhere (Odum and Odum, 1983; Doherty et al., 1992; Odum et al., 1993; Ulgiati et al., 1994; Brown and McClanahan, 1996; Odum, 1996).

3. Diagramming emergy indices versus renewable and nonrenewable input flows

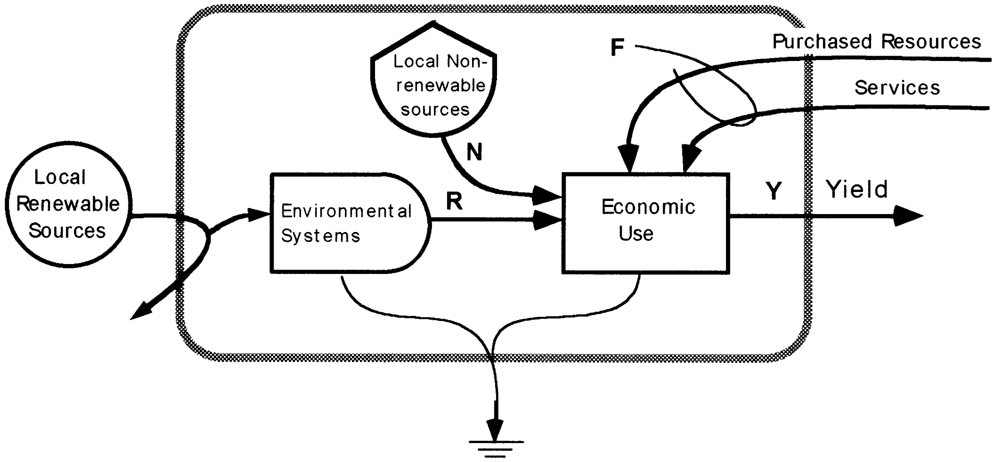
Three main emergy flows can be recognized when evaluating a system (Fig. 1): renewable flows from within (R), nonrenewable flows from within (N), and flows imported from outside the system (feedback flows, F), sometimes referred to as purchased flows.

The renewable flows (R) are: (i) flow limited (we cannot increase the rate they flow through the system); (ii) free (they are available at no cost); (iii) and locally available.

The nonrenewable flows from within (N) are: (i) stock limited (we can increase the rate of withdrawal, but the total available amount is finite in the time scale of the system); (ii) not always free (sometimes a cost is paid for their exploitation); (iii) locally available.

The feedback flows (F) may be: (i) stock limited (as above); (ii) never free; (iii) never locally available, always imported.

The above characteristics of emergy flows make it possible to calculate different indices that can be very useful when a system's behavior is monitored and investigated. According to Fig. 1 and footnotes of Table 1 and Table 2 and , three indicators can be defined as follows: (i) 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. If ϕ_R is defined as the fraction of renewable to total emergy used, the ELR is linked to ϕ_R by means of the equation $ELR = (1/\phi_R) - 1$. This means that the environmental loading (stress applied to the environment) can also be expressed by the fraction of renewable emergy driving a process. The lower the fraction of renewable emergy used, the higher the pressure on the environment; (ii) 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 with inputs other than local inputs and gives a measure of the



Yield (Y) = R+N+F
Φ_R= Fraction Renewable = R/(R+N+F)
Emergy Yield Ratio = EYR = Y/F
Environmental Loading Ratio = ELR = (F+N)/R
Emergy Sustainability Index = ESI = EYR/ELR

Fig. 1. Diagram illustrating emergy based indices and ratios.

ability of the process to exploit local resources accounting for the difference between local and imported. The higher the EYR, the higher this ability, which is not a negligible factor in economic systems; (iii) the index of sustainability (SI), defined as the ratio of the above EYR to the ELR, globally indicates if a process provides a suitable contribution to the user with a low environmental pressure.

For the sake of clarity, suppose we have three systems, driven by a different share of emergy inputs.

	System 1	System 2	System 3
Locally renewable (sej)	10	10	20
Locally nonrenewable (sej)	20	30	20
Imported from outside (sej)	50	40	40
Total emergy used, U (sej)	80	80	80

For these systems, emergy indicators will be as follows.

	System 1	System 2	System 3
Fraction renewable emergy, ϕ_R	0.12	0.12	0.25
EYR	1.6	2.0	2.0
ELR	7.0	7.0	3.0
S.I.	0.2	0.3	0.7

Most systems under human control are based on the exploitation of locally available resources, N and R, by means of an emergy investment, F, from outside. The amount of the investment that is required to exploit a local renewable or nonrenewable resource, is a key parameter when evaluating the feasibility of a process and its relationship with the outside environment and economy. The ratios of N and R to the investment F (N/F and R/F) can be used as measures of this relationship. Let it be given that: $\eta = R/F$ and $\vartheta = N/F$. In this way, the three independent variables give rise to two functions $\eta(R, F)$ and

$\vartheta(N, F)$, that might be called exploitation functions. These functions define a measure of the locally available renewable or nonrenewable emergy flows that are exploited by means on an emergy investment from outside the system.

In terms of the exploitation functions, the EYR can be written as:

$$\begin{aligned} \mathrm{EYR} &= Y/F = (F + R + N)/F \\ &= (\Sigma_i F_i \mathrm{Tr}_i + \Sigma_k R_k \mathrm{Tr}_k + \Sigma_j N_j \mathrm{Tr}_j)/\Sigma_i F_i \mathrm{Tr}_i \\ &= 1 + \Sigma_k R_k \mathrm{Tr}_k/\Sigma_i F_i \mathrm{Tr}_i + \Sigma_j N_j \mathrm{Tr}_j/\Sigma_i F_i \mathrm{Tr}_i \\ &= 1 + \eta + \theta \end{aligned} \quad (1)$$

Where: F, purchased inputs; R, renewable inputs; N, nonrenewable inputs; Tr, transformity.

The inputs to the system (R_k, N_j and F_i), are measured by their available energy content multiplied by their respective transformities (Tr). It should be underlined that all of the emergy indices, not just the EYR, are functions of the individual inputs R_k, N_j and F_i as well as of their transformities. A system can be driven, and eventually optimized, by modifying the amount and the quality of these input flows.

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 EYR. This can be inferred from Fig. 2, where an EYR diagram is plotted. A point on the three-dimensional surface represents the state of a system. The point moves over the surface, according to changes in the value of the exploitation functions. Thus EYR is a measure of the actual exploitation of local resources, renewable or not, compared with the input from outside. The same value of the index may result from high η and low ϑ or vice-versa: the EYR does not make any difference between renewable and nonrenewable exploitation functions, which is not a negligible problem in man-made systems and processes.

The environmental loading ratio (ELR), can provide additional information to the EYR. We may write:

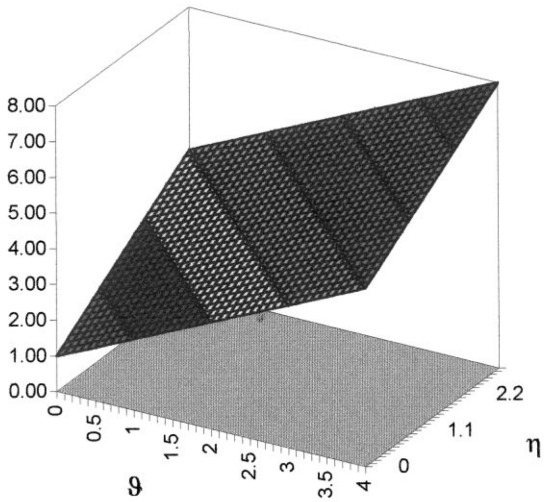


Fig. 2. Simulation of emergy yield ratio (EYR), versus the exploitation functions of locally available, renewable and nonrenewable flows (see text for simulated EYR function and definitions).

$$\begin{aligned} \mathrm{ELR} &= (F + N)/R \\ &= \Sigma_i F_i \mathrm{Tr}_i/\Sigma_k R_k \mathrm{Tr}_k + \Sigma_j N_j \mathrm{Tr}_j/\Sigma_k R_k \mathrm{Tr}_k \\ &= 1/\eta + \theta/\eta = (1 + \theta)/\eta \end{aligned} \quad (2)$$

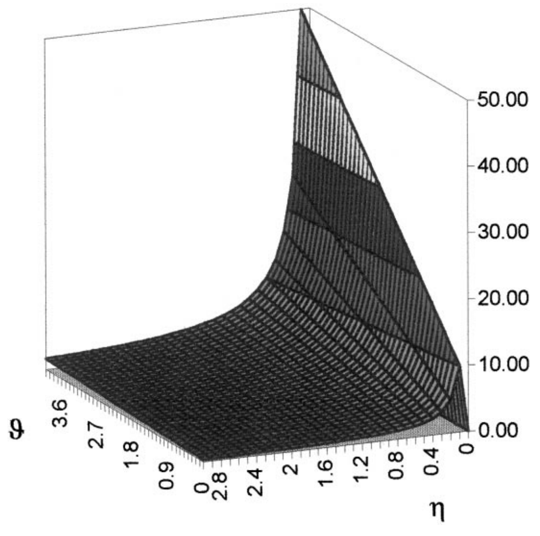


Fig. 3. Simulation of environmental loading ratio (ELR), versus the exploitation functions of locally available, renewable and nonrenewable flows (see text for simulated ELR function and definitions).

The plot of ELR versus η and ϑ (Fig. 3) does not show the same symmetrical shape of the EYR diagram (Fig. 2). 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 suggesting a larger environmental stress. Therefore, a simultaneous increase of both EYR and ELR, indicates that a larger stress is being applied to the environment. On the other hand, 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 $\eta \ll 1$. A possible meaning of this behaviour 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 organisation (Murota, 1987; Tsuchida and Murota, 1987). A natural system running on 100% locally available renewable inputs would have an ELR = 0.

An aggregate measure of yield and environmental loading may provide a better means of monitoring a system's behavior. This aggregate measure assumes that the objective function for sustainability is to obtain highest yield ratio at the lowest environmental loading (minimizing exploitation of nonrenewables): a measure of this ability can be provided by the Sustainability Index (SI) = EYR/ELR. Its expression in terms of the exploitation functions is:

$$\mathrm{SI} = S(\eta, \theta) = \mathrm{EYR}/\mathrm{ELR} = (1 + \eta + \theta)\eta/(1 + \theta)$$
$$= \eta + \eta^2/(1 + \theta) \quad (3)$$

SI = $S(\eta, \vartheta)$ is graphed in Fig. 4 as a function of both variables (ranging from 0 to $+\infty$), and shows a different sensitivity to variations of the components of the emergy inputs. SI = $S(\eta, \vartheta)$ 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

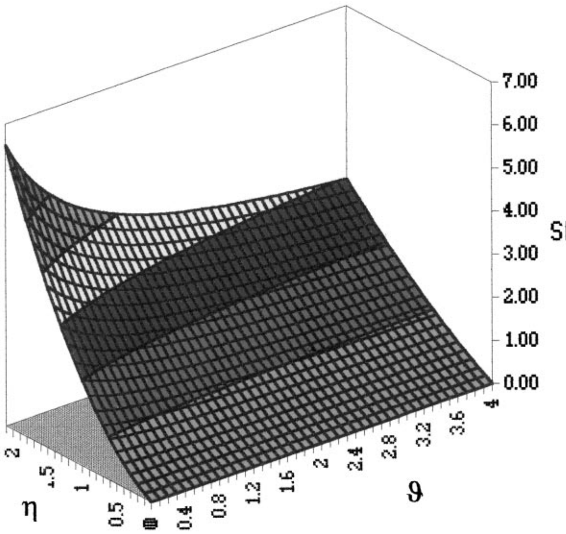


Fig. 4. Simulation of the sustainability index (SI), versus the exploitation functions of locally available, renewable and nonrenewable flows (see text for simulated SI function and definitions).

feedback from outside: the number of variables is three, not just two. This means that a higher sustainability is not just provided by a low requirement of feedback, 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 favor a system's sustainability, provided that it allows the exploitation of a large amount of emergy from renewable sources.

It follows from the above-defined functions and relative diagrams that each position on the tridimensional surface corresponds to a possible state accessible to a system. Each position relates to a different ability of the system to contribute to the global economy and to stress the environment.

Changes in the exploitation functions η and ϑ with time, cause a system to trace a trajectory over the $S(\eta, \vartheta)$ diagram surface. The trajectory links states of different sustainability, thus illuminating its trend towards a more or less sustainable state. According to the oscillating steady state paradigm, descending and ascending trends alternate in the time course of a system's life.

In the following sections, we may apply the index SI = $S(\eta, \vartheta)$ (hereafter only SI) to produc-

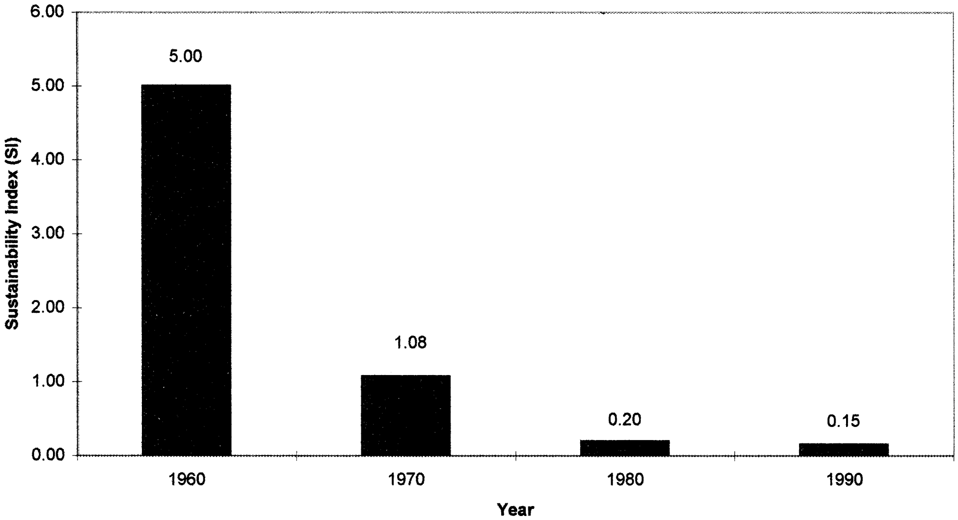


Fig. 5. Trend of the sustainability index for four different time periods in Taiwan's recent past, based on the data of Huang and Shih (1992).

tion processes and to national economies yielding a hierarchy of the different states, scaled by a decreasing value of the index itself.

4. Monitoring trends of sustainability in man-made systems

Table 1 gives comparative indices for seven countries (Papua New Guinea, Ecuador, Thailand, Mexico, USA, Italy, and Taiwan). 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 SI 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.

Sustainability index given in the last column of Table 1 is a measure of the long-term global position of a nation's economy relative to others. Low SI's (USA, Taiwan, Italy) are indicative of economies that import a large fraction of their total emergy use and consume a relatively large percentage of their total emergy consumption in the form of nonrenewable emergy.

If historical data are available, the SI can be calculated for different years showing important trends. The graph in Fig. 5 shows SI 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 become increasingly dependent on larger flows of nonrenewable emergy and imports of purchased energy and materials. A similar trend has been calculated for Italy (Ulgiati and Brown, 1998): the SI was 0.26 in 1984, 0.17 in 1989 and 0.13 in the year 1991.

Table 2 gives the results of emergy analyses of various processes ranging from agricultural production to hydroelectric production of electricity. The products are ordered according to their SI (last column). For the land based systems (agriculture and shrimp) the data in the fourth, fifth, and sixth columns are yearly emergy flows based on 1 ha of production. The emergy flows for the hydroelectric dam in Thailand are total flows per year where the purchased energies have been

Table 1
Emergy indices of national economies

Reference	Country	Total emergy (sej/year)	Emergy flow (sej/year)					
			Renewable (R)	Nonrenewable (N)	Purchased (F)	EYR[a]	ELR[b]	SI[c]
Doherty et al. (1992)	Papua New Guinea (1987)	12.1 E22	1.05E+23	1.06E+22	5.30E+21	22.8	0.15	152
Odum and Arding (1991)	Ecuador (1986)	9.6 E22	4.81E+22	4.21E+22	6.20E+21	15.5	1.0	15.48
Brown and McClanahan (1996)	Thailand (1984)	15.2 E22	7.60E+22	2.70E+22	4.85E+22	3.1	1.0	3.14
Brown et al. (1992)	Mexico (1989)	61.2 E22	1.39E+23	3.66E+23	1.08E+23	5.7	3.4	1.66
Odum (1996)	USA (1983)	790.5 E22	8.24E+23	5.18E+24	1.90E+24	4.2	8.6	0.48
Ulgiati et al. (1994)	Italy (1989)	126.5 E22	1.21E+23	3.57E+23	7.89E+23	1.6	9.5	0.17
Huang and Shih (1992)	Taiwan (1990)	21.4 E22	2.13E+22	4.02E+22	1.52E+23	1.4	9.0	0.16

Sum of renewable emergy inputs available within system boundary (R); sum of renewable emergy inputs available within system boundary (N); sum of all emergy inputs imported from outside the system (F).

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

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

[c] Sustainability index = EYR/ELR.

Table 2
Emergy indices of products

Reference	Product	Transformity (sej/J)	Emergy flow (sej/year)					
			Renewable (R)	Nonrenewable (N)	Purchased (F)	EYR[a]	ELR[b]	SI[c]
Brown and McClanahan (1996)	Hydroelectric plant (Thailand)	1.5 E5	1.30E+21	3.80E+21	5.00E+20	11.2	3.3	3.39
Ulgiati et al. (1993)	Corn (1 ha, Italy)	5.3 E4	1.42E+15	7.80E+13	4.20E+15	1.4	3.0	0.45
Odum and Arding (1991)	Cultivated shrimp (1 ha, Equador)	13.0 E6	4.90E+20	—	1.69E+21	1.3	3.4	0.37
De Carvalho Macedo (1992)	Bio-ethanol (1 ha, Brazil)	2.3 E5	1.52E+15	5.08E+15	6.57E+15	2.0	7.7	0.26
Brown and McClanahan (1992)	Cement (1 kg, USA)	6.3 E8	2.00E+11	1.90E+12	1.00E+12	3.1	14.5	0.21
Ulgiati et al. (1993)	Fruit (1 ha, Italy)	2.2 E5	1.42E+15	7.80E+13	1.32E+16	1.1	9.4	0.12
Brown et al. (1993)	Crude oil (Alaska)	5.3 E4	8.50E+19	1.13E+23	8.16E+21	14.9	1429	0.01

Sum of renewable emergy inputs available within system boundary (R); sum of renewable emergy inputs available within system boundary (N); sum of all emergy inputs imported from outside the system (F).

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

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

[c] Sustainability index = EYR/ELR.

Table 3
Emergy, energy and carbon flows and indices in US corn production since 1945–1994[a]

Year	N/F	R/F	SI	ϕ_R	Transformity (E4 sej/J)	CO_2 release (g CO_2/g corn)	Output/Input E.R.
1945	0.04	0.68	1.12	0.40	8.41	0.40	3.06
1950	0.14	0.65	1.02	0.36	8.18	0.49	2.57
1954	0.18	0.56	0.83	0.32	8.60	0.61	2.09
1959	0.24	0.50	0.70	0.29	7.24	0.58	2.23
1964	0.28	0.45	0.61	0.26	6.36	0.56	2.30
1970	0.29	0.37	0.48	0.22	6.30	0.62	2.08
1975	0.37	0.39	0.50	0.22	5.96	0.61	2.17
1980	0.32	0.29	0.35	0.18	6.04	0.64	2.02
1989	0.30	0.28	0.34	0.18	5.85	0.67	1.94
1994	0.23	0.28	0.34	0.19	5.11	0.60	2.10

[a] Our calculations based on Pimentel et al. (1973), Pimentel and Pimentel (1979), Pimentel et al. (1988), Pimentel and Wen (1990) and Ulgiati et al. (1997).

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 (hydropower and Alaskan oil) has 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 SI for the processes given in Table 2 was for production of electricity in a hydroelectric plant in Thailand. Hydroproduction 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 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 SI indicates a moderately sustainable process. The lowest SI 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 SI 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 1970's).

Finally, Table 3 shows the trend of emergy indices in US corn production since 1945 to 1994. Data are from (Pimentel et al., 1973; Pimentel and Pimentel, 1979; Pimentel et al., 1988; Pimentel and Wen, 1990; Ulgiati et al., 1997). Energy and emergy transformation coefficients have been normalized according to Odum (1996) and Giampietro et al. (1997), in order to process all data in the same way. In the above-cited papers a decrease in the output/input energy ratio (E.R.) of corn has already been underlined. The E.R. appears to have stabilized around a value of 2 in the last 40 years. Increased carbon emissions were observed until 1989, after which first signals of a declining trend appear. Transformities show declining values over the whole investigated period: this trend can be interpreted as a signal of increased efficiency in the use of global input resources and a lower demand for ecosystem support. Transformities, however, do not provide direct information about the renewable or nonrenewable quality of input flows. We can get this information from the trend of the emergy exploitation functions N/F and R/F as well as the SI diagrammed in Fig. 6. The SI of corn production had a very steep decrease until the end of the 1960's, then it slowed to apparently stabilize in the 1980's at about 0.37–0.34.

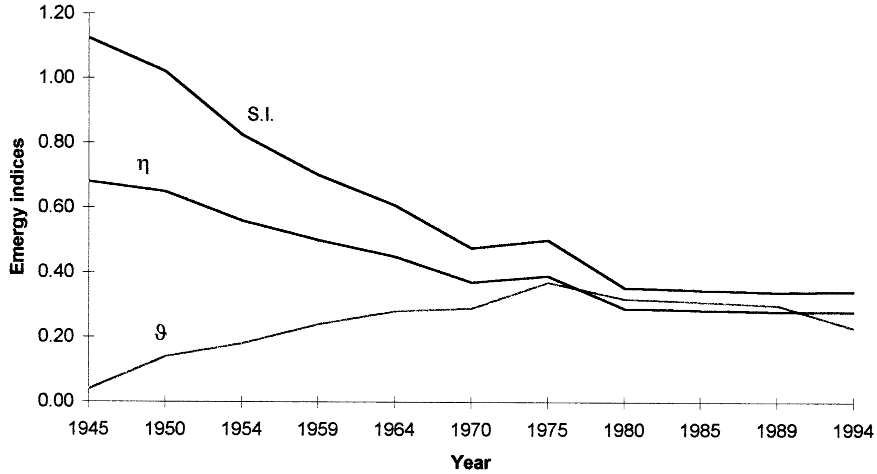


Fig. 6. Trends of the emergy exploitation functions N/F and R/F as well as the SI for US corn production from 1945 to 1994, based on published data (Pimentel et al., 1973; Pimentel and Pimentel, 1979; Pimentel et al., 1988; Pimentel and Wen, 1990; Ulgiati et al., 1997).

Fig. 7 shows a comparison between plots of the SI and the ϕ_R indices in US corn production. Both indices decline: the less steep trend of ϕ_R can be explained by its ability to account for only the emergy supply side, while the SI also accounts for the emergy yield side.

Therefore, when calculating the SI = ELR/EYR, the result indicates something more than just the renewable fraction of available input flows. The SI indicator embodies in one plot the ability of outside investments to exploit the local resources (F vs $N+R$; economic sustainability), as well as the quality of these resources (R vs $N+F$; ecological sustainability).

5. Discussion

There are no clear trends in the relationship between EYR and ELR (Tables 1–3). It appears that high ELR's result from processes with both high and low EYR's. Combined as a single ratio these two ratios provide an aggregate measure of economic (large yield) and environmental (low stress) compatibility. The higher the SI, the higher the yield per unit environmental stress provided.

When evaluating relationships between man-made processes and their environment, this index might be used in two ways: (a) to compare different processes yielding the same product. The higher the SI the larger the economic and ecological compatibility of the process in comparison with alternatives for the same product; (b) 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 SI shows progress towards a more environmentally sound pattern of production for a given process. Unfortunately, a decreasing trend is more likely to be observed in present economies.

The example of corn production clearly shows that the increase in productivity/ha may play an important role in the sustainability of the process. If an optimum performance is reached, where the input emergy increase is lower than the product yield increase, transformities decrease down to a theoretical minimum, that avoids misuses of environmental contributions. Furthermore, if technological innovation or a more intelligent use of resources will provide a way to increase the share of local renewable inputs versus nonrenewable and purchased ones, this will increase the sustainability of the process itself, as monitored by the

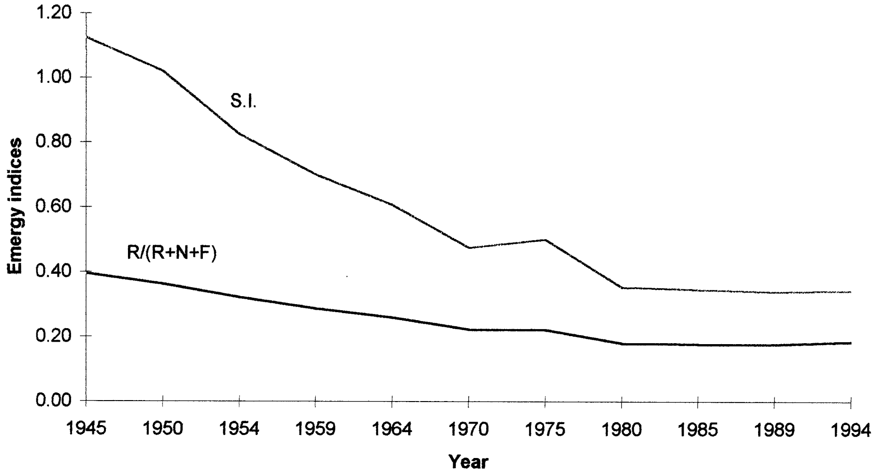


Fig. 7. Comparison diagrams between $\phi_R = R/(R+N+F)$ and SI indices, showing a steeper decrease of this latter.

increasing value of the SI. Optimum conversion efficiency together with the optimum mix of input emergy flows are therefore important components of sustainability. Transformities and SI are very effective indices in evaluating these trends and eventually may help environmental policymaking.

When economies are evaluated as with the national economies given in Table 1, 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, SI, 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 SI can be used in two ways to evaluate regional economies: (a) to compare different economies in order to evaluate their relative long-term 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; (b) to follow trends in a single economy over time. Changes in the index suggest that sustainability of an economy is increasing or decreasing depending on the direction of change of the index.

Of the countries evaluated (Table 1), Papua New Guinea (PNG) had the highest SI, while the USA, Italy and Taiwan, the lowest. Some may argue that the quality-of-life in these last three 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 SI 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 SI is inversely proportional to economic development status.

The proposed SI 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, an $SI < 1$ appears to be indicative of consumer products or processes, and an $SI > 1$ indicative of products that have net contributions to society. As it relates to economies, a low SI (< 1) is indicative of highly developed consumer oriented economies, and high SI (> 10) is indicative of economies that have been termed undeveloped. While SI ratios between 1 and 10 are indicative of what have been termed developing economies.

6. Conclusions

According to the oscillating steady-states paradigm, nothing is sustainable in the sense of being constant at a given level of activity and structure. Trends characterized by increasing amounts of assets and structure are always followed by declines, which can be gradual or catastrophic. Assessing sustainability therefore entails monitoring the present state of a system by means of some well-defined sustainability indicators and being able to forecast the system's behavior according to changes in its driving forces.

The oscillating pattern may be the general pattern of all systems and therefore cannot be avoided; however it may be possible to avoid catastrophic declines. By means of acting on the system's organization as well as on the exploitation functions, we can force the system to approach states that are characterized by a lower transformity and a higher SI, corresponding to a more efficient process and a more sustainable performance. The proposed emergy based indices can be usefully applied to monitor the system's oscillations, to forecast the system's behavior, and to adopt suitable policy measures to drive it over a more sustainable path. Maybe technological innovation and environmentally concerned policy measures will be able to slow or even reverse the trends towards increasingly lower values of the sustainability indicators. In the presence of increased scarcity of basic resources, societies will have to improve their conversion efficiency and the conversion efficiency of many processes for maximum power output, together with an increased reliance on locally available renewable emergy sources. If monitoring past trends will help planning future development, a prosperous way down (Odum, 1996) instead of a catastrophic downsizing can be designed and actually reached.

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