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Emergy and exergy stored in genetic information

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Abstract

The emergy and exergy of genetic information and its biological carriers are evaluated. Emergy used to build and maintain biological organisms (which we suggest are the carriers of genetic information analogous to books or a communications network) was evaluated on an areal basis using average global emergy input to the biosphere. The chemical exergy of genes is calculated relative to detritus as the reference environment. Using generalized data for populations of organisms from bacteria to large mammals, an emergy–exergy ratio for genes and solar transformities of biomass are calculated.

The exergy used to maintain genetic information is shown to be between about 0.1 and 1000 MJ/m^2. The emergy–exergy ratio for gene maintenance (a measure of the emergy required per Joule of genetic information is between about 1.0 and 20,000 sej/J. Generalized solar transformities for organisms are calculated and vary between about 2 sej/J of biomass (soil bacteria) to 75 million sej/J (mammel biomass). An interesting relationship between the emergy costs of gene maintenance and the solar transformity of biomass leads us to conclude that as the complexity of the biological carrier of information increases, the emergy costs of maintaining the carrier increases faster than the information carried.

We propose that the emergy required to generate the genetic information contained in the biosphere today is enormous and we suggest that it might be on the order of 2×10^{10} sej/J of genetic information.

Keywords: Emergy embodied exergy; Genetic information

1. Introduction

This paper was initiated by H.T. Odum in the spring 2002. It was discussed by e-mail in the spring and summer of 2002 and finished the spring and summer of 2003 by S.E. Jørgensen and M.T. Brown. As the papers on emergy and exergy have involved in the last decade, they are using related concepts and reaching compatible conclusions. It is therefore interesting to compare the emergy and exergy costs of genes, which is the basis for exergy calculations of living components of ecosystems (see Jørgensen and Mjer, 1977; Jørgensen et al., 1995, 2000 and Jørgensen, 2002). Emergy is calculated according to Odum (1983, 1987, 1996 (Chapter 12 gives detailed guidelines on how to calculate emergy)).

Emergy is the available energy of one kind (for instance solar energy) required directly and indirectly to make a product or service. Its unit is emjoule. When emergy is expressed as solar emergy the units are solar emjoules (sej). The ratio of emergy to available energy is called transformity. By definition the transformity of

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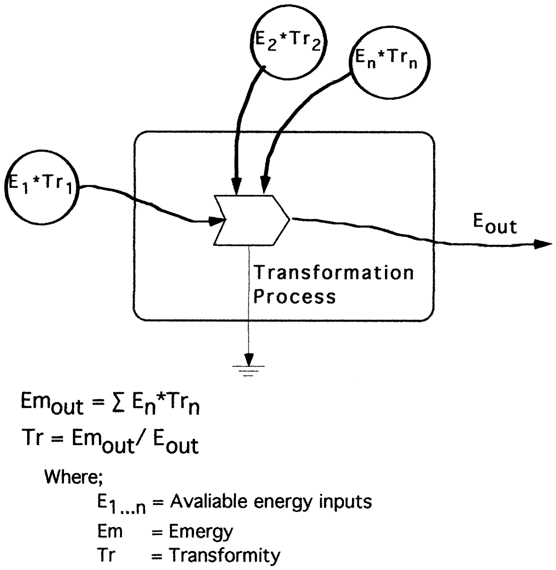

Fig. 1. Emergy is defined as the energy of one form required directly and indirectly to make energy of a different form. Shown is a transformation process where three different forms of energy (E_1, E_2, E_n) are transformed into a fourth energy (E_{out}). In practice, the input energies are multiplied by their transformities (Tr_1, Tr_2, Tr_n) to yield the emergy of inputs. The transformity of the output (Tr_{out}) is calculated by summing the input emergies and dividing by the energy of the output (E_{out}).

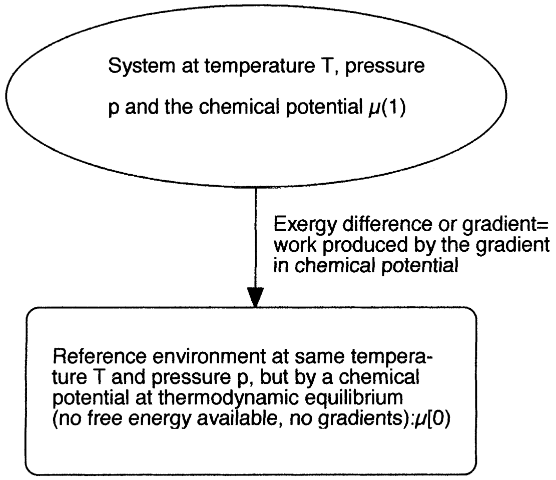

Fig. 2. It is beneficial in ecological context to define the exergy as shown, i.e., the amount of energy that can be extracted from an ecosystem when it is brought in equilibrium with the same system but at thermodynamic equilibrium at the same temperature and pressure.

solar energy is 1 sej/J. Transformities for most forms of available energy have been calculated and are given in Odum (1996). Fig. 1 illustrates the calculation of emergy and transformity.

Exergy is the amount of energy which can do work when the system is brought into equilibrium with its environment. As the exergy of living systems is dominated by the chemical (or rather the biochemical) energy, it is beneficial to define exergy as shown in Fig. 2. The environment is assumed to be the same system at thermodynamic equilibrium at the same temperature and pressure.

Calculations of emergy and exergy are shown in the next section, which makes it possible to carry out a straight forward comparison. These results are discussed in the following section, which leads to some interesting observations regarding the emergy and exergy content of genes and the relationship to globally calculated transformities for populations of organisms in the last section.

2. Calculations of the emergy and exergy content of genes

Table 1 shows the results of the calculations. For various populations (column A) and ecosystems (column B), the generation time (column C) is found by the application of the allometric principle (see Peters, 1983). The concentration of the considered organism in g/m^2 is shown in the fourth column, named D. The concentrations can be found in Jørgensen, 2000. The fifth column, E, in Table 1 indicates how many times higher exergy the considered organism has than the exergy in detritus of the same system (designated β), corresponding to information embodied in the organisms (see one of the following references for a full explanation: Jørgensen et al., 1995, 2000 and Jørgensen, 2002). As detritus has, on average, an embodied exergy content of 18.7 kJ/g, the embodied exergy in the considered case, column F, can be found by multiplying the values in column D by 18.7β. The emergy used (column G) can be calculated as the total emergy per square meter per day multiplied by the turn over time (column C), as described in footnotes c and d to Table 1. The last column, H, is the ratio of emergy to embodied exergy.

Table 1
Exergy content of genes, emergy of maintenance, and emergy–exergy ratios for different populations of organisms

A	B	C	D	E	F	G	H
Population	Ecosystem	Turnover time (days)	Biomass[a] (g dry weight/m^2)	β (exergy ratio)	Exergy[b] (MJ/m^2)	Emergy used[c] (Msej/m^2)	Exergy– emergy ratio (sej/J)
Detritus	Ocean	1	5	1	0.0935	86.6	0.9
Soil bacteria	Meadow	0.01	20	2.7	1.01	0.9	0.9
Phytoplankton	Lake	1	10	3.8	0.71	86.6	121.8
Phytoplankton	Ocean	1	5	3.8	0.36	86.6	243.7
Zooplankton	Lake	7	2	38	1.42	606.0	426.4
Corn[d]	Field (USA)	100	1800	30	1009.80	1188657.5	1177.1
Wheat[d]	Field (NL)	110	1800	30	1009.80	1189523.3	1178.0
Mice	Meadow	100	0.6	430	4.82	8657.5	1794.5
Snails	Intertidal sea	300	10	32	5.98	25972.6	4340.3
Fish	Lake	1000	1.5	300	8.42	86575.3	10288.2
Deer	Forest	2000	1.1	430	8.85	173150.7	19575.9

[a] Biomass of populations per meter are as follows:
Soil bacteria—20 g/m^2 (Table 11.2, Brady and Weil, 1999).
Phytoplankton (ocean)—5.0 g/m^2 (Table 15-1, Lieth and Whittaker, 1975).
Phytoplankton (lake)—10.0 g/m^2 (Table 15.1, Lieth and Whittaker, 1975).
Snails (intertidal)—10 g/m^2 (Tables 3–14, Odum, 1971).
Mice—0.6 g/m^2 (Tables 3–14, Odum, 1971).
Deer—1.1 g/m^2 (Tables 3–14, Odum, 1971).
[b] Exergy = biomass × β × 18.7 kJ/g.
[c] Total emergy used = global emergy flow ((15.8 ± 24 sej per year/(5 ± 14 m^2 × 365 days)) × turnover time).
[d] Total emergy used = global emergy flow ((15.8 ± 24 sej per year/(5 ± 14 m^2 × 365 days)) × turnover time) + nonrenewable emergy used per crop (1.18 ± 12 sej/m^2; nonrenewable emergy from Brandt-Williams, 2001).

Table 2 shows the results of calculations for the emergy to maintain biomass. Using the generalities of turnover time and density of biomass as well as the global average emergy flow (called empower, i.e., sej per time) in Table 1 and calculating the available energy in biomass (using 4.5 kcal/g dry weight) we obtain transformities for organism maintenance.

3. Discussion of the results

The last three columns of Table 1 summarize the results. Generally, the later the organisms is in the food-web which often coincides with organisms that are more developed, the more expensive is the exergy in the genes expressed in emergy units. This is of course not surprising when calculating emergy of various organisms. Calculating emergy in this manner assumes that all the emergy input to each square meter of the earth's surface is assigned to all organisms inhabiting that area. In other words, all functions, services, and populations supported by a square meter of the earth's surface are co-products. One cannot produce, for instance, vegetative biomass with out the services of soil bacteria, or deer browsing vegetation and carrying seeds, just as a lake cannot support fish without the base of the food chain expressed in phytoplanklton grazed by zooplankton and in turn consumed by higher order fish. So in essence all levels of the food chain are co-products of the emergy input. The emergy applied to the wheat and corn fields includes not only the global renewable base of the biosphere, but significant amounts of energy coming from various human sources, including fossil fuel. These nonrenewable sources account for about 1.2 million Msej per season. It is therefore necessary to add this amount to the renewable emergy base to account for the total emergy applied. The calculations in the table are therefore based on the total emergy applied including the emergy of the fossil fuel.

Table 2 shows the results of calculating global average transformities for populations using the free energy of biomass (assuming an energy content of 4.5 kcal/g for biomass). The transformities calculated in this manner are higher than the emergy–embodied exergy ratios calculated in Table 1 (column H). It is

Table 2
Available energy of biomass, emergy of maintenance, and transformities for different populations of organisms

A	B	C	D	E	F	G
Population	Ecosystem	Turnover time (days)	Biomass[a] (g dry weight/m^2)	Energy[b] (MJ/m^2)	Emergy used[c] (Msej/m^2)	Transformity (sej/J)
Soil bacteria	Meadow	0.01	20	0.38	0.9	2.3
Phytoplankton	Lake	1	10	0.19	86.6	459.5
Phytoplankton	Ocean	1	5	0.09	86.6	919.0
Zooplankton	Lake	7	2	0.04	606.0	16082.2
Corn[d]	Field (USA)	100	1800	37.68	1188657.5	31543.6
Wheat[d]	Field (NL)	110	1800	37.68	1189523.3	31566.6
Mice	Meadow	300	10	0.21	25972.6	124063.1
Snails	Intertidal sea	100	0.6	0.01	8657.5	689239.3
Fish	Lake	1000	1.5	0.03	86575.3	2756957.0
Deer	Forest	2000	1.1	0.02	173150.7	7518973.7

[a] Biomass of populations per meter are as follows:
Soil bacteria—20 g/m^2 (Table 11.2, Brady and Weil, 1999).
Phytoplankton (ocean)—5.0 g/m^2 (Table 15-1, Lieth and Whittaker, 1975).
Phytoplankton (lake)—10.0 g/m^2 (Table 15-1, Lieth and Whittaker, 1975).
Snails (intertidal)—10 g/m^2 (Tables 3–14, Odum, 1971).
Mice—0.6 g/m^2 (Tables 3–14, Odum, 1971).
Deer—1.1 g/m^2 (Tables 3–14, Odum, 1971).
[b] Energy = biomass × 4.5 kcal/g dry weight × 4187 J/kcal.
[c] Total emergy used = global emergy flow ((15.8 ± 24 sej per year/(5 ± 14 m^2 × 365 days)) × turnover time).
[d] Total emergy used = global emergy flow ((15.8 ± 24 sej per year/(5 ± 14 m^2 × 365 days)) × turnover time) + nonrenewable emergy used per crop (1.18 ± 12 sej/m^2; nonrenewable emergy from Brandt-Williams, 2001).

interesting to note that the differences between the values in column H Table 1 and column G in Table 2 increase with each "step in the food chain". Table 3 lists the ratio of the two values showing that the emergy–embodied exergy ratios are between 3 and 400 times lower than the transformities calculated in Table 2. This results from the difference between the embodied exergy of genes verses the energy of total biomass. The calculated embodied exergy of genes is much higher than the calculated energy of biomass. On the surface this seems to make sense, however, the result is a lower ratio of emergy to embodied exergy in Table 1 than the transformities in Table 2. Since we believe that transformities are a measure of the convergence of biosphere energy into various products or processes, the fact that the emergy–embodied exergy ratio is lower does not make sense. This does not appear to be correct and we suggest that the fault rests in assuming that the daily flows of emergy are the costs to make genetic information. This assumption is incorrect. when we consider the enormous information content of the genes that is the result of millions of years of evolution.

Table 3
Comparison of emergy–exergy ratio of genes and the solar transformity of biomass

Population	A	B	C
	Emergy–exergy ratio (sej/J)	Solar transformity (sej/J)	Ratio of B/A
Soil bacteria	0.9	2.3	2.7
Phytoplankton	121.8	459.5	3.8
Phytoplankton	243.7	919.0	3.8
Zooplankton	426.4	16082.2	37.7
Corn	1177.1	31543.6	26.8
Wheat	1178.0	31566.6	26.8
Mice	1794.5	124063.1	69.1
Snails	4340.3	689239.3	158.8
Fish	10288.2	2756957.0	268.0
Deer	19575.9	7518973.7	384.1

We have only calculated the emergy corresponding to a repetition of the genes (a new generation), but the genes can only be transferred to next generation at this relatively low cost of emergy, because the information in the genes is already there. The obvious question would be: how much solar emergy has been used to establish the present genes on earth accounting for the entire evolution. If we presume an average β value of 80 (trees with a value of 50–85 is the dominant biomass on earth) and consider that the biomass on earth is estimated to be 2×10^{18} g (see any global carbon cycle), the exergy of the genes on earth today is estimated to be 3.0×10^{24} J. The emergy input to the biosphere (15.8×10^{24} sej per year (Odum et al., 2000) since the evolution started 3.8 billion years ago, assuming the same intensity as today, will be:

$$(15.8 \times 10^{24})\text{sej per year} \times (3.8 \times 10^{9})\text{year} = (6.0 \times 10^{34})\text{sej}$$

and the emergy–exergy transformity is:

$$\frac{6.0 \times 10^{34}}{3.0 \times 10^{24}} = 2.0 \times 10^{10}\,\text{sej/J}$$

Or, to state it another way, the emergy cost has therefore been 2.0×10^{10} times the exergy content of the genes.

4. Conclusions

The emergy–exergy ratio varies from about one to about 20,000. The highest emergy–exergy ratios correspond to the most developed organisms, i.e., those with most no-nonsense genes. The calculations in Table 1 correspond to the emergy applied for maintenance only, while a calculation of the total emergy applied for the total development of the genes requires that we take the solar emergy since the start of evolution into account. It gives an emergy–embodied exergy ratio which is as high as 2×10^{10} sej/J.

The emergy cost of maintaining biomass (Table 2) varies five orders of magnitude, when not considering the agricultural systems evaluated, from about 1 to about 1.7×10^{5} Msej per square meter. If the nonrenewable resources used in agricultural systems are also considered, the emergy used to support agricultural biomass is six orders of magnitude greater than that for bacteria. The transformity of the various organisms, based on their biomass and turnover times varies six orders of magnitude, from about 2 sej/J (bacteria) to about 7.5×10^{6} sej/J (deer). The highest transformities correspond to the most developed organisms and those that have the largest territories.

Since the biomass of the various organisms represents the carrier of the information in genetic code, it is suggested that the cost of information transmission via living organism can be expressed as the emergy cost of maintaining the biomass carrier from year to year. (Even, if we had the number of bits of information for each organism, we could express this as emergy per bit. Others have compared the energy per bit for transmission of information over various carriers . . . i.e., telephone, radio, TV, microwave, etc., it might be very interesting comparison.) In other words, the emergy required to transmit genetic information in bacteria from generation to generation is quite small, about 1 Msej/m^2, while for a deer it is about five orders of magnitude greater. These differences are essentially the result of the differences in the turnover times of the organisms.

The increasing difference between the emergy–embodied exergy ratio of genes and transformity of biomass is extremely interesting. It suggests that there is not a constant relationship between the emergy costs of the biological carrier of information and the information carried. The transformity increases much faster than does the emergy–embodied exergy ratio, which suggests that the complexity of the carrier is increasing faster than the complexity of the information carried. Obviously, we need more analyses and examples before we were to propose a general principle.

There is no doubt, genetic information has a very high exergy content due to the enormous amount of information in the genes, and the emergy cost is even higher. The conservation of genes (which means, of course, conservation of biodiversity) is therefore extremely important. Loss of species means an enormous loss of emergy.

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