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An Energy Hierarchy Law For Biogeochemical Cycles

Howard T. Odum

ABSTRACT

The coupling of the biogeochemical cycles to the energy transformation hierarchy explains the skewed distribution of materials with concentration. When self organization converges and concentrates high quality energy in centers, materials are also concentrated by the production functions. Because available energy has to be used up to concentrate materials, the quantity of material flow also has to decrease in each successive step in a series of energy transformations. The decreasing flow but increasing concentration of materials in biogeochemical cycles is proposed as a 6th energy law, a principle of material hierarchy.

Trace materials at or near the biogeosphere background concentrations are carried in flows of air, waters, and earth crust as unspecific components with the same emergy per mass of the carrier. But at greater concentration, specific autocatalytic processes develop that concentrate materials further, use more available energy and incorporate more empower. A lead example shows emergy per mass increasing with concentration beyond a threshold.

Each type of material occupies a zone in the emergy/mass spectrum where its energy interactions amplify production. Air and water are in a lower emergy range while biological materials and heavy metals are at higher levels. Diagrams of material cycles can be improved by arranging storages and flows from left to right in order of increasing concentration and emergy per mass.

INTRODUCTION

Biogeochemistry, the study of material cycles, concerns the quantities and processes by which materials circulate. Textbooks describe processes on the many scales from molecular reactions to global and cosmic self organization (Rankama and Sahama, 1950; Mason, 1966; Siegel, 1974; Bowen, 1979; Drever, 1988; Dobrovolsky, 1994; Brownlow, 1996; Schlesinger, 1997). Interesting, non-random distributions of chemical elements have been described without adequate explanation. Quantitative diagrams of the cycles of elements have been arranged in many arbitrary formats, hard to compare from one paper to another, the only common principle being the conservation of matter. Many recent papers evaluate numerically material recycling and materials in the life cycle of cities and nations (Adriaanse et al., 1977). But mostly, the materials are considered separate from the energetics on which they depend. In this paper the coupling of material cycles to the universal energy hierarchy is explained using emergy concepts and suggested as a new energy law. First, let's review energy hierarchy concepts and the relationship of energy to material concentration.

Review of Energy Hierarchy Concepts

The energy hierarchy concept was developed by generalizing from ecological food chain examples (Odum, 1971, 1976, 1987, 1996) and offered as a 5th energy law— one that follows from the 2nd law and the 4th energy law, Lotka's concept of self organizing for maximum power (1922a, 1922b):

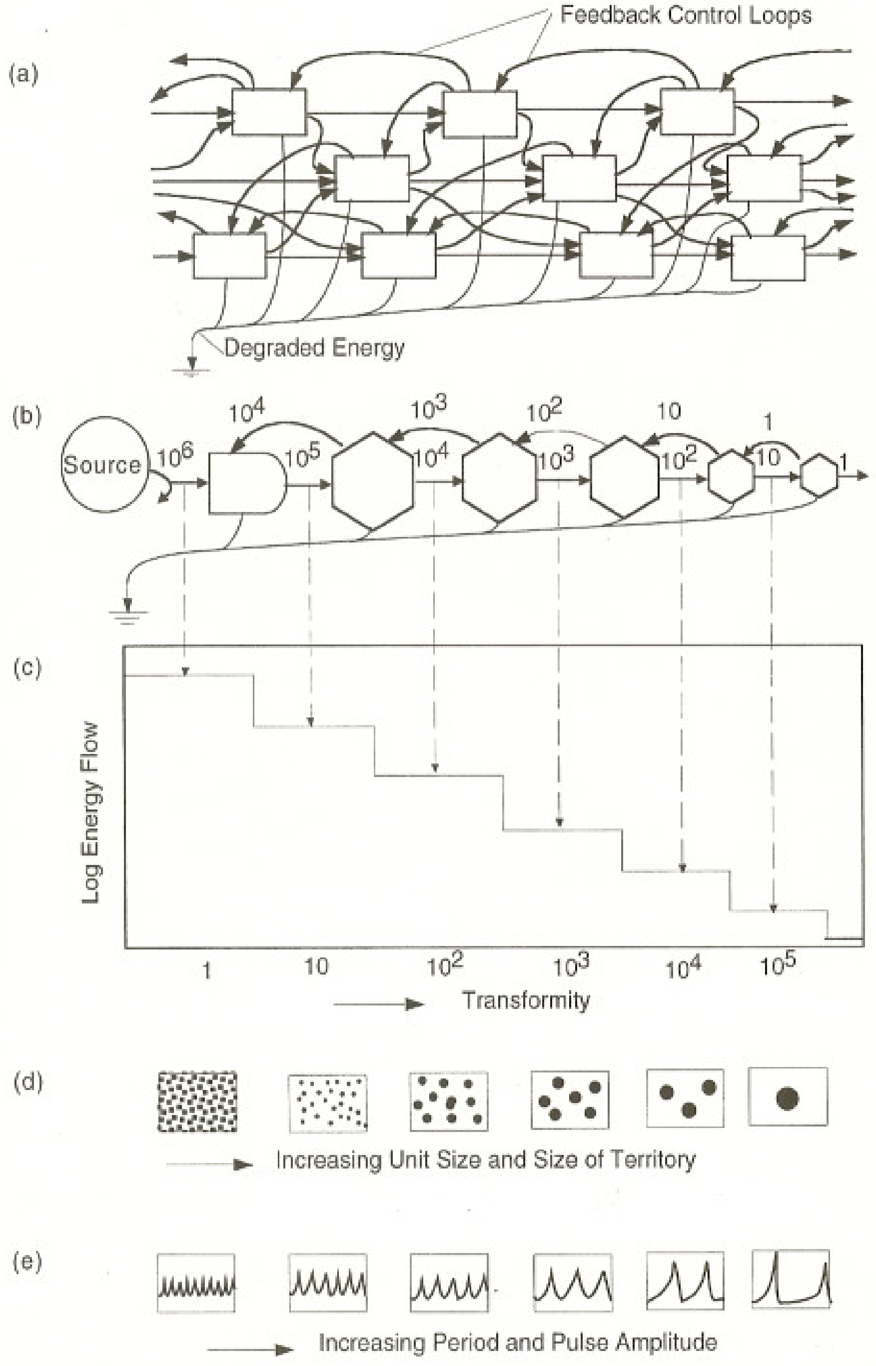


Figure 1. *Sketches summarizing energy hierarchy concepts. (a) Web of energy transformation processes (rectangles) arranged in series with energy decreasing from left to right; (b) energy system diagram of energy webs aggregated into a linear chain. Sources are aggregated into one by expressing flows in empower units of one kind before adding. Other numbers are typical energy flows at steady state; (c) energy spectrum: energy flow is plotted as a function of transformity on logarithmic scales increasing from left to right (Transformity = emergy/available energy); (d) sizes of unit centers and territories increasing with scale from left to right; (e) periods and intensities of energy accumulation, pulsing, and turnover time increasing from left to right.*

An energy transformation is a work process that converts one or more kinds of available energy into a different type of available energy.

All energy transformations can be arranged in a series, and the position of an energy flow in the series is marked by the transformity, where

Transformity is the emergy per unit available energy, and

Emergy is the available energy (exergy) of one kind required to be used up previously directly and indirectly to generate the inputs for an energy transformation. If solar energy is used as the common denominator and all available energies are expressed as solar emergy, the transformities are greater than one.

The flow of usable available energy through a network is power. The flow of emergy is called empower. (Empower = emergy flow per time.)

Units of emergy are emjoules of one kind of energy. Typical units used are solar emjoules (abbreviated sej) and for solar transformity solar emjoules per joule (abbreviated as sej/J).

The energy hierarchy concepts can be visualized with energy systems diagrams (Odum, 1966, 1971, 1983, 1994) that separate the scales with small fast turnover units on the left and items of larger scale of space and time on the right (Figure 1). Figure 1a is a network of energy transformations, which is aggregated into a linear series in Figure 1b. Available energy decreases with each transformation step, but the transformity increases from left to right. In Figure 1c available energy flow is plotted as a function of the increasing transformity on logarithmic coordinates. This plot is an energy hierarchy spectrum.

The higher the transformity the more available energy of another kind was required to make it. According to the energy hierarchy concepts, transformations that survive the natural selection processes of self organization reinforced their supporting network with a feedback of its energy output even though its energy flow is less. Commensurate reinforcement with less energy is possible because the systems concentrate the output spatially (Figure 1d) and accumulate the products and deliver their feedback actions in pulses (1e).

In terms of Lotka's principle, each transformation that survives self organization is organized to help maximize its power while reinforcing the network. However, the high level transformation processes (lower power flow on the right) are just as important as the low level processes (higher power flows on the left. Maximum power might be misunderstood to mean giving priority to low level processes. In Figure 1b the empower is the same through the whole series. Therefore, the 4th energy law is clarified by stating it as the *principle of self organization for maximum empower.*

Spatial Convergence

From observation and theory, the series of energy transformations in the universal energy hierarchy converge their transformed energies to more concentrated centers even as the total energy transformed decreases (Figures 1c). One of the reasons for this is that reinforcement feedbacks needed to prevail in self organization can be commensurate with what was required in their formation if they concentrate in area. Centers and the supporting territories of these centers increase with successive transformations along the series from left to right (Figure 2d). An example of spatial hierarchy generated by self organization is the vivid pattern of night lights of cities and towns as seen from satellite.

Accumulation and Pulsing

As suggested by pulses shown in Figure 2e, units higher in the energy hierarchy (higher transformity) have longer periods of accumulating energy storage but sharper pulses in their feedback actions. Examples are the energy feedbacks of carnivores, storms, governments, and earthquakes to their areas. By storing longer and concentrating their impact from smaller concentrated centers in shorter times, the lesser energy of higher units can have enough impact to reinforce their supporting energy transformation chain (a design that fits the maximum empower principle). The universal pulsing increases in period and intensity along the series of increasing scale from small scale molecular oscillations to large scale earthquakes (Figure 2e).

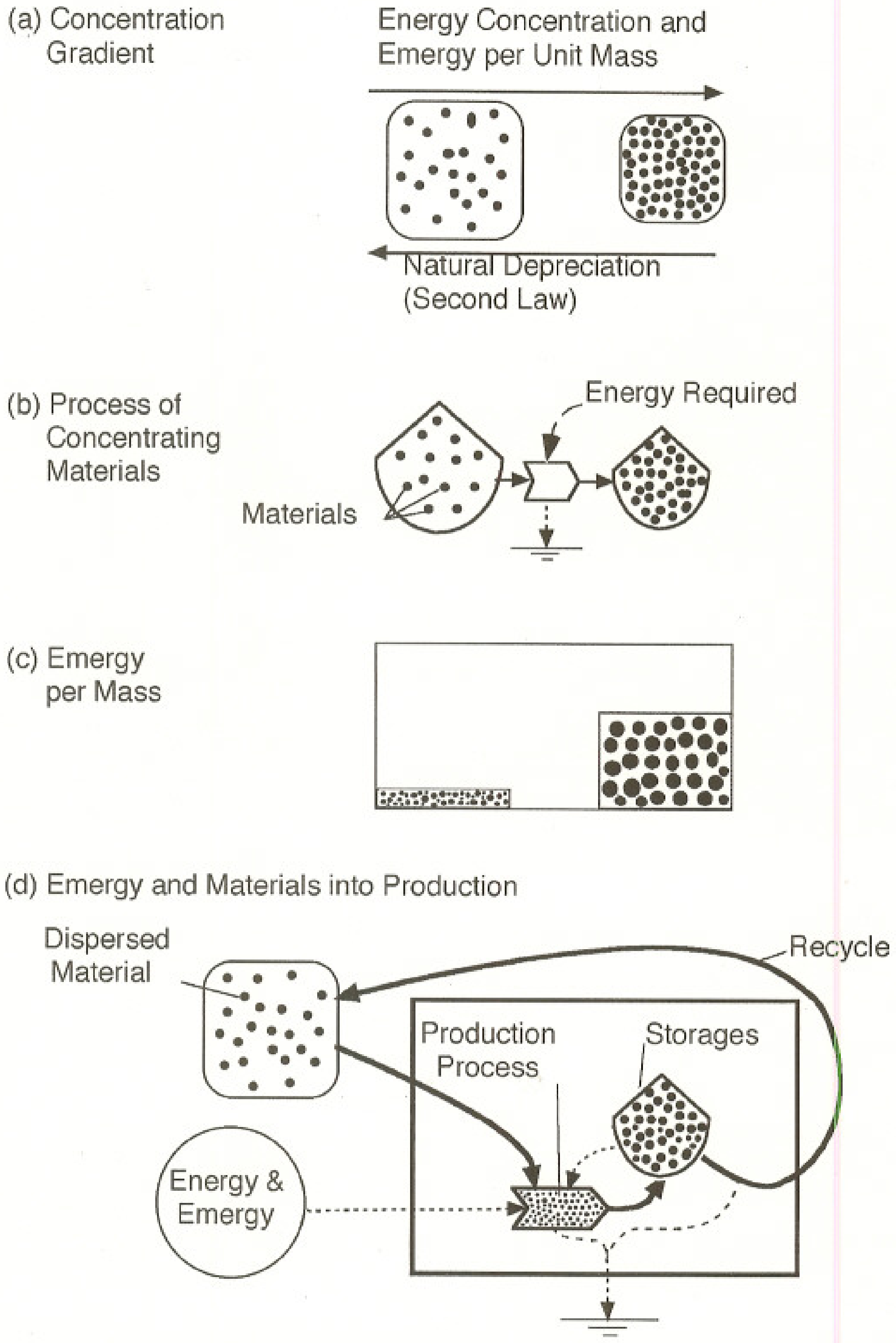


Figure 2. *Sketch showing consumption of available energy necessary to increase material concentration and emergy per mass. (a) Concentration materials indicated by density of dots; (b) use of available energy to increase concentration and energy storage; (c) emergy per mass increase with concentration; (d) autocatalytic production process utilizing available energy to concentrate dispersed materials. Dotted lines = energy flow only; solid lines = material flow.*

Energy Quality Increase

Energy flows to the right are more concentrated, have more effect per unit, are more flexible in their uses, and in these senses are higher quality aspects accompanied by higher transformity. In other words, after self organization, energy flow of higher transformity requires more for its support and has more effect.

ENERGY COUPLING TO MATERIAL CYCLES

Principles relating energy, emergy, and materials are stated next as part of the reasoning for an energy law of material distribution and processing.

Available Energy, Emergy, and Material Concentration

Using Figure 2, let's review the energetics of material concentration. According to the second law, a concentration of material sketched on the right in Figure 2a spontaneously diffuses or otherwise disperses to a lower concentration (to the left), losing the availability (exergy) of its stored energy in the process. To concentrate the material requires coupling of the material to available energy (exergy) of greater quantity that is degraded while pumping the dispersed material on the left to the concentrated state on the right (Figure 2b). In open systems operating at competitive rates, more available energy is degraded by the transformation than is stored.

Contributions of available energy to a transformation process add the emergy of that contribution. The emergy of the newly concentrated material on the right in Figure 2b has that of the initial state plus that of the available energy used up in the concentration process. Thus, any increase in concentration of material requires an increase in the emergy per mass (typical units are emjoules per gram). When concentration increases in some part of a biogeochemical cycle, the emergy per mass increases. When material disperses (right to left in Figure 3), the stored emergy decreases. The amount can be calculated by estimating what emergy is required to restore its concentration again.

Background Concentrations and Production

If a material dispersed in the earth or its oceans and atmosphere is at the lowest concentration on earth, it cannot disperse further spontaneously. It has no availability or emergy (relative to the earth). In our energy systems diagrams it has no heat sink. It is at the lowest energy state in its biogeochemical cycle. The low concentration may have been produced by active processes elsewhere in the cycle.

However, if there is available energy in its local concentration or chemical reaction potential, this exergy can be incorporated into a production process in which the material is a necessary part. The emergy of that concentration contributes to the product. The material-containing product has the emergy of the contribution from the energy and material sources (Figure 2d).

Critical Concentration for Specific Production

When materials are present in the earth solids, in waters or in atmosphere in tiny traces, they can be carried along with the flows without any special recognition or specific participation by the process. Let's refer to the main flow as a carrier. The trace materials are processed with the carrier. Carrier materials are circulated by sources of available energy, the small emergy added per gram of a trace material is in proportion to its fraction of the mass of carrier. In Figure 3, a trace material (light stippling) is shown carried along and slightly concentrated as a small percent of another flow (dark shading), thus receiving its share of that emergy input.

When the trace material becomes concentrated enough for its individual properties to be recognized and useful in self organization, it can become a necessary part of a production process. If the available energy levels for this process are large enough, autocatalytic designs accelerate emergy inflow

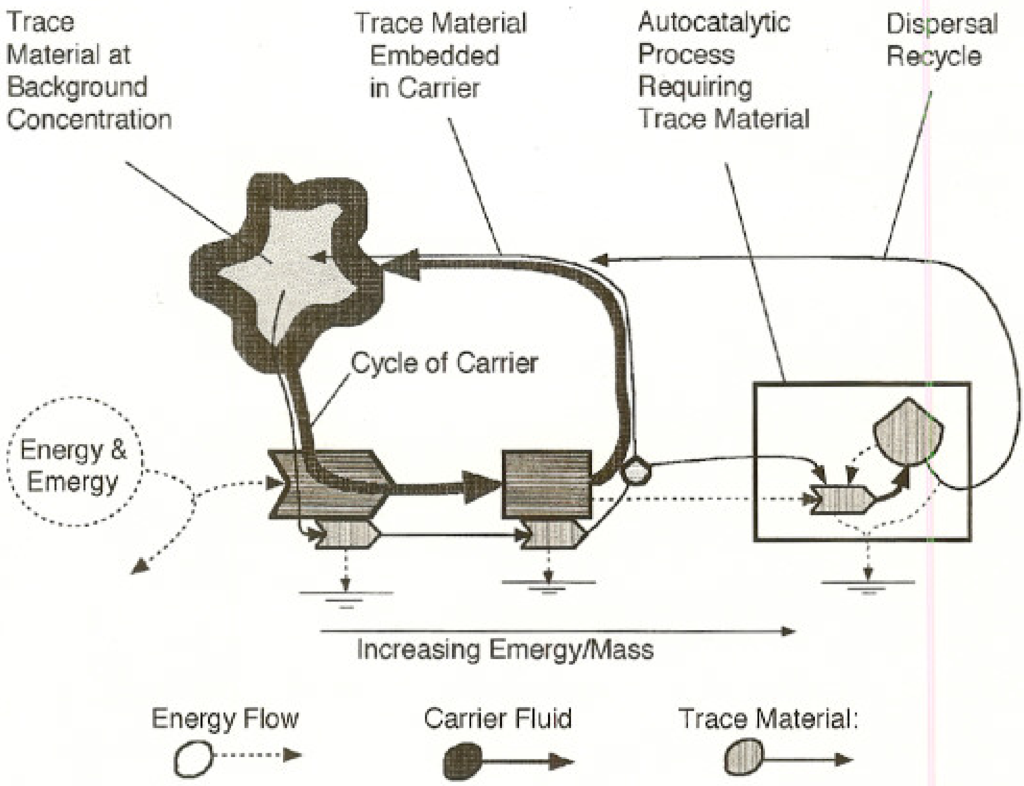


Figure 3. *Coupling of a trace material (solid lines) to energy flow and transformations (dotted lines) showing two stages. On the left there is non-specific transport of trace concentrations by a carrier material. On the right there is a specific use of the trace material in an autocatalytic production process that accelerates energy use and material concentration.*

(the maximum empower principle). An autocatalytic entity forms, the box on the right in Figure 4. Here the trace material is a necessary part of a unit's transformation. Examples are the incorporation of elements into crystal formation in rocks or the incorporation of nutrients in plant production. In other words, there is a critical concentration where a material becomes productive. For example, there is a critical concentration of sugar to support a microbial population. The situation is analogous to the critical point in flow of a fluid when laminar flow shifts to turbulence, which is an autocatalytic momentum transformation.

As Figure 4 shows, the emergy per mass beyond the critical point is that of all the necessary inputs to the transformation, not just a small percent of a carrier. Thus, emergy per mass increases sharply as material concentrations increase beyond the critical concentration. Notice the increase in slope of the graph of transformity and concentration of lead in Figure 4. Sherry Brandt-Williams (1999) found a similar shaped graph for emergy per mass and the concentration of phosphorus.

Spatial Convergence of Material Concentration

Figure 5a diagrams the way dispersed materials are incorporated into a series of three energy transformation processes (rectangular blocks). Since each energy transformation converges and concentrates the output of available energy spatially into centers, and since material concentrating is coupled to energy transformations, then materials are spatially converged and concentrated into centers also (Figure 5b).

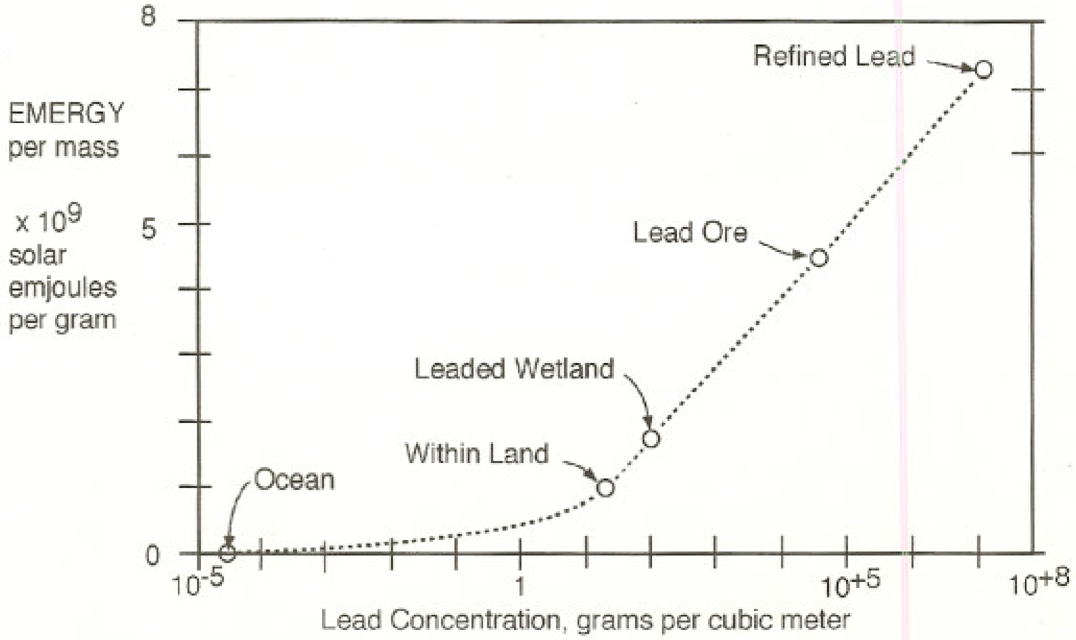


Figure 4. *Emergy per mass as a function of lead concentration (Odum, 2000a).*

Decreasing Mass with Successive Energy Transformations

However, some materials are recycled from each stage (Figure 5) because the amount of materials that is passed to higher concentration decreases. The total quantity of materials concentrated has to decrease because the available energy to concentrate materials decreases. To be effective in use at a higher level of the energy hierarchy, materials have to be transformed to higher concentration (maximum empower principle). Higher concentrations increase the feedback potential of the materials to reinforce the contributing web. But higher concentration requires more emergy use, and the system is limited by its supporting emergy budget. Thus, there is an energetic explanation for the decrease in materials carried forward with successive energy transformation (left to right in Figure 5).

For the case of one energy source from the left (Figure 6b), the empower flow is the same through each transformation unit of the series. But the emergy per mass has to increase in order to concentrate the mass. So less can be concentrated. Figure 6 shows the hyperbolic inverse relationship of mass transfer and emergy per mass when empower J_{emp} is constant.

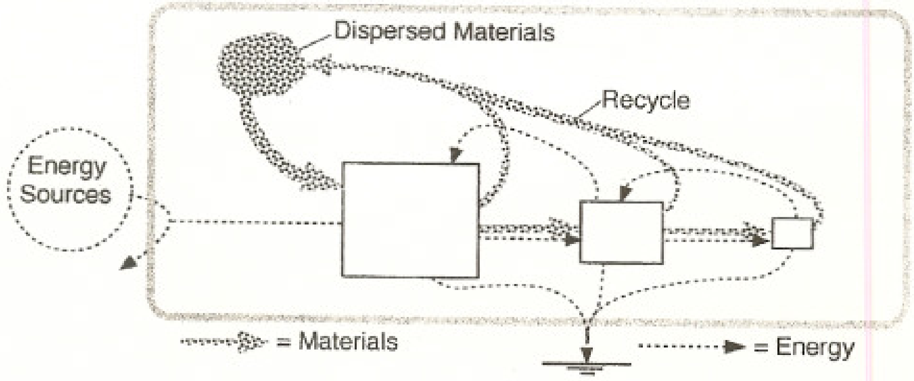
$$\text{Mass flow} = \text{empower}/(\text{emergy per mass})$$

Mass flow J_m is inverse to emergy per mass (E_m), and the amount of mass that can be concentrated for the next level decreases. Materials become distributed in an inverse relationship to their position in the energy hierarchy. Emergy per mass, like transformity (emergy/energy), increases along the energy hierarchy.

Skewed Distribution of Materials

Long discussed in geochemical literature is the skewed distribution of quantity of a chemical and its concentration. Ahrens (1954) and many since (Miller and Goldberg, 1955; Middleton, 1970) have emphasized the patterns by fitting the data to log normal distribution equations. See, for example, lead in

(a) Materials Combined with Energy Flows



(b) Spatial Convergence of Materials

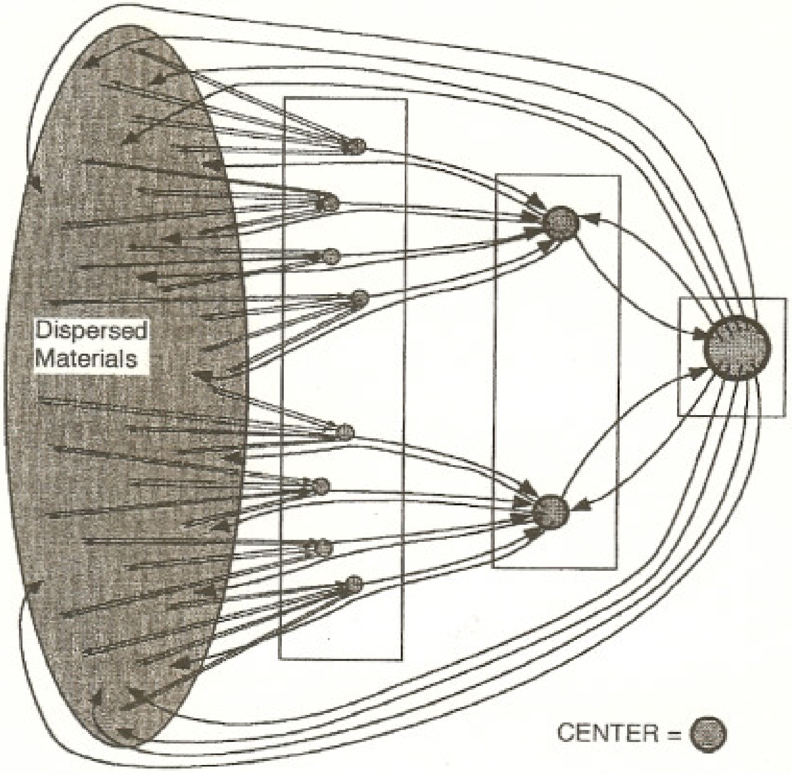


Figure 5. *Spatial convergence of materials to centers because of their coupling to the convergence of energy. (a) Materials and energy transformation hierarchy on an energy systems diagram; (b) spatial pattern of material circulation.*

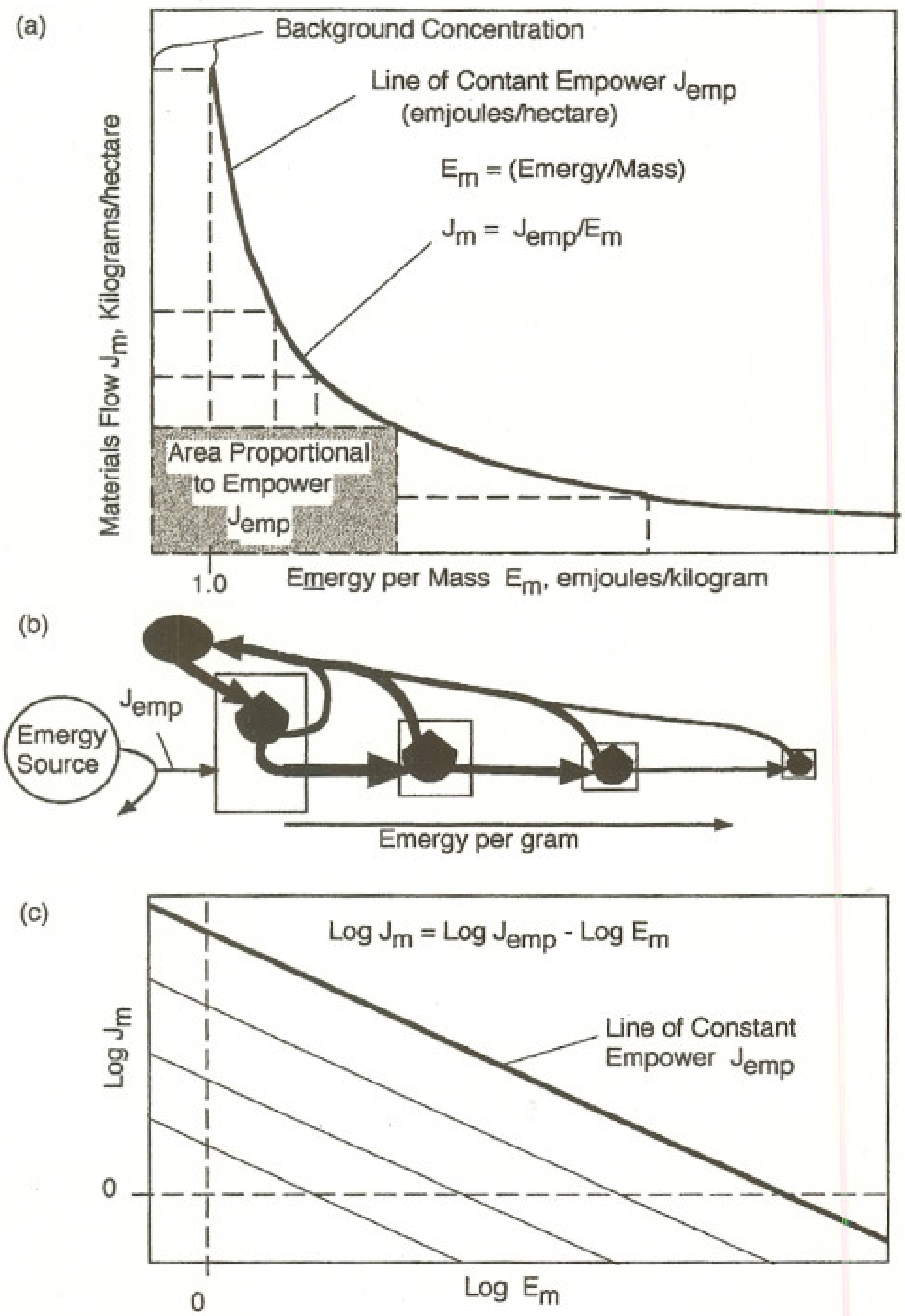


Figure 6. *Inverse relation of material flow and emergy per mass. (a) Inverse plot of rate of material concentration and emergy per mass where emergy flow is constant; (b) systems diagram of the circulation of material (dark shading driven by a flow of empower* J_{emp}*; (c) rate of materials concentration as a function of emergy per mass on double logarithmic coordinates.*

granites in Figure 7. The general prevalence of skewed distributions of materials may be interpreted as evidence for the energy hierarchy basis for material processing.

Because the principles are general, the pattern may be expected in the self organizing systems of humans as well as those in geology and ecology. Doxiadis (1977) found that the circulation of people in human settlements followed the spatial hierarchy of landscapes, with larger scale circulation from the higher centers. He showed that the mass of city buildings in centers increases as the area for the buildings decreases so that the density of materials increases along the transformation series. However, the higher the level the larger is the surrounding area that contributes. Even in cities with main emergy from fossil fuels, the surrounding environmental areas are required to interact to maximize empower. The higher the level the more empower support and accumulation there is (Figure 5). This means emergy per mass of the materials in city structure increases along the transformation series to the centers.

Material Zones in the Energy Hierarchy

Production processes prevail when their inputs develop autocatalytic production units that reinforce each other (maximum empower principle). But each material only participates in a limited

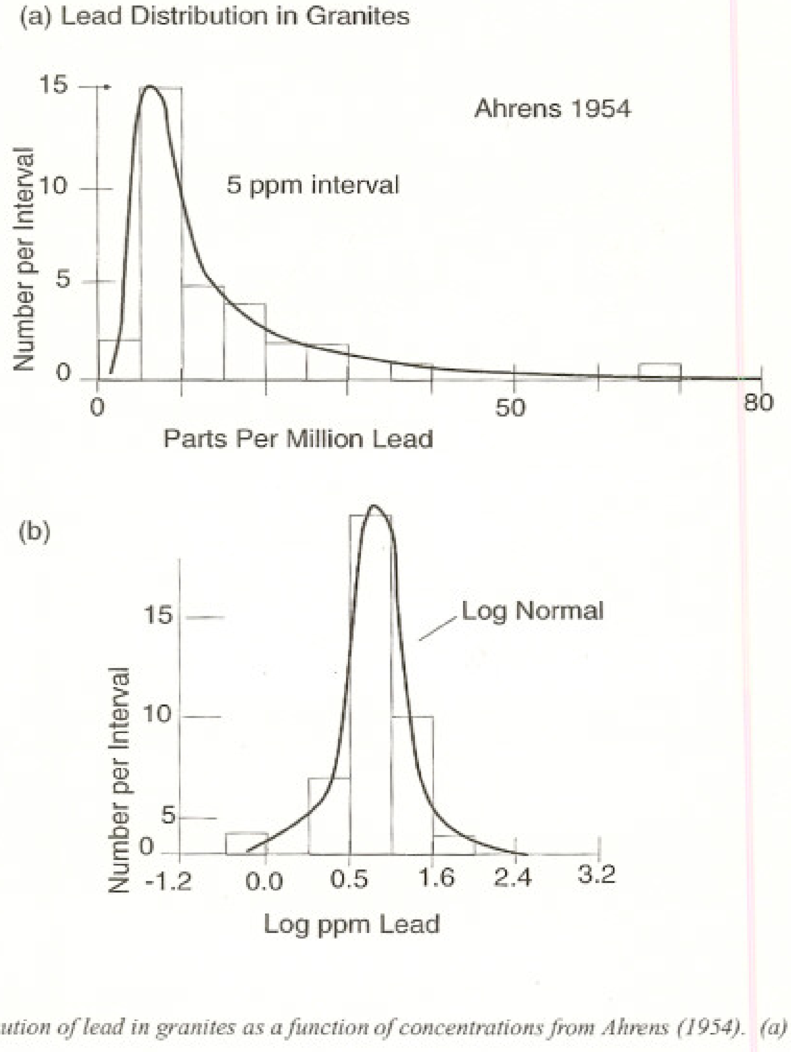
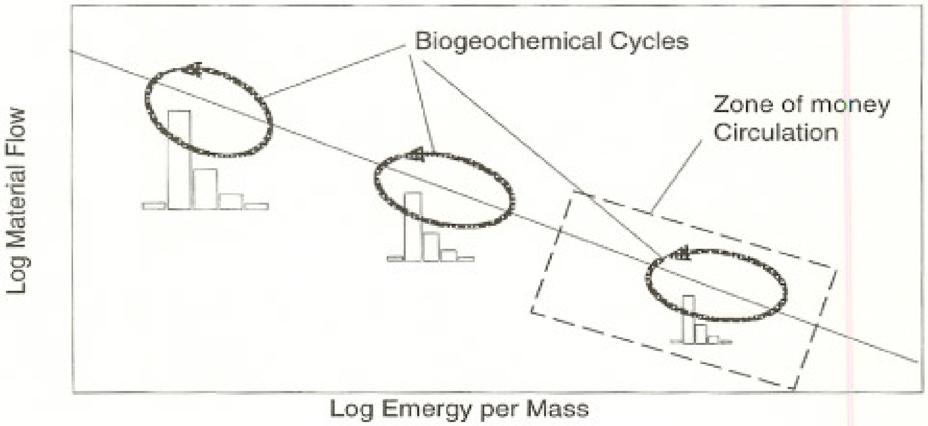


***Figure** 7. Distribution of lead in granites as a function of concentrations from Ahrens (1954). (a) Linear plot; (b) log normal plot.*

range of the energy transformation hierarchy where it can contribute production and empower. Its emergy/mass indicates the position of a material concentration in the energy hierarchy. It also indicates where in the emergy spectrum it is observed in amplifying interactions. Three transformity zones are drawn on the energy-transformity spectrum in Figure 8a where several material cycles are coupled to different zones of the energy hierarchy spectrum. Within each there is the concentration and dispersal phase and a skewed material distribution that results with decreasing energy (small bar graphs in Figure 8a).

Many values of emergy per mass of concentrated materials are available (Brown 1995; Odum 1996; Buranakarn, 1998; Odum, 2000b). The emergy per mass of material participation ranges over many orders of magnitude for different materials. In Figure 8 emergy/mass zones are indicated for water vapor in the atmosphere, fresh waters, and biogenic carbon in a rain forest.

(a) Material Spectrum



(b) Examples

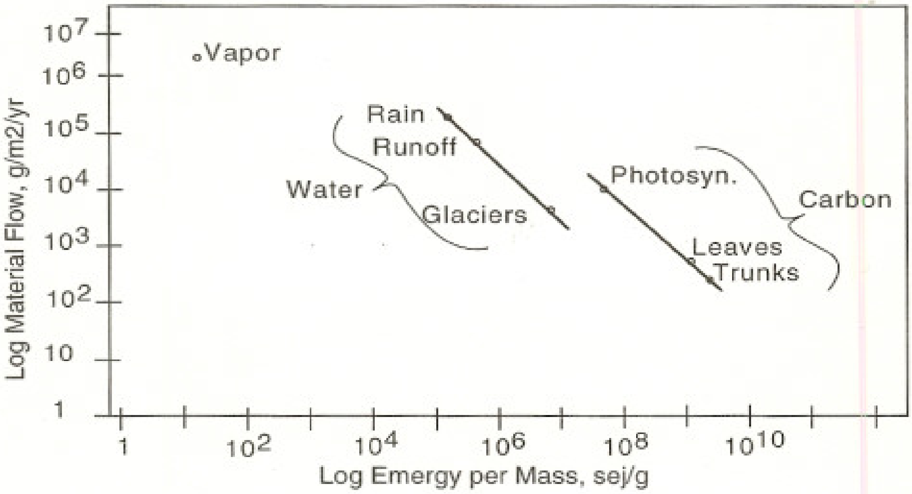


Figure 8. *Zones of material cycles of materials in the hierarchical energy spectrum. (a) Energy hierarchical spectrum from Figure 1c showing the cycles of different materials in different zones; (b) log-log plot of mass flow as a function of emergy per mass. See Endnote 1.*

On the earth, air circulates with energy interactions of low unit emergy. At the high end of the emergy/mass spectrum there is mountain building and the circulation of gold. Even within human settlements there is recycle of silver at the right, aluminum in the middle, and carbon-dioxide more to the left. Those to the right have less quantity and higher emergy per mass than those to the left. The reason items are scarce is because more emergy is required. For overall efficiency, systems can self organize to make more impact with the high emergy/mass of scarce materials hierarchically concentrated at high concentration.

Corollary of Material Pulsing

Because the reinforcing, amplifying feedback of each kind of energy occurs in pulses, the coupled materials are released in pulses also. Since there is an increase in period and intensity of energy pulses along the energy transformation series, the pulsing release of coupled materials also increases in period and intensity. The higher concentrations of materials in higher level units can accelerate their own cycles by their pulsing feedbacks. Examples are volcanic emissions, the pulsing release of wastes by birds and mammals, and the pulsing recycle of waste materials in human affairs.

AN ENERGY LAW OF MATERIAL PROCESSING

The reasoning in the preceding sections about the coupling of materials to energy hierarchy leads to a summarizing general principle:

Material cycles are hierarchically organized in a spectrum measured by emergy/mass that determines mass flows, concentrations, production processes, and frequency of pulsed recycle.

This principle is a consequence of the relationship of materials and energy in a self organizing universe. Perhaps it is useful to add it as #6 in the list of proposed energy laws in Table 1. Or perhaps it should be regarded as a corollary to the energy hierarchy principle (proposed 5th law).

Policies for Material Conservation and Recycling

Principles are useful if they help us visualize simply the vast data on material flows and distribution in our world. By recognizing the energy coupling, and using emergy and transformity indices of the energy hierarchy, numerical values can help us manage materials, material cycling, and evaluation of what is beneficial. By characterizing materials and their concentrations in units of emergy per gram, perhaps we can select a priori where in the landscape materials best fit for sustainability of the whole system.

Zone of Money Circulation in the Energy Hierarchy, Biogeoeconomics

The market economy operates in a zone of the energy hierarchy where emergy of human work is appropriate. Money circulates in markets but not to lower emergy zones of nature and not with many information transfers at very high emergy zones. Where the material cycle is within the zone of circulation

Table 1. Energy Laws Accepted and Proposed1st--Conservation

2nd--Spontaneous dispersal
3rd--No complexity of heat at absolute zero
4th--Self organization for maximum empower
5th--Energy transformations form a hierarchical series measured by transformity increase.
6th--Material cycles have hierarchical patterns measured by emegy/mass that determines its zone and pulse frequency in the energy hierarchy.

of money on the scales of transformity and emergy/mass, the materials can be processed effectively with market economy. See the examples of this biogeoeconomics principle (Boggess, 1994). High concentrations of phosphorus in fertilizer and high waste concentrations were economical to process, whereas circulating low concentrations to the environment was not economical. Materials with lower emergy/mass have to be recycled to maximize benefit, but incentives may be needed. When dilute materials with low emergy per mass values go to the environment, they need to be routed to the zone of the landscape where that emergy per mass interacts appropriately.

SUMMARY

By recognizing the energy basis for material cycling, we can understand the often observed log-normal patterns of material distributions and the spatial convergence of biogeochemical cycles to centers of concentration. A principle of universal material distribution and processing is proposed as a 6th energy law. *Materials of biogeochemical cycles are hierarchically organized because of the necessary coupling of matter to the universal energy transformation hierarchy.* Material network diagrams used to represent material flow budgets can be redrawn with a common structure from left to right in order of emergy/mass. Concentrating pathways pass left to right while dispersing recycle to lower emergy flows from right to left. More graphs are needed of emergy per mass vs material concentrations and plots of mass flow vs emergy per mass.

Endnote for Figure 8

Emergy of atmosphere from Odum, 2000c, and Odum et al., 2000; carbon flows for Tabonuco rain forest in Puerto Rico from Odum, 1970; annual empower of the forest estimated as sum of empower of transpired rain: (1.71 m^3/m^2/yr rain)(1000 kg/m^3)(4.93 E3 J/kg Gibbs energy relative to salty leaves)(1.82 E4 sej/J) = 1.53 E11 sej/m^2/yr; and the empower of eroded rock previously uplifted: (erosion 162 g/m^2/yr)(1.0 E9 sej/g) = 1.62 E11 sej/m^2/yr.

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