Ecosystem Theory and Application,
Edited by Nicholas Polunin for Environmental Monographs and Symposia.

XVII

Enmergy* in Ecosystems

by

HOWARD T. ODUM

Professor, Department of Environmental Engineering Sciences,
University of Florida,
Gainesville, Florida 32611, USA.
(Current address: *Lyndon B. Johnson School of Public Affairs,*
Drawer Y.,
University of Texas, Austin, Texas 78712, USA.)

INTRODUCTION

In the hierarchy of Nature, energy is transformed successively through many stages, resulting in products that are essential to ecosystems and to the economy of humanity. The solar energy required for a product of Nature is called the Solar ENMERGY (solar enmjoules). The solar enmergy required to generate a joule of each kind of product is the solar TRANSFORMITY of that product. In this chapter the enmergy concept is applied to ecosystems.

Just as the work of humans and machines generates inputs to the economy, the work processes of Nature also contribute. By evaluating Nature's work in making soils, minerals, clean water, biomass, information, etc., on the same basis as the works of humans, the dollar or other currency values of various aspects of Nature are estimated. These methods allow choices to be made as to which uses and management of Nature contribute most to the combined economy of humanity and Nature.

REVIEW OF PREVIOUS STUDIES

Ideas of energy being the basis of all natural and other phenomena developed with the concepts of energy in the last century. Thus Boltzmann (1905) described the struggle for existence as the struggle for free energy, while Maxwell (1877) generalized the concept of work as energy transformation. The acceptance of the Second Law of Thermodynamics implied that degraded energy was inferior, and that not all energy could do work. Carnot's formulation (1824) showed the fraction of heat that could be converted to mechanical work. The Carnot ratio ($\Delta T/T$) was an energy-quality ratio for relating heat to work.

17 Pgs

Lotka's clear statement of the maximum-power principle (1922) implied feedbacks of energy towards the further energy utility of the surrounding system. Efforts by 'technocrats' to generalize value concepts using energy (Scott, 1933; Hubbert, 1934) were not generally accepted because all kinds of energy were regarded as equal. Diagramming systems with evaluated energy-flows became common, earlier in this century, for descriptions of natural systems of The Biosphere and the economy (atmosphere, Simpson, 1929; economic use, Zimmerman, 1933; ecosystems, Juday, 1940). In webs and chains of systems, energy decreases at each stage as energy disperses and the type of energy is changed. By 1971, Tribus & McIrvine (cf. 1971) had summarized the general emerging belief that energies of different types were not equal in their ability to do work.

Lindeman (1942), in diagramming and evaluating energy transformations in ecosystems, considered various efficiencies and ratios. One of these, the ratio of energy output from a particular trophic level to that of another—the less valuable inflowing type—is the reciprocal of the transformity used in this chapter. It was probably taken for granted that a Calorie of top carnivore meant more than a Calorie of phytoplankton. There were efforts to use actual energy as a measure of what was dominant in an ecosystem (e.g. Whittaker, 1965). These efforts generated strong opposition, as most people knew that a joule in fish had more effect on an ecosystem than a joule of sunlight.

H.T. Odum (1967, 1971) used organic Calorie equivalents as a measure of embodied energy (the energy required to generate a flow of kinetic energy). As energy analysis of engineering systems became important in the new period of energy shortage, thermodynamics research workers distinguished those energies which were capable of doing mechanical work, and energy available for such a purpose was given the name of *exergy* (Evans, 1969; Sussman, 1981). However, this finds a Calorie of free energy in dynamite the same value as a Calorie in glucose, and does not recognize the very different energies embodied in differential chemical substances. We accordingly introduced the energy transformation ratio, now called transformity, as a measure of quality as applied to both environment and the economic systems (H.T. Odum, 1976, 1978; H.T. Odum & Odum, 1976). Most of the energy analysis dealing with the energy crises of 1973–80 did not recognize different qualities. Pimentel (1979), for example, calculated net energy of crops, giving a Calorie of human effort the same weight as a Calorie of oil.

Hannon (1973*a*, 1973*b*) used an input–output matrix to describe the flows of actual energy in an ecological web in the same way that dollar flows are described in the Leontief (1966) input–output matrix.

One of the several concepts of embodied energy evolved as part of studies of the input–output matrix way of representing systems (Herendeen & Bul-

---

* Originally called 'emergy', but *see* footnote and text on page 343.—Ed.

lard, 1974). The input energies to the system were assigned to the pathways in proportion to the flows in the matrix, whether they were expressed in dollars, tonnes, or actual energies. The procedure (Herendeen, 1981) calculates embodied energy per unit flow for the pathways by an inverting matrix procedure: when the data are in dollars, these ratios are of embodied energy per dollar. Such ratios are sometimes called 'energy intensity factors', and are used to estimate energy converging on a particular process of interest. The procedure divides the input energy among sectors according to the dollars, and in effect makes them linear and additive. It divides up the energy within the web in an arbitrary, automatic way.

This may not be the most useful concept of embodied energy, as it implies that less than the total input energy is required for a pathway. There is no reason why energy effects should be assigned according to dollar-flow except in the aggregate. As these systems are non-linear, linear procedures may not be appropriate.

Following procedures used in economics, where convergence to final demand was of interest, earlier calculations considered only fuels, regarding them as of the same quality, and in order to avoid double-counting, omitted feedbacks from the final-demand sector. However, omitting the last column of the matrix omitted those embodied energies that went from one sector to final demand, and then back to another sector as services.

Costanza (1979, 1980) used the input–output matrix way of assigning energy-flows to economic webs and world biospheral webs. He included all sectors—even the final-demand sector—and both environmental energies and fuels. This procedure also assigns the input energies to pathways within the web by a matrix inversion procedure that subdivides the total, so that the pathways are additive. This is a different concept of energy embodiment from one which answers the question: how much energy was required to develop the pathway?

Patten (1978), using matrix methods, developed a concept of causality, tracing effects of one sector of a web on another through successive time-steps. The ecosystems studied in this way were linearized by calculating with steady-state models. When energy is used for the numerical properties of the web studied, this approach may be a way of tracking actual energy, and might be adapted as an embodied energy method. By 1981, there was general agreement that energies were of different qualities, and that actual joules are not adequate for projecting effects of energy and its ability to support processes; but the ways of dealing rigorously with such matters of quality were much in debate.

The issues involved in energy accounting were reviewed in summaries by Slesser (1978) and Fluck & Baird (1980). Partial energy analyses were made with fossil fuels, without including energies of very different quality such as sunlight, human labour, and information.

A manual of energy analysis using solar equivalents as a common denominator was prepared along with applications to power-plant siting by H.T. Odum *et al.* (1983). Uncertainties in relating sunlight to fossil fuel were reviewed by Lavine & Butler (1982). The behaviour of embodied energy in webs was described by H.T. Odum (1983, ch. 14).

The Earth energies that are part of the total environmental works of The Biosphere were included in order to involve all sources. This and refinements in estimating sunlight equivalents of coal changed the transformities (formerly called energy transformation ratios). These new values were used to analyse 12 countries (H.T. Odum & Odum, 1983), agriculture (H.T. Odum, 1984*c*), foreign trade (H.T. Odum, 1984*b*), and coastal management (H.T. Odum, 1984*a*).

The concepts and terms of *enmergy* and *transformity* are employed in this chapter to evaluate the pertinent parts of ecosystems and to suggest hypotheses concerning energy relationships.

CONCEPTS AND DEFINITIONS

Concepts and definitions presented below are given with reference to Figs 1 and 2. As webs with branches and feedbacks are normal components of ecosystems, energy network diagrams may be necessary for clarity of definitions. In Fig. 1a, solar energy is shown driving an energy-web of a system with energy transformed in each symbol, some being dispersed in degraded form at each step as potential energy is used up. The energy transformed at each step is much less in quantity than the energy entering that step. Ultimately, transformed energies feed back to act in multiplier interactions (directly or indirectly), in mineral cycles, and in information transfers, control actions, reproduction, spatial operations, etc.

However, when some part of the system is examined in the context of narrower boundaries, as is done in Fig. 1b, there are three energy inputs observed, and someone calculating the inputs might regard them as separate contributors to the output. Yet as these pathways are by-products, they represent manifestations of the same original energy inflow (Fig. 1a).

If one of these pathways is discharging a storage made at an earlier time, it does represent a different energy manifestation from that currently incoming from the Sun. If the system has been evaluated for its steady-state average flows, then storage contributions and various feedback inputs may be ignored when the purpose is tracing contributions of energy-source. With this perspective on the nature of energy webs, we can set out definitions as used herein:

Enmergy:—This is the energy of one type which is required to generate that of another type, commonly for a product of Nature. In Fig. 1, solar enmergy is the solar energy-flow required to generate any other flow that is being considered. The units of enmergy are 'enmjoules'. In Fig. 1 all pathways have the same enmergy, namely 1,000 solar enmjoules (enmj.).

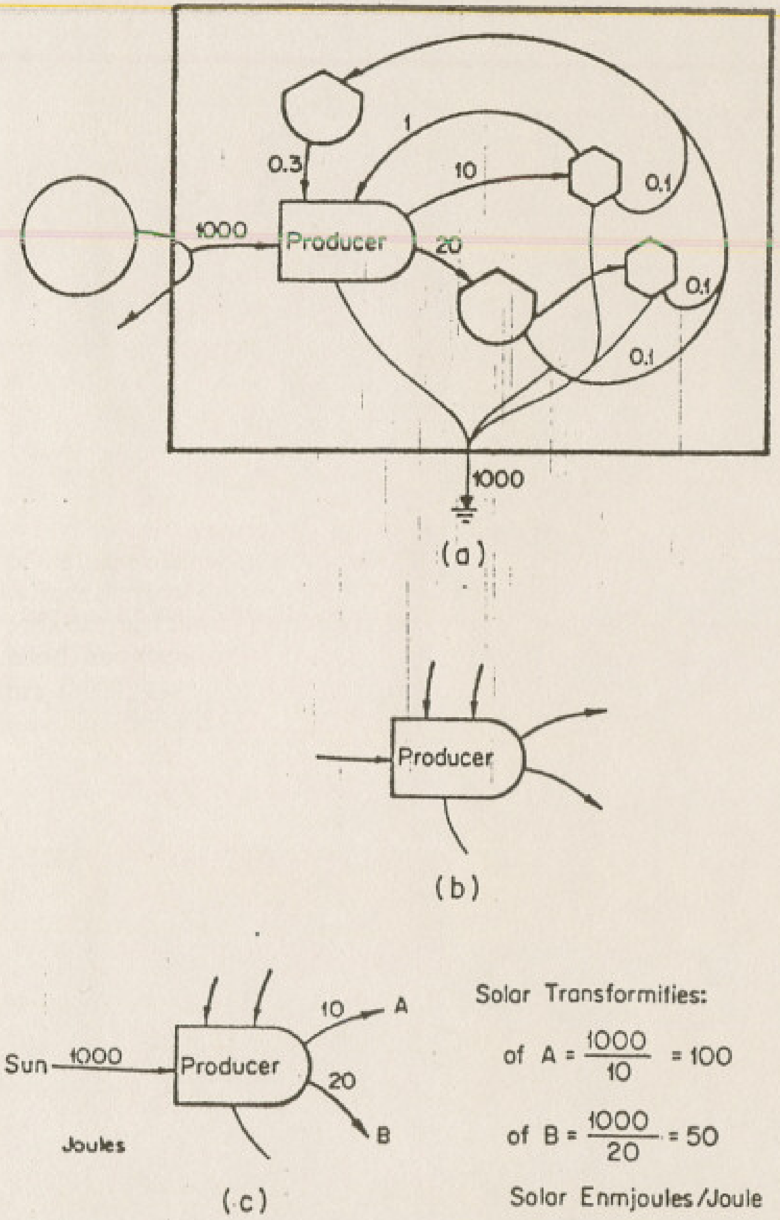

Fig. 1. A simplified system web for explaining concepts: (a) Web of producers, consumers, feedbacks, and recycle, running on one source; values are energy flows in joules per unit time. (b) Producer from the web isolated to show how more sources seem to be involved when viewed with a local viewpoint. (c) Example of transformity calculations from energy flows in a web.

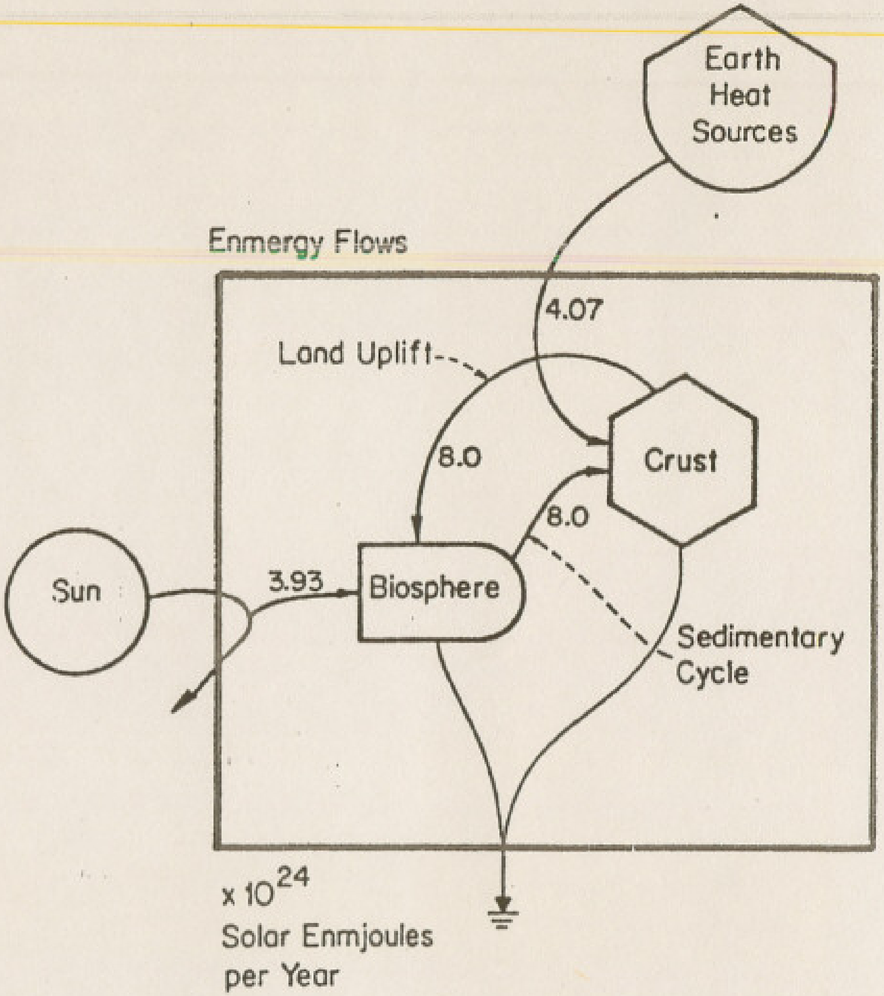

Fig. 2. Diagram summarizing the main energy basis of The Biosphere. Values are enmergy flows. The enmergy of Earth heat use was estimated from rates of Earth heat diffusion and a transformity of 6055 solar enmjoules/joule (H.T. Odum & Odum, 1983).

The term 'emergy' was suggested by David Scienceman, of University Schools Club, Sydney, Australia, 'to avoid confusion with energy', and seemed appropriate for a quantity that measures emergent properties of Nature. Dr Scienceman described the name as a contraction of 'energy memory'.* Other names that have been suggested are envergy and embergy.

Observed enmergy:—The energy-flow empirically observed to be responsible for a particular flow is the empirical quantity measured in any system, even one that is not competitive.

Maximum-power enmergy:—This is defined as the least flow of enmergy that is capable of generating the flow in question under conditions which maximize the power of the whole system. It is possible to transform energy at either slower or faster speeds than that which generates maximum power. Slower speeds give higher efficiencies and faster speeds give lower efficiencies (H.T. Odum & Pinkerton, 1955).

It is an old-standing hypothesis that systems are self-organized for maximum power (Boltzmann, 1905; Lotka, 1922) and, thus, long-operating systems may have their observed enmergy close to those which accompany designs that maximize power. If maximum power is the design principle of self-organizing environmental systems, then the maximum-power enmergy can be regarded as the open-system thermodynamic limit to energy use. Any theories or measurements that help us to estimate these enmergy values, help us to predict, from first principles, the way in which energy underlies the organization of ecosystems.

Steady-state enmergy:—This is the enmergy that is estimated from steady-state system averages. It may be that observed for short periods among empirical data. Theoretically, there may be a maximum-power, steady-state value, although we may not have either long enough data-series or adequate theory yet to compute them.

In this chapter observed, empirically-factual, enmergies are considered because they are the best estimates we have or seem likely to acquire of maximum-power and steady-state conditions. As ecosystems have 'been around' much longer than current human economic systems, the observed data in ecosystems may be closer to the ultimate best values for survival than data from economic systems.

Enmergy in enmjoules is measured by the energy units that are employed. International commissions have made the joule the standard unit of energy, although in this they have inadvertently disturbed a traditional but unstated engineering use of the joule for energy of mechanical and electrical quality. Using joules and calories as interchangeable units for energy of all types ignores energy quality.

A kilocalorie is 4,186 joules of heat in current use. Both units are used in this chapter. Kilocalorie is abbreviated Calorie or Cal. here. A current research area in ecological energy analysis uses *exergy*, the actual mechanical energy, as a measure of useful work (Jorgensen & Mejer, 1977; Mejer & Jorgensen, 1979); but this ignores the wide range of energy qualities within chemical, electrical, and mechanical, processes that have the same exergy (mechanical work).

---

* Our many years of editing experience, however, leads us to believe that it would be difficult, if indeed possible, to find any two terms that would be more likely to cause chronic confusion in print than 'energy' and 'emergy', and so (with Professor Odum's full approval) we are using 'enmergy' in the present work.—Ed.

The notation used here for powers of 10 is that used by computers and increasingly in manuscripts and printed texts. E5, for example, mean 10^5.

Enmergy Sources of The Biosphere

For the overall global web shown in Fig. 2, there are two main sources, the Sun's light and Earth's energy. As indicated in Fig. 2, the internal closed-loop pathways are all given the same value of enmergy, namely 8 solar enmjoules per year. These 24 solar enmjoules comprise the sum of the enmergy inputs of the two sources.

Other concepts of embodied energy may not be wrong: but they are different, and the numbers which these definitions generate may have different utility and theoretical meanings, such that they will need different names.

Transformity

Transformity is the joules of one energy type which are required to generate a joule of another type. The units are solar enmjoules per joule. If, as is done in Fig. 1, the feedback inputs can be ignored because they are by-products of the same original source, then the solar transformity of any flow is the ratio of steady-state inflow of solar enmjoules to the flow of joules of that pathway in the web (*see* examples in Figure 1c). A solar enmjoule per joule is equal to a solar enmcalorie per calorie (solar enmjoule per joule may be abbreviated sej/j).

Whereas the enmergy may be large or small, depending on whether there is a large or small area of the Earth involved, the transformity gives the enmjoules required per joule. It is an intensity factor (rather than capacity factor) that measures the amount of energy of solar type which was converged and dispersed in the process of generating the higher-quality flow to the right in the web.

Source Method for Estimating Transformity

One way of estimating solar transformities is from solar-based webs on which are placed actual flows of energy. The solar energy driving the steady-state system (Fig. 1c) is divided by the energy flow of the pathway.

Method of Back Calculation of Transformity from Effects

Another way of estimating transformities from systems is indirect. Estimating how much carnivore can be produced from a particular energy-flow allows that flow to be related to some other energy which also generates the carnivore. Because high-quality energies are flexible, they can often be generated from more than one source and thus it is easy to use the high-quality products as a common denominator to compare other flows. The transformities that are developed with this procedure may not be the ultimate, most efficient ones for maximum power—if the processes which are being related are new, and not yet evolved in competitive economies.

Net Production—Net Enmergy

Net production in ecology is a productive flow that is in excess of some concurrent diversions and uses. There are as many kinds of net production as there are situations with branching flows and storages. Generally, calculations of net production have been given in actual energy units or units of biomass or carbon to which energies are somewhat proportional. As shown in the example in Fig. 3a, the energy content in the productive flow to the right is much greater than the small Calorie content in feedback control pathways. Rarely has the feedback's energy been considered important in estimating net productions. The following is the traditional definition:

Net production of energy is the energy-flow at a point in a system in excess of feedback of the energy required. Unfortunately, this measure is not a measure of the net contribution of a life-supporting resource to the system: actual energy measures do not recognize energy quality, and the ultimate energy requirements are not the actual energies remaining in that pathway.

Net Enmergy

An improved concept of net enmergy was developed to include considerations of energy quality (H.T. Odum, 1976). Net enmergy is estimated after energies are multiplied by transformities to obtain solar enmergy of production and feedback. The following definition is illustrated in Fig. 3b.

Net enmergy is the enmergy contribution of a flow in excess of the high-quality energy used, where both are expressed in solar enmjoules.

In the example in Fig. 3b, the feedback is found to have the same solar enmergy as the productive flow, so that there is no 'net enmergy' in our present sense. Many processes that have net energy are found to use more enmergy than they generate when ultimate energy sources are traced, using transformities.

The *Net Enmergy Yield Ratio* is the ratio of the yield to the feedback from the economy, both expressed in enmergy units (enmjoules per unit time). The higher this ratio is, the more will be the net enmergy available for processes other than the one analysed.

The *Energy Hierarchy Graph* (Fig. 4) is a special kind of power spectral graph on which can be plotted energy flows or energy storages so as to

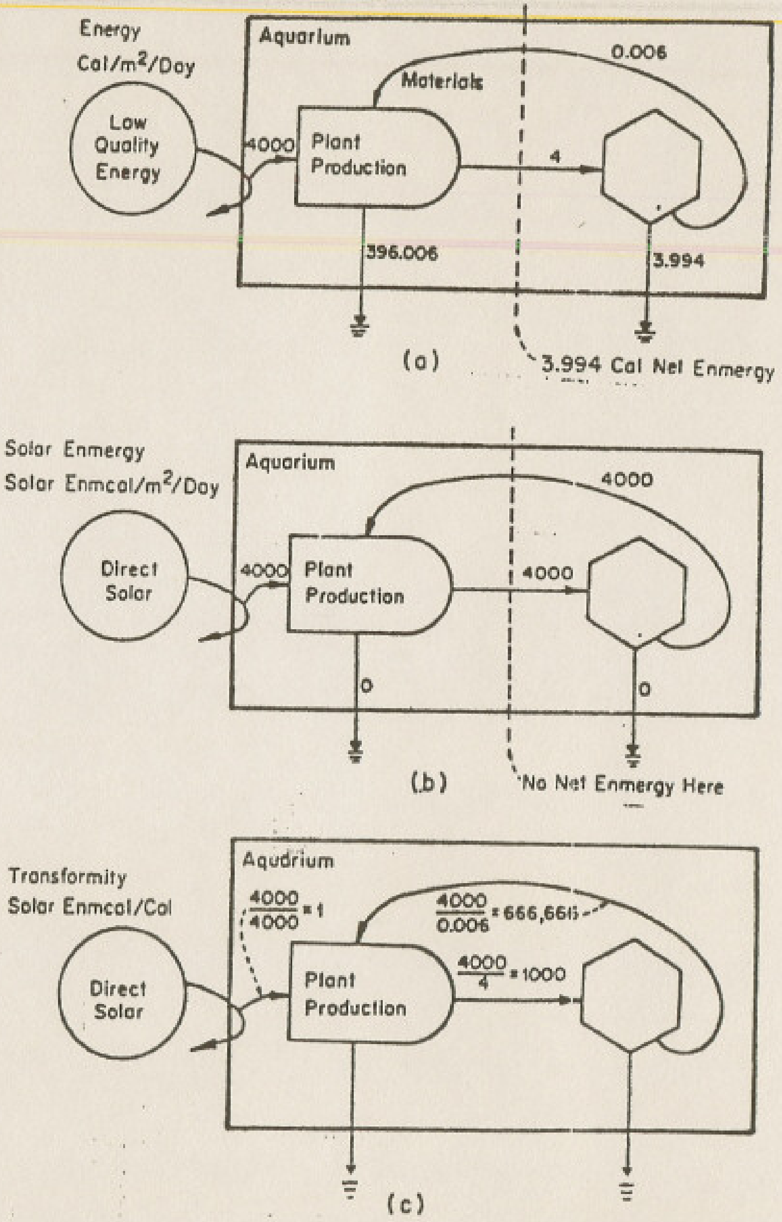

Fig. 3. Diagram of the energy web of an aquarium, illustrating the concepts of net production and net enmergy: (a) Enmergy flow with net production calculated as Calories of energy-flow. (b) Enmergy flow with net enmergy calculated in units of solar enmergy so as to reflect energy actually required directly and indirectly. (c) Transformities calculated by dividing enmergy flow in (b) by energy flow in (a).

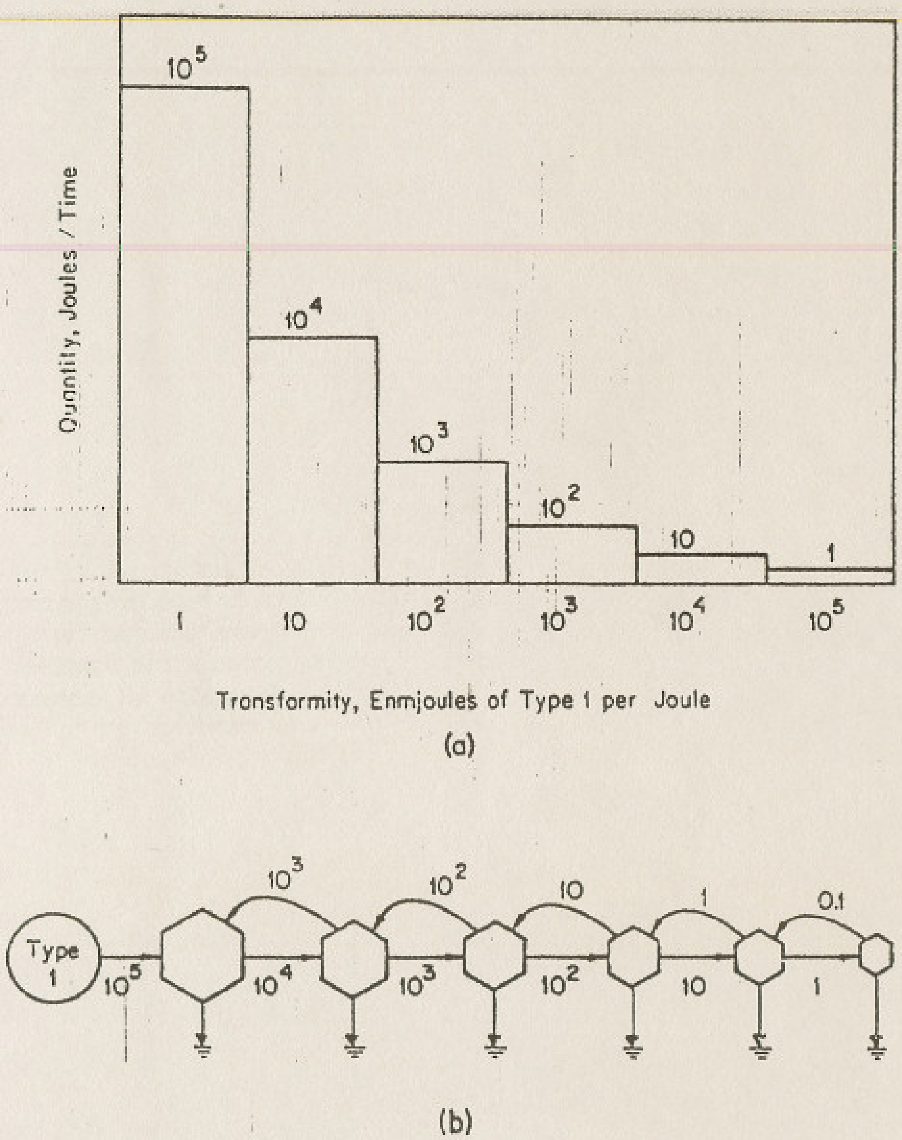

Fig. 4. Energy hierarchy graph giving the distribution of energy according to transformity on the horizontal axis: (a) the graph, and (b) system diagram of energy flow.

represent actual energy quantities according to the transformity of each. If there is one energy source that generates an energy web or chain (such as a food-chain) with dispersion of potential energies at each transformation stage, then the graph may be exponential in form if there is a succession of constant percentage drops at each stage. The product of each transformation stage is a smaller energy-flow of higher quality than that which generated it. Many ecological phenomena may be manifestations of the hierarchy of energy transformations as explained with this graph.

This graph is a generalized application of the Maxwell–Boltzmann distribution for molecules in which many lower-energy molecules on the left contribute to successively lower quantities of higher-energized molecules on the right. Whereas the Maxwell–Boltzmann distribution was applied to quasi-equilibrium states, the generalized use of the energy hierarchy graph may be applied to both open and closed systems. The energy-flow and/or -storages on the left of a point on the graph are required for the energy to the right of that point. The horizontal axis is represented by the transformity increasing to the right. The vertical axis is the quantity of energy of the transformity given on the abscissa.

Enmergy Signature

The set of inflowing energies constitutes a 'signature' of the environmental condition of an ecosystem. The combination of driving sources and their relative magnitudes, succinctly characterize the resources to which self-organizing ecosystems can develop adaptive structures and processes.

A convenient way of representing an ecosystem's biotope is to arrange sources in order of their transformity, either in a bar graph such as Fig. 4a, or around the edges of an energy system diagram such as Fig. 5. After energy flows are estimated, they may be multiplied by the appropriate transformities to provide the total enmergy expressed in solar enmjoules for each inflowing source (Fig. 5c).

Enmergy in a Storage

Ecosystems have valuable storages, such as those of living biomass, peat, soil, wood, mineral concretions, gene-pools, etc. The enmergy in a storage is the enmergy flow which is required to develop the storage, multiplied proportionately by the time needed to generate the storage. Another way to calculate the enmergy in storage is to multiply the stored potential energy by the solar transformity of the type of energy in that storage.

Energy Quality Interpretations of Ecological Phenomena

Energy quality considerations provide some new insights into ecosystems, their driving sources, their hierarchies, their populations, oscillations, and catastrophies, and their organisms or biota as well as their biology and autecology.

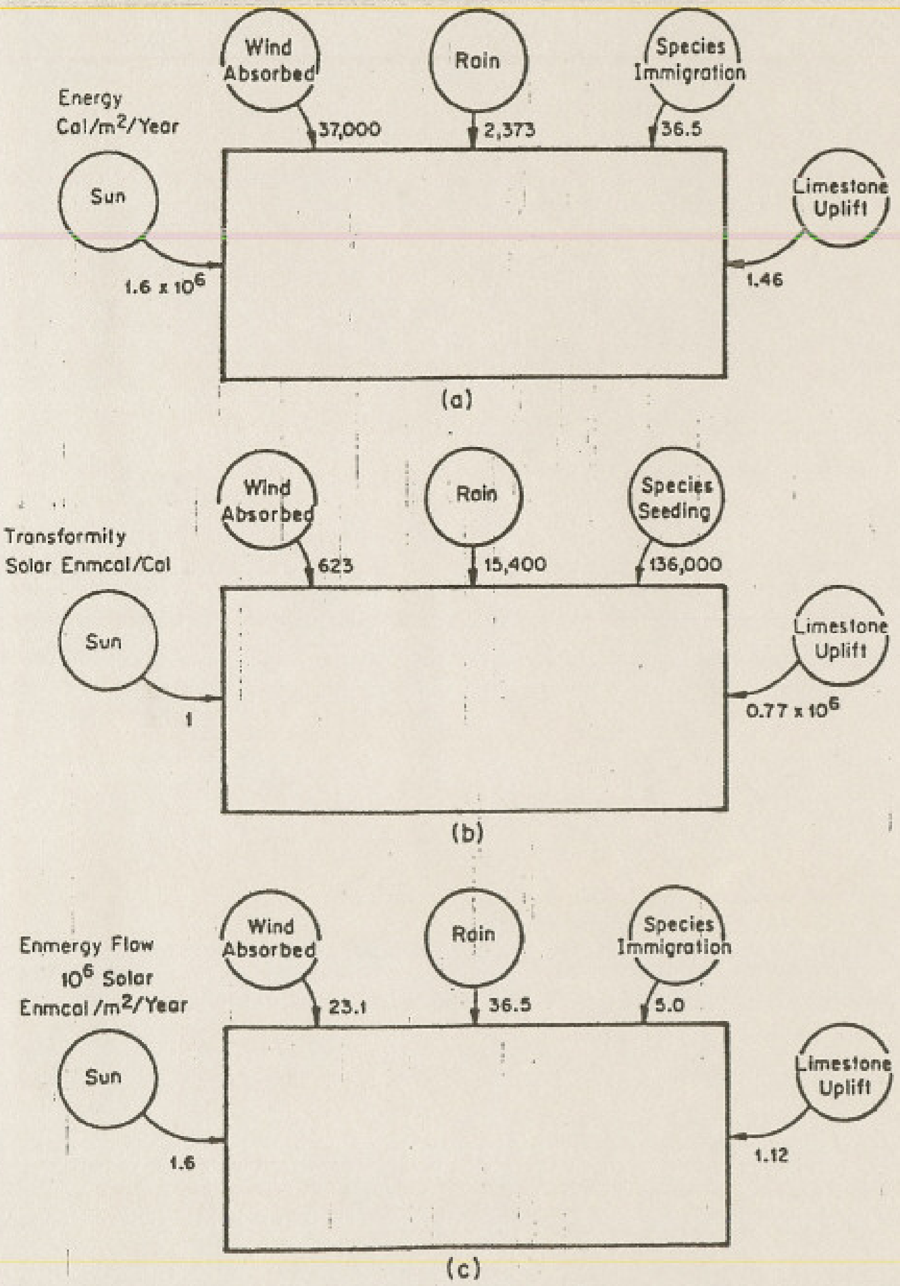

Fig. 5. Representation of forcing functions (energy sources) in Florida landscapes: (a) Energy flows. (b) Solar transformities from Table I. (c) Flows of solar enmergy calculated as product of numbers in (a) and (b).

Transformity of Ecosystem Sources Comprising Biotopes

Any overall systems view of ecosystems recognizes many outside input sources, including sunlight, rain, nutrients, geological influences, and genetic information in the seeding of species into the system. These sources may be ranked by transformity, starting with solar energy as one. Transformities for many environmental sources were determined earlier (H.T. Odum *et al.*, 1983); some of these are given here as Table I.

In order to make energy systems diagrams hierarchical, uniform, and congruent with those of other workers, the convention is suggested that external sources be arranged from left to right in order of transformity. As in other webs and as was illustrated in Fig. 4, the quality (transformity) goes up from left to right as the remaining energy quantity goes down. This convention was used in the second edition of *Energy Basis for Man and Nature* (H.T. Odum & Odum, 1981)—and in *Systems Ecology* (H.T. Odum, 1983)—*see* examples in Fig. 5. Energy sources are also the external forcing functions of simulation models. Mathematical definitions of transformity in terms of Fig. 4 and hierarchical spectra were given elsewhere (H.T. Odum, 1984*b*).

TABLE I

Transformities of Some Main Sources 'Driving' Ecosystems. *

Energy source	*Solar enmjoules per joule*
Flows	
Sun	1
Wind	623
Rain over land (chemical energy)	1.54×10^4
Waves	2.59×10^4
Tide, physical potential	2.36×10^4
Stream flow, physical energy	2.36×10^4
Earth cycle	2.9×10^4
Primitive human labour	8.1×10^4
Species seeding†	4.4×10^5
Storages	
Wood biomass	3.5×10^4
Soil	6.3×10^4
Phosphate	4.1×10^7

* A selection from a larger table of transformities calculated from analysis of environmental systems and from the world web of energy-flow (H. T. Odum & Odum, 1983).

† Transformity of seedfall = 4.4 E5 solar enmjoules per joule:

$$\frac{(8.0\ \text{E24 solar enmjoules per year})}{(1.5\ \text{E 14 m}^2\ \text{land})\ (2\ \text{g/m}^2\ \text{day litterfall})\ (1.67\ \text{E4 joules/g})\ (0.01\ \text{seeds})\ (365\ \text{days/y})}$$

An examination of the outside sources arranged in order of their transformity gives also an arrangement in inverse order of their flow of energy. Multiplying these, as in Fig. 5c, produces a source 'signature' expressed in enmergy units (solar enmjoules). Autecological traditions have always recognized the importance of various types of environmental factors without regard to actual energy. This tradition is continued by using enmergy for determining the influence of sources. Because rain represents a large area of oceanic solar energy embodied in the water that converged on land, many ecosystems have more solar enmergy in rain than in direct sunlight (*see* example, Fig. 5c).

Chemical Substances in Hierarchies of the Universe

That the Universe is hierarchically organized has been made obvious by those reporting results of astronomical studies. The energies incoming from space are hierarchically organized, with much low-energy radiation and less high-energy radiation. The matter of the Universe in stellar dust, and the matter of the Earth, also reflect the prior hierarchical distributions of energy in the processes that generated the elements. For example, there is very abundant hydrogen and much smaller amounts of the heavy elements.

Within the Earth, the geological and geochemical processes also constitute a hierarchical system. Dilute energies of sun, radioactive heat, and residual heat, are converged within Earth's systems by means of hydrological and sedimentary cycles into highly-organized and intense pulses of earthquake and volcanic eruptions that build continents, mountains, trenches, and volcanoes. These Earth hierarchies produce further chemical concentrations of elements that were already in a hierarchical distribution pattern resulting from cosmic actions. Further differentiation generates distinct patterns of commonness and rarity, which become available to the ecosystems for developing their structures and functions.

The enmergy and transformities of chemical substances are calculated from the energy required to generate or concentrate them from precursor states. The minerals developed in the lithosphere represent the hierarchical energy transformation process. Rarer forms of elements, crystals, and other compounds, have higher transformities. They are scarce because they require more resources than was the case with common substances. Items at the end of a hierarchical transformation-chain have to be scarce.

When ecosystems are depicted with various chemical substances—such as nitrogen, phosphorus, and copper—these can be drawn from left to right in the order of their abundance in the ecosystem, and this may also represent their order in the scale of quality (in the sense of transformity). This theory suggests that the elements with the highest transformity have the most effect per unit weight. Knight (1980, 1981), studying the productivity of microcosms, found positive and negative effects and high transformity for cadmium.

Transformity in Ecosystem Webs

Driven by the enmergy 'signature' represented in Fig. 5, ecosystems develop web-patterns connecting producers, consumers, control feedbacks, material recycles, hierarchical convergence, and storages. If the various components are arranged according to their transformity, with low quality on the left and high quality on the right, then the energy systems diagrams are simpler than otherwise, with fewer crossing lines. Diagrams become standard patterns, so that one person's diagrams are similar to and congruent with those done by another—*see* example in Fig. 6.

First, energy flows are written on the pathways, as is often done in energy analyses of ecosystems. Such a diagram, as in Fig. 6, is a first-law diagram with energy inflow equal to that stored and outflowing (as described by the First Law of Thermodynamics). The further to the right that energy flows and is transformed, the less actual energy remains, but the higher is its quality.

Next, it is possible to estimate transformities for flows and storages by estimating the solar enmergy that is responsible for the web. For example, the ratio of solar enmergy driving the web to the energy flowing through a fish population is the solar transformity of fish production.

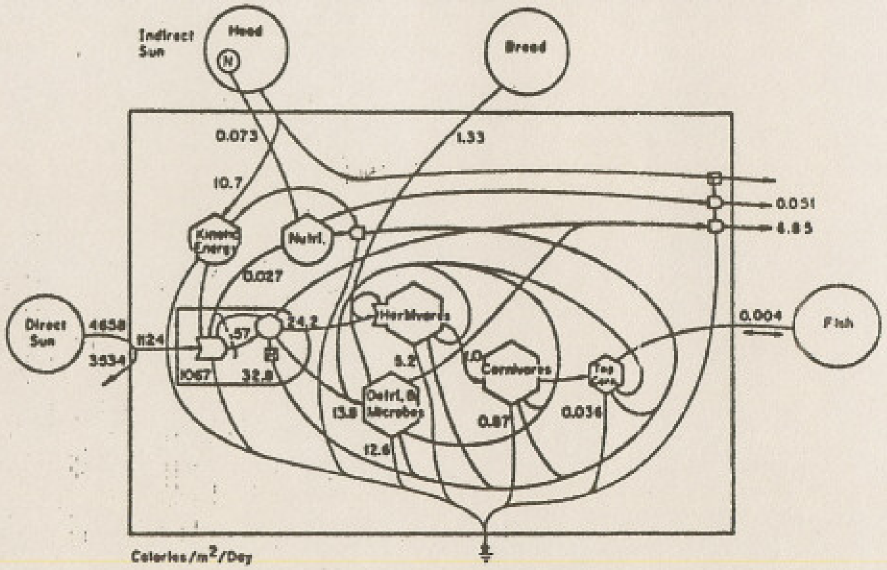

Fig. 6. Energy-flow in Silver Springs, Florida (H.T. Odum, 1955; Knight, 1981). Refer to Table II for transformities evaluating quality of energy increasing from left to right in the web.

The resulting transformities in Table II increase from left to right by position in Fig. 6. That animals, larger and longer in development, should have higher-quality energy than other sources, is to be expected, and it is useful to have a quantitative measure for comparing energy-chains.

TABLE II

Solar Transformities for Components of Silver Springs, Florida* (cf. Fig. 6).

Item	Transformity* solar enmcal./Cal.
Sunlight	1
Light absorbed in plants	224
Gross plant production	4,421
Food to herbivores	10,413
Organic matter to detritus	18,260
Hydrostatic head of inflow spring	23,600
Herbivores used by carnivores	252,000
Food to top carnivore	7,000,000
Nutrient use	9,333,000
Migrating fish	63,000,000

* Transformities in the table were calculated by dividing the solar enmergy of the river water by each energy flow.

Ratio of Solar enmergy of sources in Fig. 6 to energy flows in the system. Although there are 4,658 direct solar Calories per square metre per day driving the Silver Springs system, the solar enmergy received through the physical water-flow is greater:

Solar enmergy = (physical energy used) (solar transformity of river flow)
Solar enmergy = (10.7 Cal/m^2/day) (2.36 × 10^4 solar enmcal./Cal.)
= 2.52 × 10^5 solar enmcal./m^2/day in spring water used.

Return feedback required is the nutrient content of the produce removed in the export of 4 Calories to the right. If 1 g organic matter was removed containing 1% P, then return feedback of phosphorus needs to be 0.01 gram P/m^3/day. The plant use maintains the phosphorus concentration at about 0.001 gram P/m^3. The feedback thus constitutes a 10-fold concentration stimulus. The energy per gram

$$\Delta F = J\,\frac{RT}{}\ \ln\left(\frac{10}{1}\right)^{m}$$

$$\Delta F = \frac{(.01\ \text{g/day})\,(3 \times 10^{-3}\,\text{Cal/deg mole})\,(300\ \text{deg K})\,(2.3\ \log_{10}10)}{(35\ \text{g/mole})}$$

$$\Delta F = 5.9 \times 10^{-4}\,\text{Cal/day}$$

Although the calculation of one nutrient was used, others would give similar results if the feedback adds about ten times the lowest concentration from which the plants can draw nutrients.

Energy flows for Florida:
Wind Kinetic Energy —
Wind vertical gradient 2 m/m/s
Wind energy absorbed = (1000 m) (1.23 kg/m^3) (2 m^2/s) (2 m/s) · m × 10^{-3} m/m/s) (7534)
= 37,067 Cal/m^2/yr
Rain chemical potential energy —

$$= \frac{(1.5\ \text{m/yr})\,(10^6\ \text{g/m}^3)\,(2 \times 10^{-3}\ \text{Cal/deg/mole})\,(300)\,(\text{Ln}\ \frac{999{,}990}{965{,}000})}{(18\ \text{g/mole})}$$

= 2373 Cal/m^2/yr

Uplift of limestone —
= (2 g/cm^3) (10^4 cm^2/m^2) (0.5 cm/1000 yrs) (0.146 Cal/g)
= 1.46 Cal/m^2/yr
Energy in species seeding:
Assume 1% of litterfall as seeds etc. or about
(5 cal/g) (2 g/m^2/day) (365 days) (.01) = 36.5 Cal/m^2/yr

One of the interesting aspects of the transformities is the ability to set equivalences between things that are not part of the same web. For example, electricity and high-enmergy fish are similar in their transformity. One consequently has a choice between damming rivers to use water potential for electricity, or retaining high-quality food resources without a dam.

Transformity in Population Age-structure

Reproduction is an energy-consuming work-process which transforms various organismic energies and materials into reproductive propagules such as seeds, spores, eggs, larvae, offspring, etc. These have high enmergy as a result of the transformation—so long as they are still concentrated with the parent organism. But then these propagules disperse over a larger area, losing their concentration. This is a control feedback which decreases the enmergy per unit space. As a small high-quality energy package, a propagule interacts with lower-quality energies of the environment to develop growth and ontogenetic changes. Each of these changes upgrades the individual to a higher and higher quality by successive transformations.

The stages of development are accompanied by gradual decline in population numbers with mortality. Eventually, a high-quality mature stage is reached that once again generates reproductive propagules for dispersal.

The pattern of change of population number and size is often represented by age-structure graphs such as those in Fig. 7. Many young individuals on the left, through successive steps, generate a few mature individuals on the right. The age-structure graph generally has the shape of the transformity spectral pattern in Fig. 4. The individuals lost, and the energies flowing in their support, are embodied in those that survive to the next stage. These were necessary inputs. The role that the organisms play in the ecosystem as they are transformed to older stages increases; the realms which they cover and interact with increase accordingly, as the enmergy per individual increases.

Transformity in Life-cycles

The transformity concept provides another dimension with which to examine complex life-cycles such as those of Algae, parasites, biota having an alternation of generations, etc. The energy-quality concept suggests that such diagrams may be drawn using the conventions of Fig. 5a, with low quality but high quantity on the left, being transformed to higher quality with less and less numerous units on the right. Return feedback pathways represent products, services, and stages, which are being dispersed and thus are losing enmergy concentration. An example in Fig. 8 illustrates the concept, with dispersal processes lowering enmergy concentration. Wright (1968) models

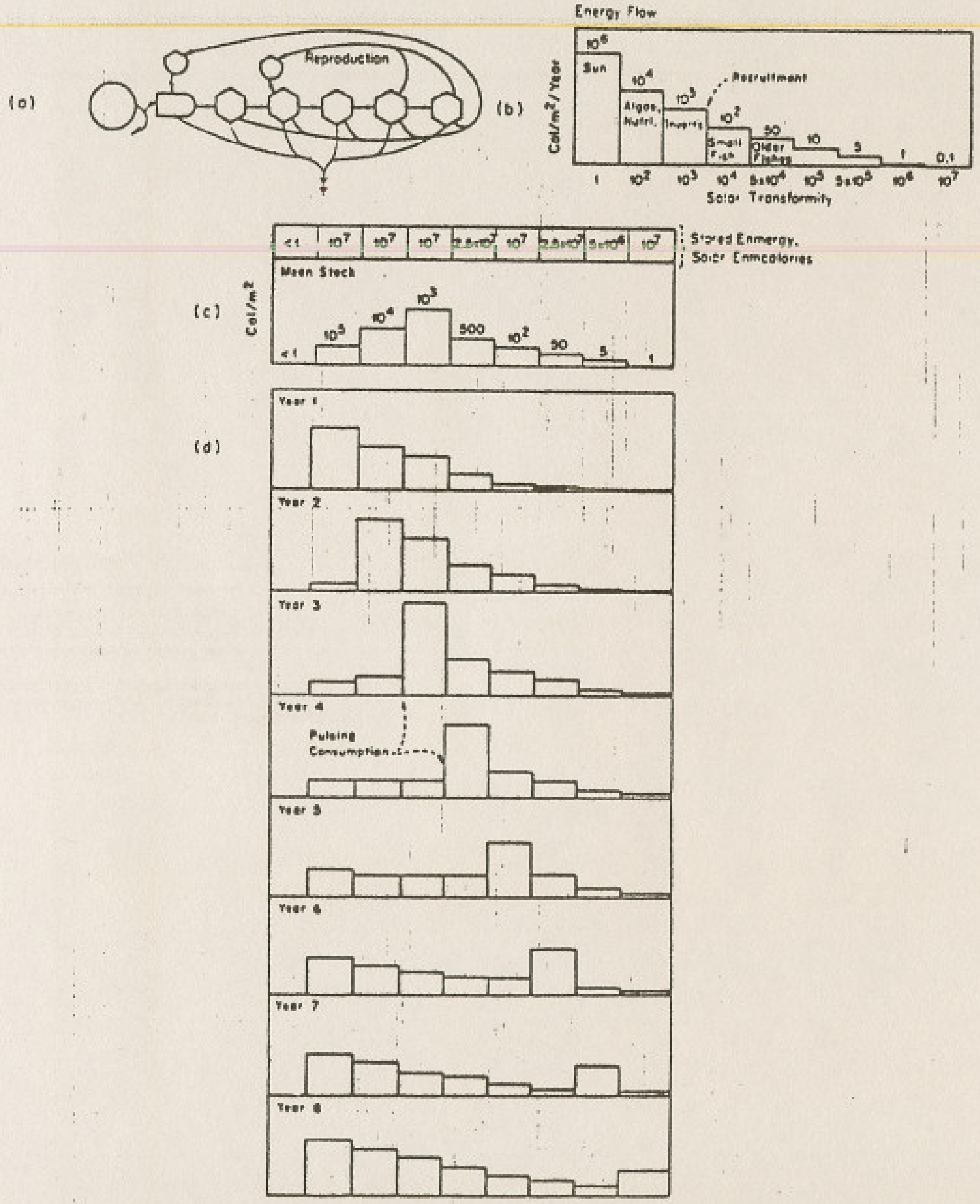

Fig. 7. Typical age-structure diagram interpreted as an energy-quality spectrum embedded in an ecosystem hierarchy. The system has energy transfers in part by consumption and in part by survival; (a) system diagram, (b) energy-flow being indicated as a function of transformity, (c) energy storages on the same plot—enmergy at each stage is also given as product of stored energy and transformity, and (d) movement of a dominant year-class as a pulsation of enmergy.

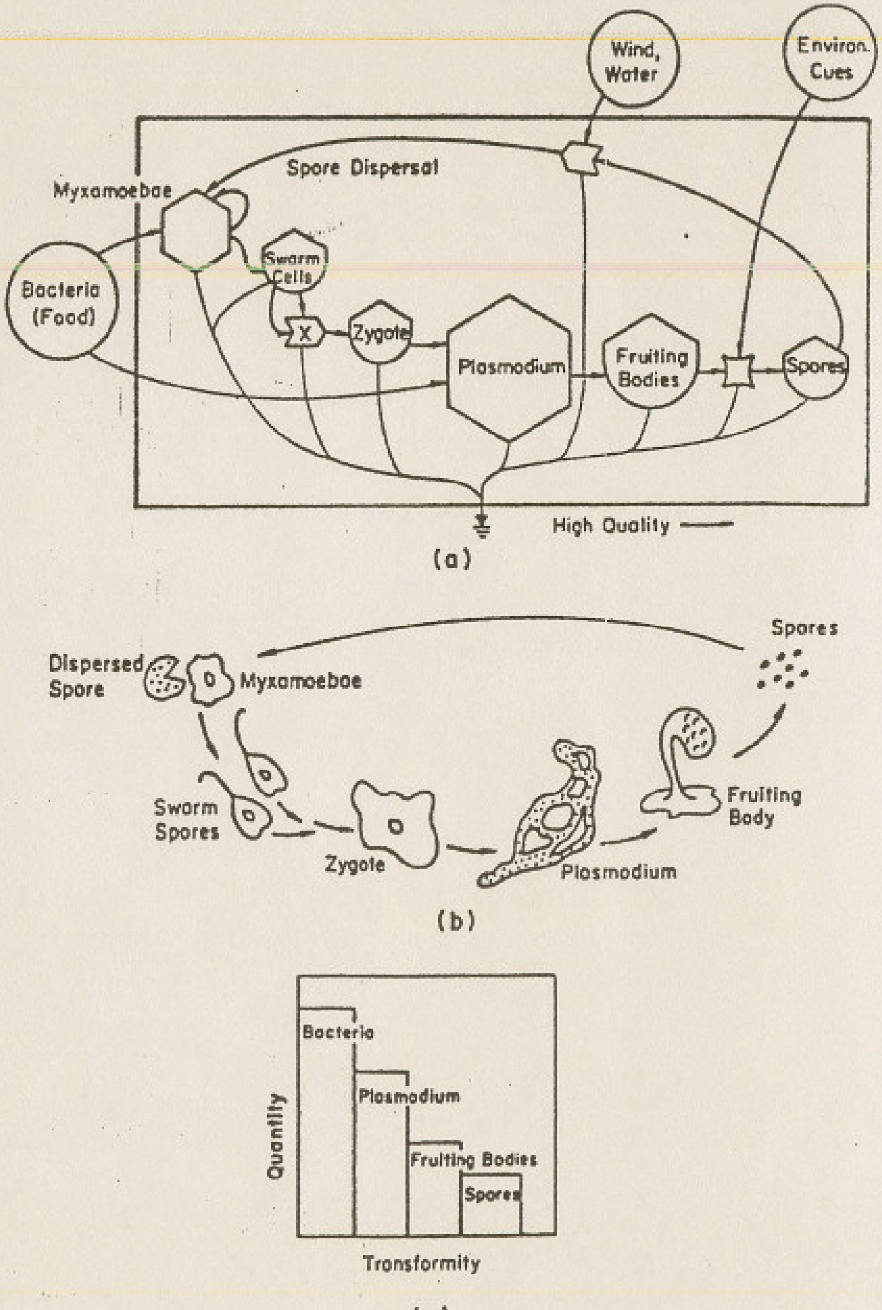

Fig. 8. Energy quality in the life-cycle of a slime-mould: (a) energy diagram, (b) sketch, and (c) spectral graph.

slime-moulds, providing a systems view of convergence of biochemical processes in differentiation.

Transformity and Size

In general, whether one is considering increasing size with age within members of one species, or whether one is comparing organisms of different sizes belonging to different species, the larger organisms have larger realms from which they derive inputs, whether directly or indirectly. Larger units may also feed back their services to larger areas. It may be inferred that larger size-units have more enmergy and higher solar transformity than small ones. Large size is one form of high quality and hierarchical position in ecosystems.

Even in non-living phenomena, such as turbulent eddies in the sea or cloud-formation systems in the atmosphere, the larger units represent the convergence of enmergy from larger areas. In terms of Fig. 4, many small units contribute to or evolve into a few large units on the right.

Another example is the convergence of rivulets to form small streams and then small streams converging to form large streams. Numerical examples are given by H.T. Odum (1985) for swamp watersheds and by Diamond (1984) for the Mississippi Basin. The feedback and dispersal of high-quality energies of major rivers to the far larger spatial area of The Biosphere is observed in the distributaries of deltas.

Larger units cover larger territories, but they have less total quantity than the units from which they draw energy by transformations. As was indicated in Fig. 4, total quantity declines along the energy-chains from left to right, although the unit size increases.

Transformity Within Organisms

Energy quality within an organism may be related to the energy transformations and feedbacks of the system of organs. The organs of the body with larger volumes converge sunlight or food sources into successive physiological transformations to form higher-quality structural products and tissues, finally converging on those organs which are smallest but have the greatest general feedback control roles, e.g. nerves and hormones (*see* Fig. 9).

The energy used by an organism has food quality, which is increased by cumulative transformations within the organism, so that output services are of much higher quality. These products may be further transformed by successive consumers, which are drawn to the right on ecosystem diagrams—following the convention of drawing higher-transformity items on the right. Units at the base of a food-chain may be defined as producers, because of their role in contributing moderate-quality inputs to consumers of higher quality.

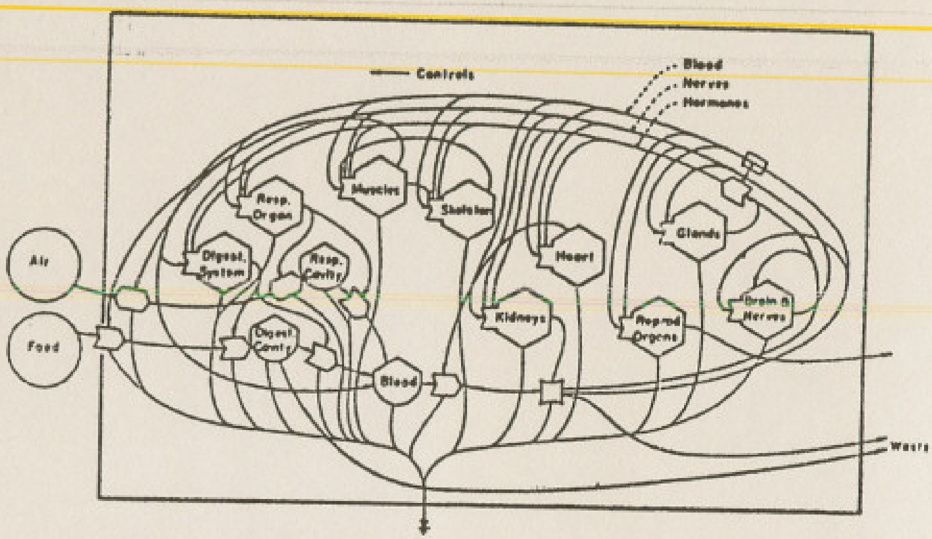

Fig. 9. Diagram of the organ systems of an organism, arranged in order of transformity from left to right.

Consumers are those organisms which transform their inputs into high-quality services and products, but feed these back—so as to control larger areas through dispersion of materials, information, and other work. For either producers or consumers, the contribution of work output to other aspects of the system is of higher quality than most inputs. To evaluate the energy quality of an organism's contribution, the output products and work have to be evaluated—not just the organism's total energy consumption. Examples of energy transformation between organisms and within an organism are given in Figs 3 and 9, respectively.

A single tree demonstrates spatially the convergence and concentration of energy quality within an individual. Dilute solar energy and energies of water, etc., are converged first in leaves and then concentrated in twigs, limbs, and trunks, and, after storage, in flowers and finally fruits. Ultimately these are dispersed again to where interactions can occur between high-quality feedbacks and raw materials, diluting energies to produce new plants of intermediate energy-quality.

Parasites Compared with Predators

Although parasites and predators both draw energies from host populations, their energy-quality roles are quite different. The predator represents the higher-quality unit with larger size, larger-sized supporting territory, and convergence of the embodied energies of the prey population.

rank-order diagram may really be a hierarchical energy-quality representation of species, of which the most common ones are the main processors of lower-quality inflowing energies, whereas the scarce ones to the right may be high-quality information processors. The scarce, rare species in an ecosystem are of high quality by virtue of their scarcity that results when a large enmergy is used for their generation. The role of the rarer genetic storage is as a contingency that is available to help adapt the ecosystem to less-common conditions.

Transformity and Humans

Humans gradually evolved to become top members of ecosystems, in part because of their unique information-processing abilities. In energy-system diagrams organized by quality, the humans and their systems-work go on the right of the diagrams. The things that individual humans do will converge in larger, higher-quality processes and storages—of social institutions, culture, universities, governments, medical processes, etc. Diagrams of the convergence of lower-quality energies into the higher-quality aspects of human organization are given elsewhere (H.T. Odum & Odum, 1981; H.T. Odum, 1983), but the shape of the diagrams is much like that of the ecosystems (cf. the diagram given by Adams, 1975).

The flows of money circulate through parts of human webs. The ratio of dollar flow to accompanying energy-flow increases towards the high-quality right, as do the transformities.

Noise, Pulsing, and Catastrophe

A review of the several levels of biological organization, including those of organisms and ecosystems, suggests the increasing periods and magnitude of the 'pulses' which need to be considered in any models or theories of time and space.

Systems of all sizes are observed to pulse in their performance, alternating a productive growth with a consumptive use of storages that may recycle materials for another round of alternating growth and pulsed consumption. In general, the small systems have short, small pulses and the large systems have long, large pulses. In the hierarchical organization of systems, the many small units with their short pulses converge through energy transformations to generate the larger, centralized units with large pulses separated by long intervals of time. Models of this phenomenon are discussed elsewhere (H.T. Odum, 1981; Richardson & Odum, 1981; H.T. Odum, 1982).

As illustrated in Fig. 11, the many small, low-quality pulses are filtered out when they are converged to larger units, so they may not be of much interest at this larger level of organization except as noise, generating useful variation. This perception interprets noise as deterministic but uninteresting,

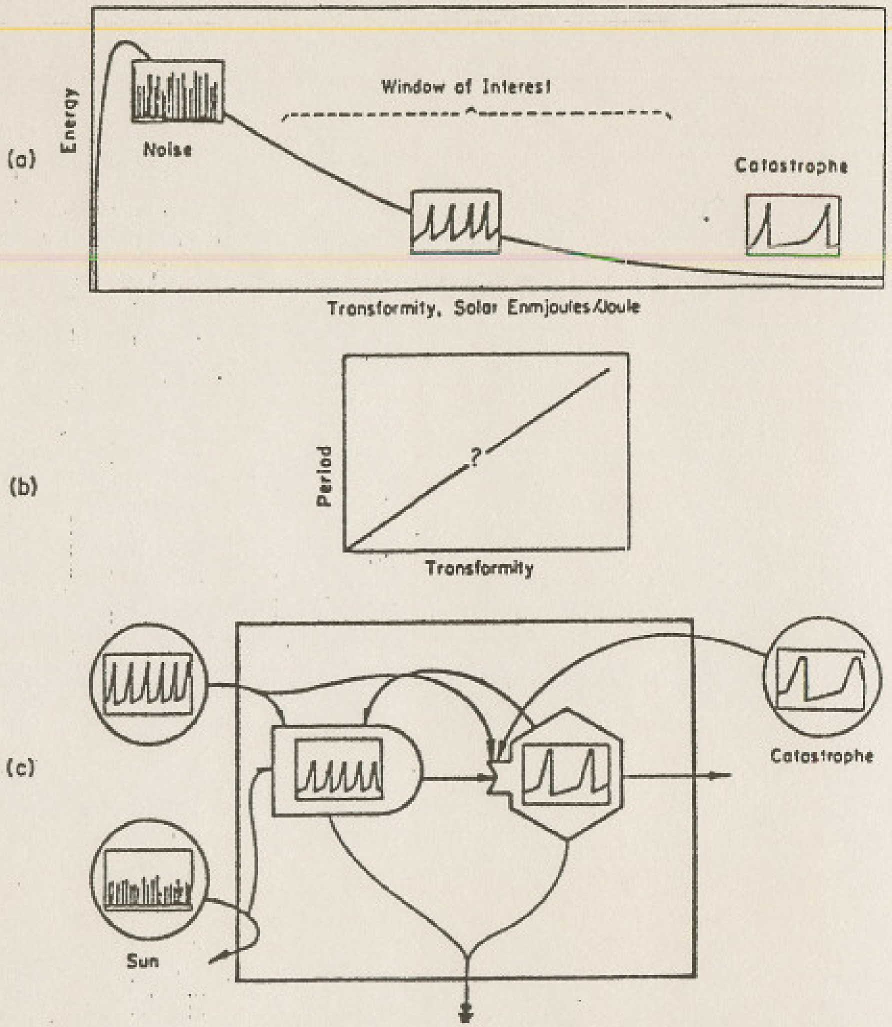

Fig. 11. Frequency of pulses as a function of position in energy quality hierarchy: pulses smaller than the system of concern are considered as 'noise', and larger pulses of systems larger than that of concern are regarded as catastrophes: (a) Energy-transformity spectrum; (b) Oscillation period as a function of transformity; (c) Systems diagram of production and consumption with oscillation frequencies appropriate to sources and hierarchical position.

rather than as indeterminate randomness. Campbell (1984) analysed various ecosystem designs as adaptive filters of varying inputs.

As explained and modelled by Alexander (1978), the pulses of systems of much larger size than the above in which one's system of interest is embed-

A small parasite on the body of its host is in parallel with some of the organs of the host, drawing enmergy from the lower-quality biological and physiological systems of the host's body. The parasite develops through sharing the enmergy of its host. The predator develops through using enmergy of many hosts, and thus is higher than the parasite in the energy-quality chain, with higher solar transformity.

Transformity in the Cell

The hierarchical distributions of cellular structure suggests that the enmergy is converged from energy sources through physiological transformations to the nuclear genetic material in the centre, with feedback of control actions cascading back through messenger control actions. Fig. 10 shows energy transformation ratios, from sunlight to the genetic strands, for an aggregated cellular chain of a plant cell. Within the spatial realm of the cell, the genes are the top members and controllers, towards which energies are transformed and controls are distributed and diverged.

It is sometimes a habit of thinking in biology to examine hierarchies without regard to the spatial concentration in which they actually occur in an ecosystem. Looking at the concentration of structure and function in a cell through a microscope, allows one to forget that the particular cell type under consideration may be in low concentration when examined in terms of the entire ecosystem. The cells may therefore be of low quality when considered in the ecosystem, but may be converged in the ecosystem to units of much higher quality. Whereas a gene may control the cell, it is in turn controlled by much more concentrated, higher-order systems that utilize the converging work transformations of countless genes. The gene is a small, highly efficient micro-robot slave which receives its controls from the larger-system phenomena. Its energy quality, when calculated per area of the ecosystem, is moderate if it is computed in relation to its formation from existing templates.

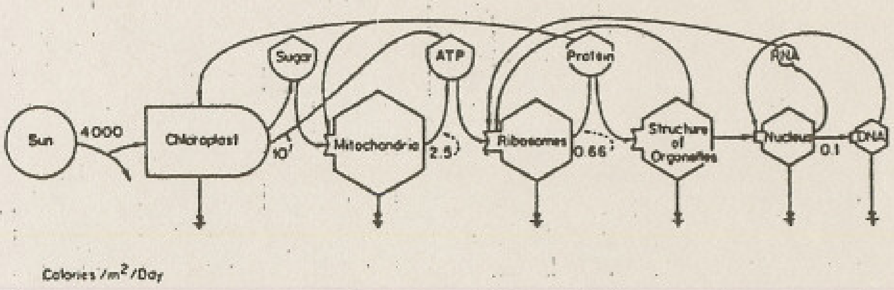

Fig. 10. Energy-flow in algal cells in Cal/m^2/day. Solar transformity of DNA = 4,000/0.1 = 40,000 solar enmcalories/calorie.

However, a successful gene that has been selected by the larger environmental system and is held by many individuals of the species over the landscape, is then a shared information unit. Such successful, shared information has higher-than-otherwise transformity of the additional work done by the environment in its development and selection.

Transformity of Evolutionary Steps

Energy changes are always calculated relatively to some energy reference-level. We sometimes calculate hydroelectric potentials from sea-level reference, and fuel potential energies relative to atmospheric oxygen concentrations. Enmergy and transformities similarly depend on the difference between the item of interest and a reference state. With information, the enmergy that is added in making a copy is relatively small so long as there is an original available. The enmergy in duplicating text in a printing press or in organismic reproduction is relatively small.

However, if there is no template and one has to be redesigned by some work processes from some materials of much less energy quality, then the added enmergy is much greater. The long time taken by an author to rewrite a book involves protracted addition of enmergy. Similarly, the considerable energy required to maintain a population with choices and selection actions—such as may be necessary to develop a species from the next nearest one available—is the added enmergy of that evolutionary step. The greater the differences and the longer the necessary evolution (or the larger the populations necessary to do the work), the greater will be the transformity of the species.

If one has the last male and female specimens of a species or copy of a book, it has a high transformity of its evolutionary replacement rather than the smaller transformity of its duplication. Thus, the enmergy concept and transformities supply a scale of evolutionary value that, at least in principle, can distinguish which species are deserving of more conservation effort, etc.

As part of a project on power-plant siting and endangered species (H.T. Odum *et al.*, 1983), R.L. Knight suggested getting an average enmergy in species by dividing the total number of species that were estimated ever to have existed on Earth, into the total solar enmergy estimated as utilized by The Biosphere over that long period of time. The result of this calculation was a very high transformity of 5 x 10^{21} solar enmjoules per joule.

Transformity and Rank Order

A favourite graph for representing species diversity has been the quantity-rank-order diagram which, in general, puts the most common (highest ranking) species first, the next most common next to it to the right, etc., producing a declining curve not unlike that represented by the steps in Fig. 4a. The ded, have such infrequent pulses relative to the smaller systems that they seem to be catastrophes. They may be regular but appear irregular to those with shorter lifetimes in the smaller systems. The pulses of much larger systems are so infrequent that they are ignored on a probability basis as too infrequent to prepare for. Moreover, the energy required to retain an adaptation may be larger than the catastrophic action itself. Each system may adapt to pulses of quality-range that include one or two orders of magnitude lower quality and one or two orders of magnitude higher quality.

Alternation of Production and Consumption

We are accustomed to the concept of alternation of production and consumption because we are accustomed to the daily and seasonal pulses of solar energy. Indeed the alternation of production and pulsed consumption may be a more general property of all energy hierarchies than is commonly supposed. Production is a large-volume process composed of small, fast-period units that are filtered by the convergence through system storages to consumers. The consumers at a higher-quality position in the hierarchy have larger units and time-periods, so that they draw from the production of longer periods during their pulsing consumption. This alternating pattern generates increased power in some production–consumption models, at least in some ranges of values (Richardson & Odum, 1981; H.T. Odum, 1982).

Nested Pulses

If alternating periods of gradual productive accumulations are followed by pulsating consumption as a property of energy-quality hierarchy, then there is a size- and time-level of accumulation and pulse for each stage in the hierarchy. The ecosystem is made up of different-sized (and -timed) accumulation-pulse regimes, each nested within the next (*see* Fig. 11).

Pulsation of Human Civilization

Many of the rises and falls of human cultures and civilizations may have been manifestations of buildup of soils, forest biomasses, and dominant year-classes—e.g. among fishes—followed by relatively brief bursts of human civilization rapidly consuming those storages. On a small scale this is also the case with shifting agriculture. On a very large scale, the mineral and fuel deposits of The Biosphere are gradually generated and brought to the surface by the Earth's sedimentary and volcanic cycles. The current explosive pulsation of civilization is sometimes called 'King Hubbard's Blip', and appears to be the same phenomenon on a very large scale of size and time. If this is a correct interpretation, several inferences about the future are possible.

The pattern of moving from our recent growth-period to a lower-energy civilization may be steep and its impact catastrophic. as rapid consumption, returning the system to gradual production again, may be the pattern for maximum power. It may be the pattern that maximizes the economy at each point in time, even during a period of overall decline. For the long-range future, pulsations of civilization based on soils and biomass will surely repeat themselves over and over; but another blip as large as the present one will inevitably be a very long time to come in the future, as the rate at which Earth's resources form and come to the surface is of the order of magnitude of 3.6 cm per 1,000 years (Judson, 1968).

THEORIES TO BE TESTED ABOUT ENERGY QUALITY

Up to this point the present chapter has defined transformity and enmergy as means to indicate the accumulated value of successive energy transformations and as a way to distinguish items and processes quantitatively in regard to energy invested in their existence.

New theory may result from using these measures, and several ideas are suggested for empirical testing. Reasoning from the maximum-power principle suggests some relationships, and the empirical confirmation of these will help us further in understanding energy organization of the ecosystem or, for that matter, any system.

Pulsating Period and Embodied Energy

Following the concept of hierarchical spatial convergence introduced with Fig. 4, the greater the enmergy of a unit of a process is, the longer will be the period between pulsations. This relationship may make it possible to determine pulsating frequency from the size of a system, which means that the external pulsation of an outer system may be inferred from its size without knowing its nature, and *vice versa*. The period of pulsating may help to determine the ultimate enmergy territory from which the pulsation has drawn its support, and to which it may direct its feedbacks. The rarer the component is, the longer will be the period between its surges.

Effect Proportional to Enmergy

As described in an earlier essay (H.T. Odum, 1979), the items of larger enmergy may be expected to have larger effects on the systems from which they draw their support. The reasoning is that surviving system designs are those which maximize their supporting system's power and thus their own basis for existence. Items which require many energy transformations and much enmergy constitute a liability—unless they feed back with reward amplification loops to the broader, spatially larger support-system. Therefore, the systems observed as surviving the self-design process will have a correlation between enmergy and feedback effect. Knight (1981), in studies of cadmium, started the process of correlating transformity characteristics of chemical substances with their amplification action (positive or negative toxic action).

To many people, the value of something is proportional to the effect it has. This enmergy-effect hypothesis suggests that items which are valuable in the sense of the high enmergy are also valuable in the sense of having a large amplifier effect. Items that have large amplifier effects also have steep action-responses. They have a large derivative on a limiting-factor graph. In economics they might be described as having a large marginal effect, and thus be considered valuable to those concerns where such a process is connected to human economy.

It goes without saying that high-quality energy can have important amplifier effects only if it can find lower-quality energy with which to interact. High-quality energy cannot be in excess of its hierarchical rarity without losing its effect. Too many PhDs, too many eagles, or too much mercury, will be selected against—until the hierarchical abundance indicated on the left in Fig. 4 is re-established.

Value and Scarcity at the End of Hierarchy

The correlation of scarcity with perceived value is often attributed to human behaviour, but the reverse may be more likely. Because they require more energy, high-transformity items are inherently scarce, and those items which are retained by selection are those which are found to have large effects. Human behaviour that leads to survival learns to prefer that which is scarce because of its greater-than-otherwise effects.

Transformity, Transportation, and Transmission

Scanning of energy-flows of different types suggests that higher-quality energies may be more easily transported than lower-quality energies. Certainly, the higher the transformity is, the more enmergy can be transported for the same effort. For example, birds represent a convergence of solar energy into high-quality form. Transporting birds containing a few grams of sugar, carries more enmergy than transporting the same enmergy in leaves.

Electric power-lines transmit enmergy of coal more cheaply than transporting the coal as coal before its conversion to electricity. If this transportation theory is general, then one of the properties of high-quality energy is its transportability, and it is this property that makes possible the feeding back of small energies of high transformity to give back to the large supporting area the large stimulating effect that is required for the hierarchy to be competitive, to maximize power, and to deal with necessary contingencies.

Strange Equivalences and a Final Word

High-quality energies include some very contrasting kinds of energy. Some are very hot, with intense concentrations of energy; others are very cold, as in the case of an iceberg. Some are neutral in temperature, being in the form of information and culture, while others are large, as in the case of an elevated mountain.

Transformities are easily calculated from the abundant data existing on energy-flows in The Biosphere. These form a scale of values that is at least a handy way to calculate what energies have been responsible for an entity, and may yet constitute the thermodynamic basis of pertinent values. If theoretical reasoning is confirmed by means of empirical testing, enmergy and transformity should provide ways to predict catastrophes, presuppose hierarchical distributions, and relate genetics with energetics—so unifying biogeochemistry, population ecology, and community ecology with common measures, and ultimately leading to an understanding of the hierarchical organization of Nature and her component ecosystems and ecobiomes.

ACKNOWLEDGEMENT

This chapter is based in part on an invited paper prepared for and given at a plenary session of the Second International Congress of Ecology, Jerusalem, 1979, and subsequently revised and widely updated.

SUMMARY

The concept of enmergy in ecological systems is examined in this chapter. An intensive measure of enmergy, the transformity, is the ratio of the joules of one type that is required in a competitive web to generate a joule of another quality. Transformities provide an energy-value system for the ecosystem. Values range from 1 solar enmjoule per joule for sunlight, by definition, to 10^{21} solar enmjoules per joule for the most valuable entities such as unique gene-reservoirs. The enmergy values suggest systematic ways of modelling and diagramming ecosystems so as to include hierarchical manifestation of energy-flow, to make diagrams by different workers congruent, and to organize voluminous data on energetics of ecosystems for easy reference.

Because of the apparent correlation of operational time with the transformity, temporal characteristics of ecosystem components and phenomena may be classified according to transformity, low values being regarded as 'noise', intermediate values as dynamic phenomena, and large values as catastrophic phenomena. Other hypotheses are that amplifier effects are proportional to enmergy, enmergy is more efficiently transmitted in high-quality than low-quality form, more high-quality than low-quality embodied energy can be stored, and high-quality energy is more flexible in use than is low-quality energy.

REFERENCES

Adams, R.W. (1975). *Energy and Structure: A Theory of Social Power*. University of Texas Press, Austin, Texas, USA: 353 pp., illustr.

Alexander, J.F. (1978). *Energy Basis of Disasters and the Cycle of Order and Disorder*. Ph.D. dissertation, Department of Environmental Engineering Sciences. University of Florida, Gainesville, Florida, USA: 232 pp. (mimeogr.), illustr.

Boltzmann, L. (1905). Der zweite Haupsatz der mechanischen warme Theorie. *Almanach der K. Acad. Wiss. Mechanische, Wien*, 36, pp. 255–99.

Campbell, D.E. (1984). *Energy Filters and Ecosystem Design*. Ph.D. dissertation, Department of Environmental Engineering Sciences, University of Florida, Gainesville, Florida, USA: 450 pp. (mimeogr.), illustr.

Carnot, S.N.L. (1824). *Reflections on the Motive Power of Heat and on Machines Fitted to Develop This Power* (2nd edn; 1960). American Society of Mechanical Engineers, 107 pp., illustr.

Costanza, R. (1979). *Embodied Energy Basis for Eonomic–Ecological Systems*. Ph.D. dissertation, Department of Environmental Engineering Sciences. University of Florida, Gainesville, Florida, USA: 250 pp. (mimeogr.), illustr.

Costanza, R. (1980). Embodied energy and economic evaluation. *Science*, 210, pp. 1219–24, illustr.

Diamond, C. (1984). *Energy Basis for the Regional Organization of the Mississippi Basin*. M.S. Thesis, Department of Environmental Engineering Sciences, University of Florida, Gainesville, Florida, USA: 136 pp. (mimeogr.), illustr.

Evans, R. (1969). *A Proof that Energy is the Only Consistent Measure of Potential Work*. Ph.D. dissertation, Dartmouth College, Hanover, New Hampshire, USA: 129 pp. (mimeogr.), illustr.

Fluck, R.C. & Baird, D.C. (1980). *Agricultural Energetics*. AVI Publishing Company, Westport, Connecticut, USA: 192 pp., illustr.

Hannon, B. (1973*a*). An energy standard of value. *Annals of the American Academy of Political and Social Sciences*, 410, pp. 139–53, illustr.

Hannon, B. (1973*b*). The structure of ecosystems. *Journal of Theoretical Biology*, 55, pp. 252–67, illustr.

Herendeen, R.A. (1981). Energy intensities in ecological and economic systems. *Journal of Theoretical Biology*, 9, pp. 607–20, illustr.

Herendeen, R.A. & Bullard, C.W. (1974). *Energy Costs of Goods and Services 1963 and 1967*. Document No. 140, Center for Advanced Computation, University of Illinois, Champaign–Urbana, Illinois, USA: 43 pp., illustr.

Hubbert, M.K. (1934). *A Primer on Technocracy*. Technocracy. New York, NY, USA: 6 pp.

Jorgensen, S.E. & Mejer, H. (1977). Ecological buffer capacity. *Ecological Modelling*, 3, pp. 39–61, illustr.

Juday, C. (1940). The annual energy budget of an inland lake. *Ecology*, 21, pp. 438–50, illustr.

Judson, S. (1968). Erosion of the land or what's happening to our continents. *American Scientist*, 56, pp. 356–74, illustr.

Knight, R.L. (1980). *Energy Basis of Control in Aquatic Ecosystems*. Ph.D. dissertation, Department of Environmental Engineering Sciences, University of Florida, Gainesville, Florida, USA: 198 pp. (mimeogr.), illustr.

Knight, R.L. (1981). A control hypothesis for ecosystems—energetics and quantification with the toxic metal cadmium. Pp. 601–16 in *Energy and Ecological Modelling* (Eds W.J. Mitsch, R.W. Bosserman & J.M. Klopatek). Elsevier Publishing Company, Amsterdam, The Netherlands: [not available for checking].

Lavine, M.J. & Butler T.J. (1982). *Use of Embodied Energy Values to Price Environmental Factors: Examining the Embodied Energy/Dollar Relationships*. (Report to the National Science Foundation, PRA-8003845.) Center for Environmental Research, Cornell University, Ithaca, New York, USA: [not available for checking].

Leontief, W.W. (1966). Input–output economics. *Scientific American*, 185, pp. 15–21, illustr.

Lindeman, R.L. (1942). The trophic–dynamic aspect of ecology. *Ecology*, 23, pp. 399–418, illustr.

Lotka, A.F. (1922). A contribution to the energetics of evolution. *Proceedings of the National Academy of Sciences*, 8, pp. 147–55, illustr.

Maxwell, J. (1877, reprinted 1975). *Matter and Motion*. Macmillan, New York, NY, USA: 162 pp., illustr.

Mejer, H. & Jorgensen, S.E. (1979). Energy and ecological buffer capacity. Pp. 829–46 in *State of the Art in Ecological Modelling: Proceedings of First Conference on Ecological Modelling*. International Society for Ecological Modelling, Copenhagen, Denmark: 891 pp., illustr.

Odum, E.C., Scott, G. & Odum, H.T. (1981). *Energy and Environment in New Zealand*. Joint Centre for Environmental Science, Christchurch, New Zealand: 129 pp., illustr.

Odum, H.T. (1955). Trophic structure and productivity of Silver Springs, Florida. *Ecological Monographs*, 27, pp. 55–112, illustr.

Odum, H.T. (1967). Energetics of food production. Pp. 55–94 (Chapter 3) in *The World Food Problem, Vol. 3*, Report of President's Science Advisory Committee, Panel on World Food Supply, Washington, DC, USA: 332 pp., illustr.

Odum, H.T. (1971). *Environment, Power, and Society*. John Wiley & Sons, New York, NY, USA: 336 pp., illustr.

Odum, H.T. (1976). Energy quality and carrying capacity of the Earth (response at Prize Ceremony, Institut de la Vie, Paris). *Tropical Ecology*, 16(1), pp. 1–8, illustr..

Odum, H.T. (1978). Energy analysis, energy quality, and environment. Pp. 55–87 in *Energy Analysis, a New Public Policy Tool* (Ed. M. Gilliland). AAAS Selected Symposium 9, Westview Press, Boulder, Colorado, USA: 110 pp., illustr.

Odum, H.T. (1979). Energy control of ecosystem design. Pp. 221–35 in *Marsh–Estuarine Systems Simulation* (Ed. P.F. Dame). Belle W. Baruch Library in Marine Science, No. 8. University of South Carolina Press, Columbia, SC, USA: 260 pp., illustr.

Odum, H.T. (1981). Energie, économie et hiérarchie de l'environnement. Pp. 155–63 in *Etudes et Recherches*. (Compte Rendu du Colloque des Troisièmes Assises Internationales de l'Environnement, Volume 4: Société et Environnement.) Ministère de l'Environnement, Paris, France: 180 pp.

Odum, H.T. (1982). Pulsing, power, and hierarchy. Pp. 33–54 in *Energetics and Systems*. Ann Arbor Science, Ann Arbor, Michigan, USA: 132 pp., illustr.

Odum, H.T. (1983). *Systems Ecology*. John Wiley & Sons, New York, NY, USA: 644 pp., illustr.

Odum, H.T. (1984*a*). Energy analysis evaluation of coastal alternatives. *Wat. Sci. Tech.* (Rotterdam), 16, pp. 717–34, illustr.

Odum, H.T. (1984*b*). Embodied energy, foreign trade, and welfare of nations. Pp. 185–200 in *Integration of Economy and Ecology, and Outlook for the Eighties* (Ed. Ann-Mari Jansson). (Proceedings from the Wallenberg Symposia.) ASCO Laboratory, University of Stockholm, Stockholm, Sweden: [not available for checking].

Odum H.T. (1984*c*). Energy analysis of the environmental role in agriculture. Pp. 24–51 in *Energy and Agriculture* (Ed. B. Stanhill). Springer-Verlag, Berlin, West Germany: 192 pp., illustr.

Odum H.T. (1985). Water conservation and wetland values. Pp. 98–111 in *Wastewater and Wetlands*. Water Resources Institute, Amherst, Massachusetts, USA: [not available for checking].

Odum H.T. & Odum, E.C. (1976). *Energy Basis for Man and Nature*. McGraw Hill, New York, NY, USA: 297 pp., illustr.

Odum, H.T. & Odum, E.C. (1981). *Energy Basis for Man and Nature* (2nd edn). McGraw Hill. New York, NY, USA: 337 pp., illustr.

Odum, H.T. & Odum, E.C. (Eds) (1983). *Energy Analysis Overview of Nations.* International Institute for Applied Systems Analysis, Working Paper WP–83–82, Laxenburg, Austria: 467 pp. (mimeogr.), illustr.

Odum, H.T. & Pinkerton, R.C. (1955). Time's speed regulator: the optimum efficiency for maximum power output in physical and biological systems. *American Scientist*, 43, pp. 321–43, illustr.

Odum, H.T., Lavine, M.J., Wang, F.C., Miller, M.A., Alexander, J.F. & Butler, T. (1983). *A Manual for Using Energy Analysis for Plant Siting.* (Nuclear Regulatory Commission.) NUREG/CR–3449, National Technical Information Service, Springfield, Virginia, USA: [not available for checking].

Patten, B.C. (1978). The system approach to the concept of environment. *Ohio Journal of Science*, 78(4), pp. 206–22, illustr.

Pimentel, D. (1979). *Food, Energy, and Society*. John Wiley & Sons, New York, NY, USA: 165 pp., illustr.

Richardson, J. & Odum, H.T. (1981). Power and a pulsing production model. (Paper presented at the International Symposium on Energy and Ecological Modelling, Louisville, Kentucky.) Pp. 641–7 in *Energy and Ecological Modeling* (Eds W.J. Mitsch, R.W. Bosserman & J.M. Klopatek). Elsevier Publishing Company, Amsterdam, The Netherlands: [not available for checking].

Scott, H. (1933). *Introduction to Technocracy.* J. Day, New York, NY, USA: 61 pp., illustr.

Simpson, G.C. (1929). Distribution of terrestrial radiation. *Mem. Royal Meteorological Society*, 3, pp. 26–7, illustr.

Slesser, M. (1978). *Energy in the Economy.* St Martin's Press, New York, NY, USA: 164 pp., illustr.

Sussman, M.V. (1981). *Availability (Exergy) Analysis.* Milliken House, Lexington, Massachusetts, USA: [not available for checking].

Tribus, M. & McIrvine, E.C. (1971). Energy and information. *Scientific American*, pp. 179–88, illustr.

Whittaker, R.H. (1965). Dominance and diversity in land comunities. *Science*, 143, pp. 250–60, illustr.

Wright, B. (1968). Differentiation in cellular slime mold. Pp. 115–29 in *Systems Theory and Biology* (Ed. M.D. Mesarović). Springer-Verlag, New York, NY, USA: 403 pp., illustr.

Zimmerman, J.E. (1933). *World Resources and Industries.* Harper, New York, NY, USA: 831 pp., illustr.