II.6 Ecosystems as Energetic Systems

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1. Introduction

This chapter is a brief synopsis of energy systems representation of ecosystems, roughly defined as an environmental system with living populations. Like a short course given with limited time, this text with limited space touches on what is most important.

For concepts to be useful to human minds, that part of the continuum of complexity of the universe which we can sense has to be simplified. Once we define the scale of our interest, we abandon this interest if we simplify by reducing scale to smaller parts and mechanisms. Instead, we have to retain the whole, larger-scale system and simplify by aggregating parts and processes into fewer units and pathways. Because many of the concepts depend on system connections, a diagrammatic network language is required to keep an holistic perspective about design, cycles, and the controls of the larger scale while also viewing the parts with analytic precision. We start by introducing concepts using energy systems diagram to make network relationships clear. In Figure 1 are the energy systems symbols. How they are used to represent ecosystems is shown in Figure 2.

1.1 Concepts and measures

The following are procedures and principles used to represent ecosystems with energy systems concepts and measures (Figure 2):

1. A window frame of attention is defined.
2. Adopting a boundary identifies all the inputs from the continuum of structure and processes outside the window frame as sources.
3. Position in the diagram reflects the scale of turnover and territory. Structures and processes are arranged from left to right in order of increasing scale.
4. Entities of scale smaller than the main window of interest are included but aggregated. For example, processes of a population of micro-organisms might be aggregated as a single pathway.
5. Since energy accompanies everything, pathways are flows of energy with or without material or information. Energy inflowing either increases storages inside or exits as outflows. Pathway flows are in power units, since useful energy per time is power.
6. Total resource available to the defined area is the sum of the inputs expressed on a common basis as emergy (spelled with an 'm'). Emergy is defined as the available energy of one kind of energy previously used up to make the product. Flow of emergy per time is empower.
7. Inflows include those of the smaller scale, items of similar scale located elsewhere and items of the larger scale such as those from the economy, human society, and the earth.
8. Energy transformations from left to right illustrate first and second energy laws, with available energy passing out through the heat sink. Energy flows decrease from left to right, but the capabilities of that energy increase.
9. As a result of self organisation for maximum empower, structure of relationships has autocatalytic loops within components and between aggregates. These 'feedback' loops pass from right to left as inputs to production-transformation processes and are drawn with counter-clockwise arcs to production (interaction) symbols.
10. Effective reinforcements of production processes require matching of high quality feedbacks (small energy flows) interacting and amplified by larger flows of lower quality energy.

2000.
Handbook of Ecosystem Theories and Management ed by
S. E. Jorgensen and F. Mueller Lewis Publishers, Boca Raton, FL.

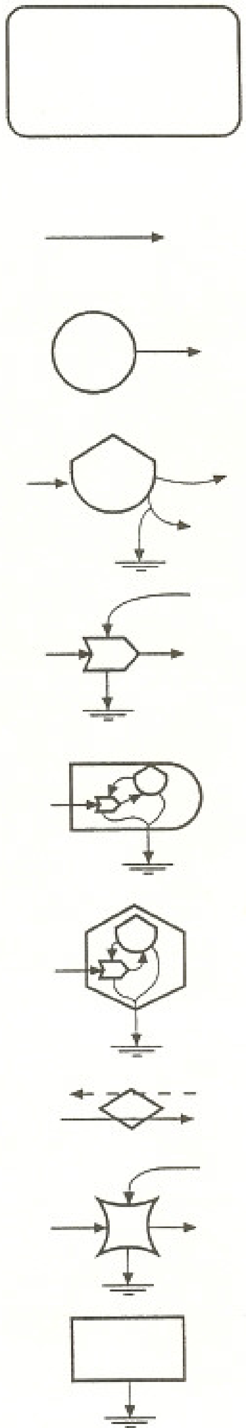
11. Production symbols combine necessary flows of different kinds and usually imply multiplicative production functions between items of different scale. The reinforcement of the feedback loops at the system level tends to eliminate the tendency for isolated production processes to become limited by one or more factors.
12. Position in energy hierarchy from left to right is measured by the increasing transformity from left to right. Transformity is emergy required per unit of transformed energy.
13. To the right energy components and their flows are of a higher quality and capable of greater action per unit in feedback reinforcements to other parts of the system.
14. Materials are bound into structure of higher quality to the right, being released by consuming processes there and circulating back to lower concentrations on the left where they can be incorporated into production processes again.
15. Items to the right form into more concentrated centres, spatially; higher in energy hierarchy.
16. On each scale; production generates storages that grow followed by pulses of consumption and transformation of these stores by other units to the right. Thus pulsing pairs appear during self organisation.
17. The larger the scale of the pulse pair, the longer the interpulse period and the sharper the pulse's feedback actions.
18. The multiplicative interaction of dynamic pulsing at many scales produces patterns of variation resembling skewed statistical distributions (Log normal, Weibull).
19. Where it is desirable to show in the diagram the self organising mathematical relationships that generate pulsing, connections between pulsing pairs include 3 parallel competing pathways (a linear pathway, autocatalytic loop, and quadratic autocatalytic loop).
20. Where it is desirable to make the system quantitative, values of flows and storages are placed on the diagram in whatever units are appropriate. These may be values for a given time or averages as if the system were in steady state.
21. Where a time dimension is desirable, the numerical values are used to calibrate the coefficients of equations for computer simulation programs. The equations may be included at the foot of the diagram, thus translating the kinetic aspect of the model.
22. Information has high transformities and belongs on the right of the systems diagrams where their feedback control loops may be the most important. To maintain information requires a circle of duplications, reapplication and selection.
23. Humans, their economy, and their information processing interact as part of a larger scale (high transformity) and are shown on the right.

Energy systems diagrams are concentrated ways of showing many systems relationships.

1.2 Appropriate complexity

For a top down overview, introductory education, public policies, and simple computer simulations of the broadest features, a system of ten or less components is desirable. Diagrams with 30 or more components may serve as an inventory, but this level of complexity is hard to evaluate, simulate, or anticipate consequences. Very complex diagrams may be useful as a pre-aggregation exercise. The complex diagrams help consider more items in the aggregating process. Complex diagrams have been used as a system checklist, an impact statement, and sometimes on walls as aesthetic art of complexity.

ENERGY SYSTEMS SYMBOLS



System Frame: a rectangular box drawn to represent the boundaries of the system selected.

Pathway Line: a flow of energy, often with a flow of materials.

Source: outside source of energy; a forcing function.

Storage: a compartment of energy storage within the system storing quantity as the balance of inflows, outflows and depreciation.

Interaction: process which combines different types of energy flows or material flows to produce an outflow in proportion to a function of the inflows.

Producer: unit with one or more storages and autocatalytic interactions that collects and transforms low quality energy under control interactions of higher quality flows.

Consumer: unit that consumes and transforms energy with one or more store and autocatalytic interactions.

Transaction: a unit that exchanges goods or services(solid line) for money(dashed line) according to price.

Switching Action: symbol that indicates one or more switching functions where flows are interrupted or initiated.

Box: miscellaneous symbol for whatever unit or function is labled.

Figure 1: Energy Systems Symbols

2. Energy hierarchy and transformity

Geological processes, atmospheric systems, ecosystems, and societies are interconnected, each receiving energy and materials from the other, interacting through feedback mechanisms to self-organise in space, time, and connectivity. While processes of energy transformation throughout the geobiosphere build order, cycle materials, sustain information and degrade energy in the process, they organise units in an energy hierarchy.

2.1 Energy hierarchy

When many of one type of unit are combined to form a few of another, the relationship is hierarchical. Since there is energy in everything including information, and since there are energy transformations in all processes, most if not all things form a hierarchical series. The scale of space and time increases along the series of energy transformations. Many small scale processes contribute to fewer and fewer of larger scale. In our systems diagrams scale increases from left to right (Figure 3).

Energy is converged to higher order processes where with each transformation some energy is passed along the web and much is degraded as a consequence of the 2nd Law of Thermodynamics. For each transformation step, much energy loses its availability, and only a small amount is passed along to the next step. For some purposes the energy transformation processes normally interconnected in webs can be aggregated as simpler transformation chains.

Examples include water streams converging in a watershed, the leaf cells processing energy to tree trunk growth and the convergence of energy in ecosystem food chains. Convergence of energy through a series of energy transformations yields a final product which carries less energy than invested to start the chain, due to the entropic degradation. However, the higher position of the item in the energy hierarchy makes it more valuable, as a large convergence of resources was required to support the process. We may say that the final product has a higher quality than initial products.

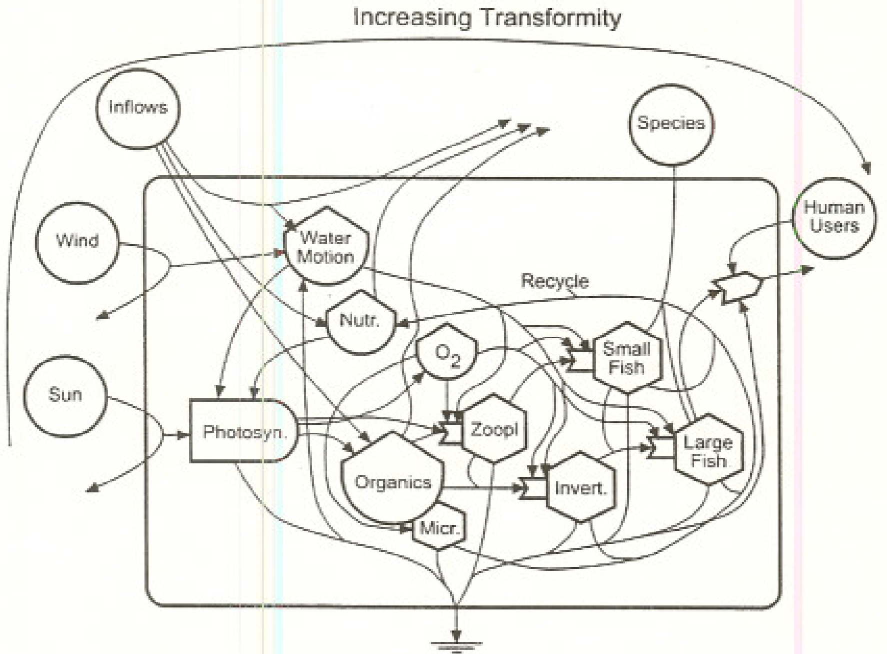


Figure 2: Systems diagram of typical ecological systems (a) Terrestrial ecosystems; Aquatic ecosystems

Hierarchical Levels

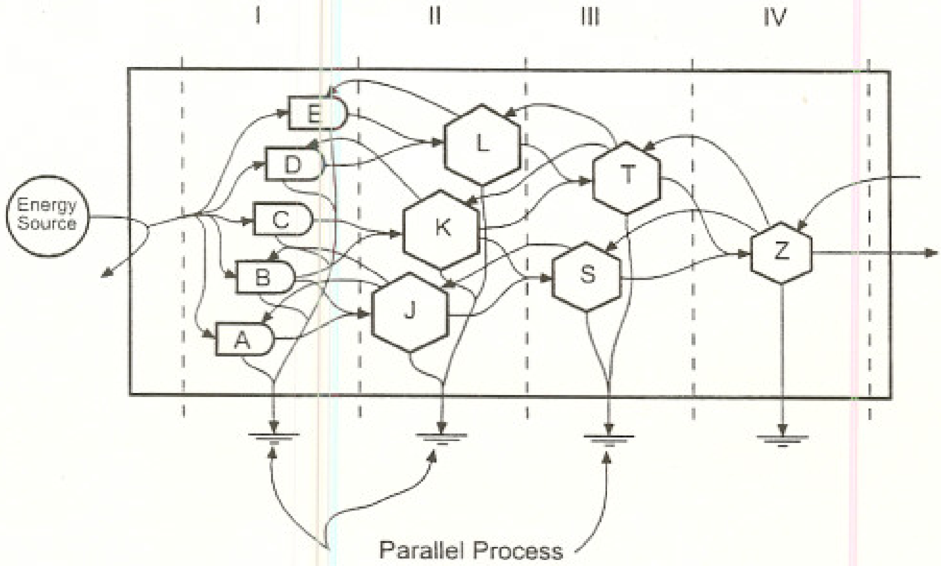


Figure 3: An energy web organised hierarchically, showing levels and parallel processes, and reinforcing feedbacks (right to left)

2.2 Emergy, empower, and transformity

Whereas different amounts and qualities of energy are found along the energy hierarchy, the concept of emergy, spelled with an 'm' (Odum, 1983, 1996) is used to express all available energy flows in a comparable way. By definition, emergy is the amount of energy of one form that is required, directly and indirectly, to provide an energy flow or storage. Emergy stands for energy memory (Scienceman, 1987). In many papers we standardise by expressing everything as solar emergy. The unit of emergy is the emjoule or emcalorie. In this paper solar emergy is used and expressed as solar emjoules (abbreviated sej).

The flow of emergy is empower in units of emjoules per time. Solar empower is in solar emjoules per time (abbreviated sej/t).

The emergy required to make one unit of available energy is called transformity. It is calculated from observed ratios of emergy to energy (either in storages or in flows). Solar transformity is expressed in solar emjoules per joule (abbreviated sej/J).

3. Production

Energy transformations generate a stream of products. Usually the production process occurs with interaction of two or more different kinds of inputs with different transformity. As shown with the interaction symbol in Figure 4, there is a matching between a high transformity, controlling feedback from the right with the abundant, low quality, low transformity energy from the left. In order to maximise its effect commensurate with the energy which went into its formation, high transformity items have to interact so as to mutually amplify a flow with larger energy quantity to produce outputs of intermediate transformity.

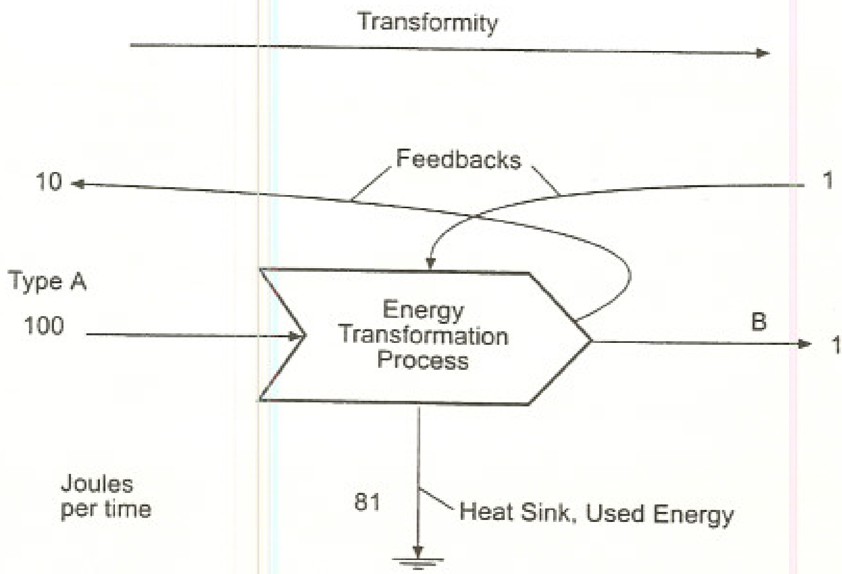


Figure 4: Energy systems diagram of a production process with values of energy on the pathways.

3.1 Autocatalytic reinforcement and maximum power

Following Boltzmann (1886), Lotka (1922) enunciated the principle of maximum power "...that in the struggle for existence, the advantage must go to those organisms whose energy-capturing devices are most efficient in directing available energy into channels favourable to the preservation of the species." Further, he states "...natural selection tends to make the energy flux through the system a maximum, so far as compatible with constraints to which the system is subjected. Therefore, power maximisation was suggested by Lotka as the measure of fit designs and offered as the 4th Law of Thermodynamics.

One of the common design mechanisms for maximising power is the autocatalytic loop from stored product back interacting and amplifying the production process. In energy systems diagrams the feedback from high quality passes back to the left (Figure 5). Living and non-living units of the environment develop autocatalytic reinforcement loops as part of production processes. Examples here include leaves capturing sunlight, animals catching their food, watershed land forms capturing runoff.

3.2 Maximum empower principle

Relative to the energy hierarchy, however, these definitions would imply that self organising processes develop the low transformity scales where energy flow is greater. We restated the principle as maximising empower, which means maximising useful work on all scales equally at the same time.

<u>Maximum Empower Principle:</u> On each scale, systems designs prevail that maximise empower, first by reinforcing inflows of available energy and second by increasing the efficiency of useful work.

Energy dissipation without useful contribution to intake and efficiency is displaced because such pathways are not mutually reinforcing. For example, drilling oil wells and then burning off the oil may use oil faster (in the short term) than refining and using it to run machines, but that design is replaced with a system that uses oil to develop and run machines, increase drilling capacity and ultimately the rate at which oil can be supplied.

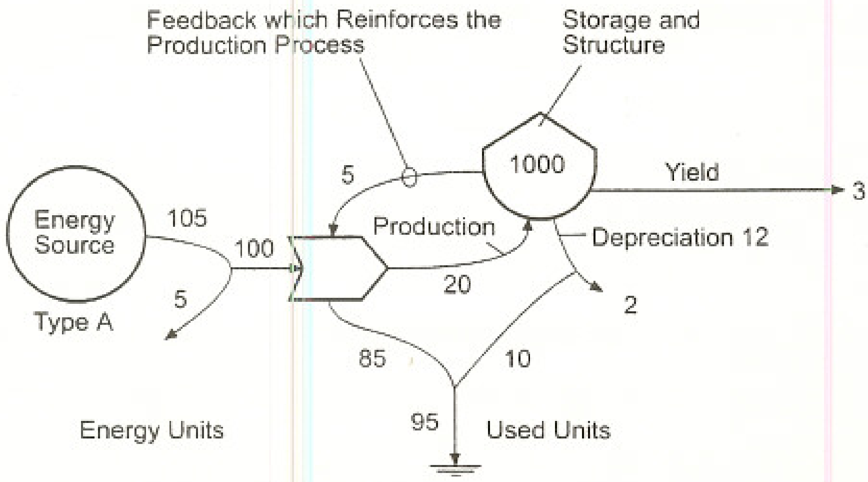


Figure 5: Configurations of productions that reinforce by feeding back higher transformity products in an autocatalytic loop

3.3 Splits and co-products

The pathways of networks depend on the human perceptions with which the complex real systems are simplified. If a product flow is divided into branches of the same kind, it is a 'split', and each branch has the same transformity and emergy per mass (Figure 6a). For example some of the fruits produced by a tree split when some wash away and some remain for local birds.

On the other hand, we may have aggregated the real world into units where there are outputs of different kind, which we call 'co-products' (Figure 6b). For example, trees produce fruits and leaf litter. Different kinds of products have different transformities. Although we may aggregate units so that two different transformity products are co-products, they may be at different levels of energy hierarchy within the unit as suggested by the dashed line details within the box (Figure 6b).

3.4 Annual emergy budget of the earth

For evaluating production within the earth's geobiosphere, the abundant general input energy is that of solar insolation, which is taken as the reference for calculating transformities. By defining average insolation at the earth's surface as reference, the transformity of solar radiation becomes one. Transformities of the main natural flows in the biosphere (wind, rain, ocean currents, geological cycles, etc.) are calculated as the ratio of total emergy driving the biosphere as a whole to the actual energy of the flow under consideration. Figure 7 shows the total emergy driving the biosphere as the sum of solar radiation, energy from the deep earth, and tidal momentum. The total of these (equal to 9.44 E24 sej/yr) is used as the base emergy because the biosphere processes that produce winds, rains, ocean currents, and geologic cycles are coupled and cannot generate one without the other.

In addition in this century, there is high emergy coming from use of fuels and mineral reserves accumulated at an earlier time (Table 1). The changes observed in global climate suggest that this emergy should also be included (Brown and Ulgiati, 1999).

Table 1: Flux of renewable and non-renewable energies driving global processes

Note Source	Energy Flux (J/yr)	Transformity* (sej/J)	Solar Emergy Flux (E24 sej/yr)	Emdollars# (E12 Em$)
Global Renewable Energies				
1. Solar insolation	3.94E+24	1	3.94	3.57
2. Deep earth heat	6.72E+20	6055	4.07	3.69
3. Tidal energy	8.52E+19	16842	1.43	1.30
	Subtotal		9.44	8.56
Society Released Energies (non-renewable)				
4. Oil	1.38E+20	5.40E+04	7.45	6.75
5. Natural gas	7.89E+19	4.80E+04	3.79	3.43
6. Coal	1.09E+20	4.00E+04	4.36	3.95
7. Nuclear energy	8.60E+18	2.00E+05	1.72	1.56
8. Wood	5.86E+19	1.10E+04	0.64	0.58
9. Soils	1.38E+19	7.40E+04	1.02	0.93
10. Phosphate	4.77E+16	7.70E+06	0.37	0.33
11 Limestone	7.33E+16	1.62E+06	0.12	0.11
12. Metals	992.9E+12g	1.0E+09sej/g	0.99	0.90
	Subtotal		20.46	18.54
	TOTAL		29.91	27.10

* Transformities from Odum (1996)
\# Emdollars obtained by dividing Emergy in column 5 by 1.1E12 sej/$ (Table 4)

1. Sunlight	Solar constant, 2 cal/cm²/min 70%absorbed Earth cross section facing the sun = 1.278 E14m² Energy Flux = (2 cal/cm²/min) (1.278E18cm²)(5.256E5min/yr)(4.186J/cal)(0.7) =3.936E24J/yr	(Von der Haar and Suomi, 1969)
2. Deep earth heat	Heat released by crustal radioactivity = 1.98 E20J/yr Heat flowing up from the man = 4.74 E20J/yr Energy Flux = 6.72 E20J/yr	(Sclater et al., 1980) (Sclater et al., 1980)
3. Tidal Energy	Energy received by the earth =2.7 E19erg/sec Energy flux = (2.7 E19erg/sec)(3.153E7sec/yr)/(1E7 erg/J) = 8.513E19J/yr	(Munk and Macdonald, 1960)
4. Oil	Total production = 3.3 E9Mt oil equivalent Energy flux = (3.3E9 t oil eq.)x (4.186E10J/t oil eq.) = 1.47 E20 J/yr oil equivalent	(British Petroleum, 1997)
5. Natural gas	Total production = 2.093 E9m³ Energy flux = 82.093 E12m³)x(3.77E7J/m³) = 7.89 E19J/yr	(British Petroleum, 1997)
6. Coal	Total production (soft) = 1.224 E9 t/yr Total production (hard) = 3.297 E9 t/yr Energy Flux = (1.224 E9 t/yr) (13.9 E9J/t) + (3.297 E9 t/yr)(27.9 E9 J/t) =1.09 E20 J/ yr	(British Petroleum, 1997) (British Petroleum, 1997)
7. Nuclear energy	Total production = 2.39 E12 kwh/yr Energy Flux = (2.39 E12 kwh/yr) (3.6 E6 J/kwh) = 8.60 E18 J/yr elec. equivalent	(British Petroleum, 1997)
8. Wood	Annual net forest area loss = 11.27E6 ha/yr	(Brown et.al. 1997)

	Biomass = 40 kg/m2	(Lieth and Whittaker. 1975)
	Energy Flux = (11.27 E6 ha/yr)(1 E4 m2/ha) (40 kg/m2)(1.3 E7 J/kg) = 5.86 E 19 J/yr	
9. Soil ersosion	Total soil erosion = 6.1 E10 t/yr	
	Based on conservative soil loss estimate of 10 t/ha/yr and 6.1 E9 ha agricultural land = 6.1 E16 g/yr (assume 1.0% organic matter), 5.4 kcal/g	
	Energy Flux = (6.1 E 16g)(.01)(5.4 kcal/g)(4186 J/kcal)	
	=1.38 E19 J/yr	
10. Phosphate	Total global production = 137 E6 t/yr	
	Gibbs free energy phosphate rock = 3.48 E2 J/g	(USDI. 1996)
	Energy Flux = (137 E12 g)(3.48 E2 J/g)	(Odum. 1996 p125)
	= 4.77 E16 J/yr	
11. Limestone	Total production = 120 E6 t/yr	
	Gibbs free energy phosphate rock = 611 J/g	(USDI. 1996)
	Energy Flux = (120 E12 g)(6.11 E2 J/g)	(Odum. 1996 p47)
	= 7.33 E16 J/yr	
12. Metals	Total global production of Al, Cu, Pb, Fe, Zn (1994) = 992.9 E6 t/yr = 992.9 E12 g/yr	(World Resources, 1997)

The total emergy driving a process measures the self-organisation work that is converged to make a product, service or stored reserve. By measuring work in emergy units, work in different parts of the energy hierarchy are comparable. Details on the procedure to perform an emergy account are published in many places (Odum, 1996).

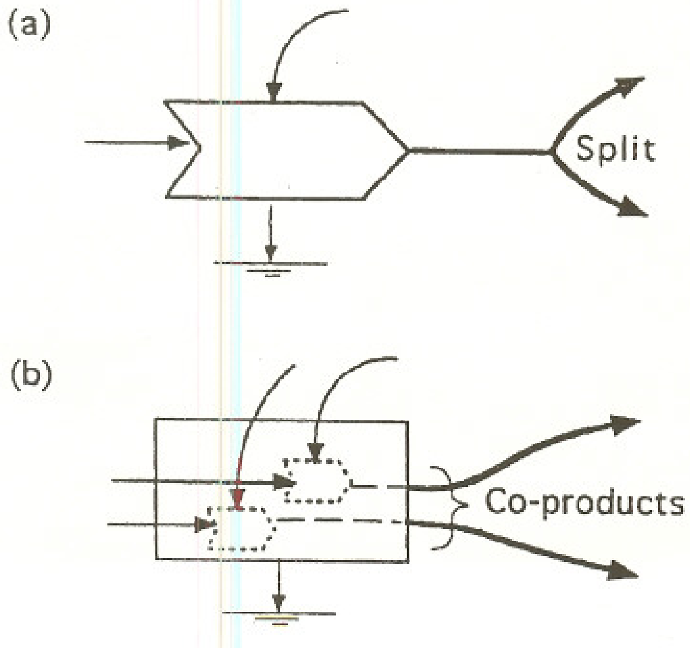


Figure 6: Configurations of production flows: (a) splits and (b) co-products

4. Material cycles

Material cycles in systems of the biosphere as part of the processing of energy transformations. There are cycles of the chemical elements, water, sediments, and waste products of society. Recycle is a part of all systems, from the scale of long term geologic cycles to the scale of ecosystems where nutrients and organic matter are recycled in relatively short term storages of plant and animal tissue. Material recycling is another way that processes are mutually reinforcing. Increasingly materials used by human economic systems are being recycled better as economic systems get better organised.

Material pathways are a regular part of an energy systems diagram, since there is always some energy in materials that are more concentrated than background. Sometimes it is useful to highlight pathways of a particular material using special shading, colour, or lines on a transparent overlay. See Figure 8.

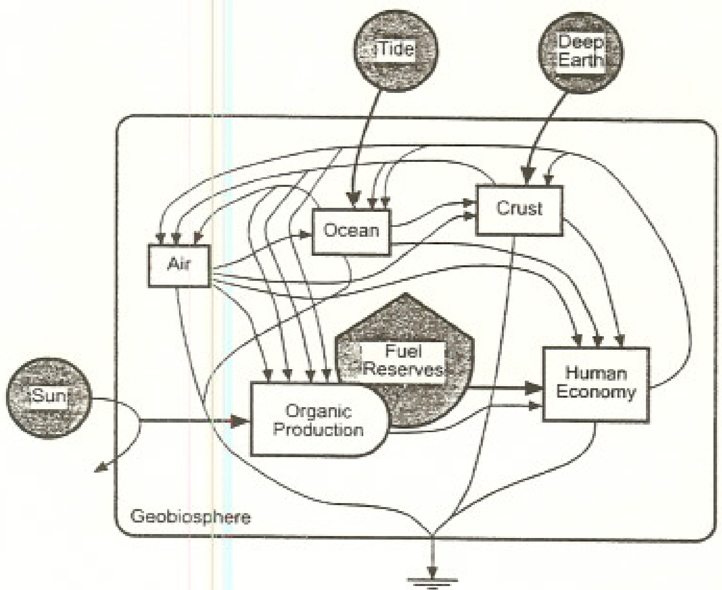


Figure 7: Systems diagram of the geobiosphere showing main emergy sources: solar insolution, tidal energy and deep earth inputs and use of mineral reserves in interconecctiong pathways of the atmospheric, oceanic and crustal systems

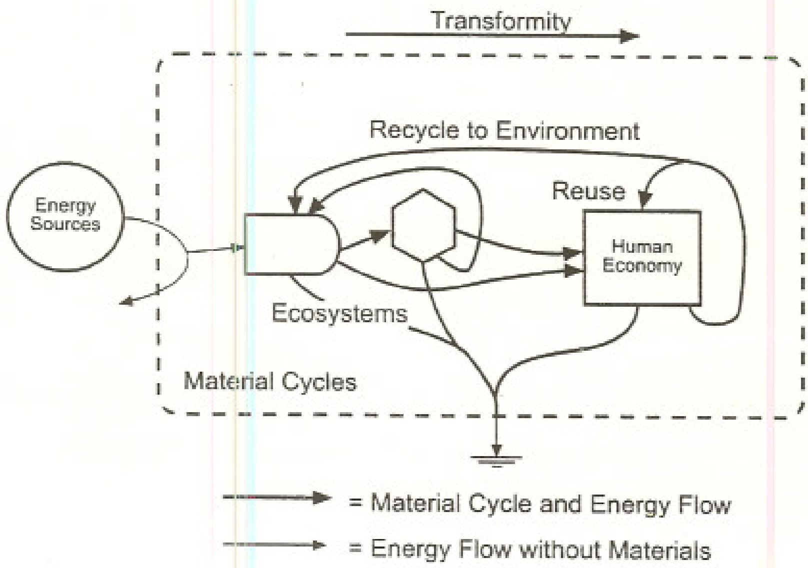


Figure 8: Systems diagram of recycling

4.1 Mass emergy

Each cycle occupies a zone in the energy hierarchy for its cycle from a dilute to more concentrated state and back again. The concentrating process requires use of available energy. The material gains emergy as it is concentrated. Emergy per unit mass (mass emergy) is a useful measure of material state which increases with concentration.

In part of each cycle the material may be incorporated into a product which has the emergy of its inputs. For example, phosphorus is incorporated into plant structures as it is concentrated. Where the material is released and dispersed into air, water, or solids at lower concentration, it loses some of its emergy. For example, the emergy per mass in phosphorus dispersing from plant decomposition decreases. The amount can be estimated from the inputs required for its reconcentrating.

Although everything on earth is more concentrated and has emergy relative to the general background of the universe, for our earth evaluations, however, we use the geobiosphere as our reference base. For many primary substances such as chemical elements, there is a general background concentration in the geobiosphere. When a recyling material disperses to this concentration, it has no remaining available energy and thus no emergy relative to the earth. For example, phosphorus at the background concentration of phosphorus in the surface layers of the ocean has no emergy.

4.2 Self regulation of cycles

Cycling allows for the continuous convergence and divergence of materials. Without continual flows of input energy that build structure, concentrations degrade away, falling into entropic disorder. It is through cycling that systems remain adaptive and vital. Materials sequestered in unreachable or unusable storages detract from function.

As Lotka (1925) showed, material cycles self regulate by developing larger storages upstream from the parts of their cycles where unit rates are slow (bottlenecks) until no part of the cycle is limiting except the driving source of available energy. Self organisation can also eliminate bottlenecks by supplying energy to accelerate the limiting step, accelerating dispersal. We might regard some products as important and the rest by-products when they appear to have no use. However, well organised systems process, cycle, and reuse all products, leaving none as waste.

4.3 Cycle management

Humans increasingly manage material cycles through the environment as part of municipal utilities and industrial ecology. Transformity of a material may be a good indicator of the appropriate part of the earth hierarchy for its use and recycle. Matching of transformities so that a material can amplify indicates an appropriate zone of the energy hierarchy for interactions. For example, it may be economic for concentrated metals and chemicals to be reused, whereas dilute organic materials and nutrients are appropriately recycled through the environment as concentrations usable by the ecosystems (an ecological engineering practice).

5. Emergy and information

The combination of parts and connections that make a system work is useful information. As used here it is something easier to copy for reuse than to remake anew. This information can be in a system's network, where its configuration makes the operation go. Or the plan for the system can be isolated as a code, message, or plan held by a 'carrier' with a very small energy content. For example, information is carried on paper, on computer disks, in human memory, in television transmissions, etc.

5.1 Information circle

Information depreciates by developing unrepaired error. Considerable to be sustainable in the long run an information storage has to be supported by a duplication and testing cycle. Emergy is required to maintain information with a cycle of repeated duplication, reusing, retesting and selecting to eliminate errors, a process that sometimes adds improvements. The circular life history diagrams taught in biology courses are examples. Very large emergy is required to generate the systems information the first time, especially genetic information.

5.2 Representing information in an energy systems diagram

Information can be represented in energy systems models in several ways. There is some information in the parts and connections of the model. Information is shown as a storage tank in Figure 9. It receives information inputs, has a copying loop, feedback control actions to the left, and depreciation pathway representing information is lost when carriers depreciate. For some purposes all this may be aggregated within a consumer symbol (Figure 9).

5.3 Emergy and complexity

Complexity of systems has long been represented by 'information theory' measures. For example, complexity in bits is the number of yes-no decisions required to define a configuration and is expressed on a logarithmic scale. In short, the information theory measure is the logarithm of the possibilities among the parts and connections. A storage may be used to represent such complexity in the aggregate. Since the possible arrangements and connections increase roughly as the square of the number of items, the emergy requirement to generate and maintain such storage may be proportional. However, information theory measures don't differentiate between useful complexity that operates a system and happenstance complexity with the same number of parts that can't do anything. The contribution of complexity to the system is best evaluated from its emergy content and empower required to sustain it.

There is great complexity at the small scales of molecules and heat where information theory measure on a logarithmic scale is molecular entropy. Information theory measures don't distinguish the same complexity on small molecular scale from that found on a large ecological scale. However, emergy does increase with scale of the units.

5.4 Scale and the hierarchy of information

Various categories of information can be placed in appropriate position in the left to right energy hierarchy by calculating their transformity. Transformities of valuable information such as the human genome and globally shared religious documents are very large because the emergy used to generate and maintain them is large and the energies of the carrier materials used to hold and carry the messages are tiny. In general, the information of higher transformity feeds back and controls items of lower transformity. For example, the human mind controls the computer. Public opinion controls individual information. To achieve the highest transformity status, information must have great generality, territory, and utility as a reinforcing control. Consider information in relation to scale starting with populations of heated molecules on a molecular scale. There the energy flows are large. The complexity on the scale of molecular chemistry has usually been viewed as degraded, disorderly statistical assemblages rather than as organised networks to be maintained. The transformities are small.

Useful information as controls emerges at the larger scale of complex molecules and living processes. The structures and information processes are facilitated by their extreme miniaturisation in living and electronic systems, but what happens on this scale is controlled by controls and selection from the larger scale of the ecosystems. Larger scale networks with long term memories control the rapid small scale information processes. For example, global changes in the self organisation of the biogeosphere control the molecular biological processing. High transformity information of life with emergy accumulated over many billion years (on the right in diagrams) controls the duplication and distribution of that information in rapid (microsecond) physiological processes (on the left in diagrams).

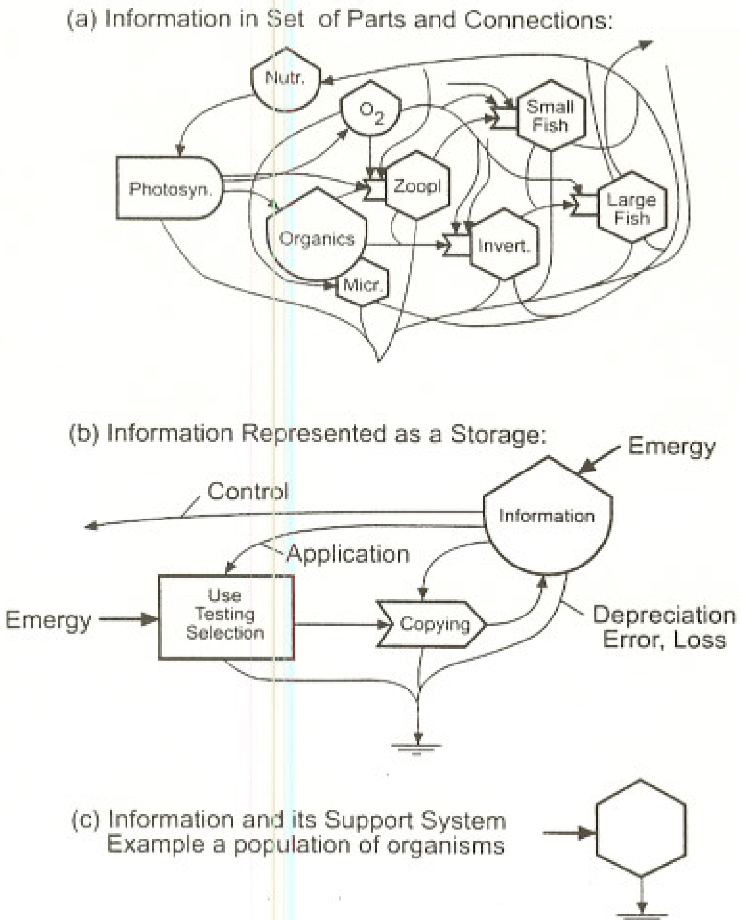


Figure 9: Ways of representing information on systems diagrams

5.5 Information as a Maxwell demon

When information developed and stored from energy flow systems feeds back to control and regulate thermal and chemical processes on a smaller scale, it fits the definition of a 'Maxwell Demon'. The traditional idea is that a Maxwell Demon cannot derive enough available energy from its own scale to select its inputs. However, real energy systems develop energy hierarchies converging resources spatially, accumulating emergy into useful information that reinforces the network maximising empower. Thus humans are the earth's information processor learning to utilise their genetic and learned information to reinforce the system which supplies their basis of life support.

6. Spatial scales and energy systems

The energy hierarchy has a spatial pattern which is exhibited within ecosystems. Many small units converge products and services to spatial centres (Figure 10). These in turn converge on even larger centres.

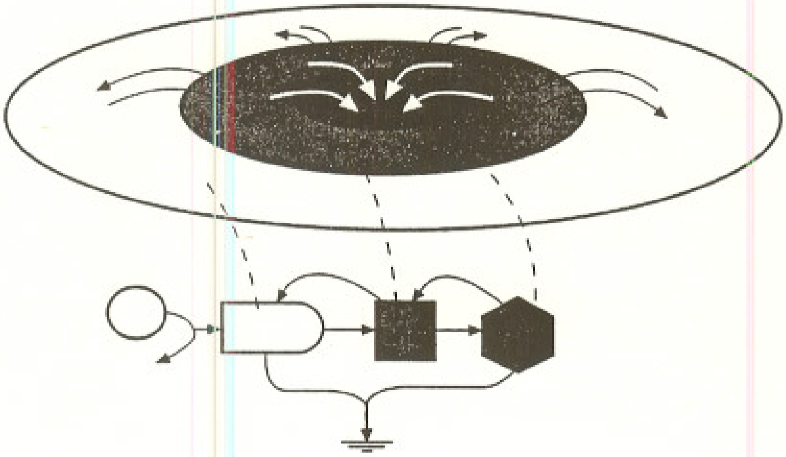


Figure 10: Spatial centres organised according to energy hierarchy

6.1 Empower density

Empower density is a measure of the intensity of activity and is evaluated as the total emergy per unit area per time (Sej/m^2/yr). Values are higher in centres in ecosystems. Highest values occur in cities (Table 2 and 3).

Table 2: Spatial Organisation of Landscape in North Florida (after Brown, 1980)

Land Use Type	Empower Density (E12 sej/m^2 *yr-1)	Emergy of Structure (E12 sej/m^2)	Structural mass (E3 kg/m^2)	% of city area
Single family residential (med. density)	20.7	149.1	181.5	81.3
Multi-family residential (avg. 4 floors)	126.6	1135.4	1170.0	4.5
Commercial strip	46.4	517.1	720.4	3.5
Commercial mall	220.7	1248.7	1429.4	0.9
Central business district (avg. 4 floors)	294.2	2026.8	2067.0	0.8

Table 3: Characteristics of urban systems in North Central Florida, USA (after Brown, 1980)

Urban Class	Population (E3 people)	Area (km^2)	Annual Empower (E21 sej/yr)	Empower Density (E12 sej/m^2 *yr-1)	Support Region (km^2)
Class 1	504	399.9	30.6	76.4	9855.1
Class 2	99	254.5	14.9	58.6	4778.3
Class 3	37	55.5	2.8	50.4	896.6
Class 4	13	18.6	0.8	44.2	263.1
Class 5	1.8	2.8	0.1	35.8	32.2

6.2 Spatial organisation of cities

Cities are points of convergence in the landscape that represent large concentrations of people, structure, and information. Energies and materials inflow from surrounding regions producing large volumes of wastes in air, water, and solid waste dumps. It has long been demonstrated that landscapes of cities are organised hierarchically, where there are many small rural towns, fewer small cities, and fewer and fewer larger cities. It has been suggested (Christaller, 1966; Losch, 1954) that the hierarchy results from the distribution of goods having varying market regions. It was found that market regions increased with city size and the array of goods increased because of the larger market areas from which to draw demand.

Probably just as important is the convergence of energies and materials into cities. Environmental support of cities must be converged from larger and larger support regions as city size increases. The larger the city the greater the area of support required to produce necessary inputs or from which inputs are extracted. Natural ecosystems provide resources like water, wood, clean air and biodiversity, while agricultural systems provide food and fibre. Heavily managed urban green spaces provide important inputs directly to humans in the form of recreation, education, and psychological relief from stress. The wastes generated by all aspects of the urban system are recycled back to the surrounding environment, some stimulating production, others having a negative effect.

The hierarchy of cities results from the interplay of both market regions and support regions. Energy and materials are concentrated in pathways of convergence and information and goods are fedback in diverging pathways of control and amplifier actions. Table 3 lists several characteristics of classes of cities in Florida, USA. Class 1 cities are the largest urban centres in the region, serving as central places and having populations of over half a million people. Class 5 cities are the smallest incorporated towns found scattered throughout the landscape having typical populations of about 2000 people. Annual empower is the total inflow of emergy per year consumed within the city. Empower density is the flow of emergy per unit area of the city per year. Annual use of emergy varies from 30.6 E21 sej/yr to only 0.1 E21 sej/yr for the class 1 and class 5 cities respectively.

The most intensely developed cities are the class 1 central places where commercial and industrial uses make up a greater proportion of the total city area than in the smaller cities. Intensity of activity can be measured by empower density (empower per unit area, sej/m^2 * yr-1). The empower density of the Florida cities ranges from about 76 E12 sej/ m^2 * yr-1 to about 36 E12 sej/ m^2 * yr-1 as given in Table 3.

Within cities spatial organisation is hierarchical from the low intensity rural fringe to the high concentrations of information and business in the Central Business District. The central city, where buildings and populations are largest, is surrounded by rings of decreasing intensity. When structure and land use 'metabolism' (energy use) are expressed as emergy, the increasing intensity of activity is obvious. Given in Table 4 are characteristics of several typical urban land uses in Florida cities and the percent of city area that is devoted to these uses. The empower density and emergy in structure increases with increasing intensity of activity while area decreases.

7. Interface of ecological systems with economic use

With the spread of human population and economic development, landscapes and waterscapes are usually controlled by the human economy. Energy Systems view of the landscape includes the environmental systems, the interface with the economy and the circulation of money and other exchanges between people.

7.1 Interface with the economy

Figure 11 includes ecosystems on the left and the interface with the economy on the right. Human society draws materials, energies, and 'services' from the environment. The materials and energies are easily understood to be things like wood, water, fruit, animals, and so forth. The services are things like waste assimilation, flood protection, or aesthetic qualities. Money circulates through the interface in payment for products and services passing to the economy again in payment for goods, services, fuels, and materials purchased from the economy. Storages of environmental products are natural capital. Some natural capital is an active part of continuing productive processes. Other storages are part of long term pro-cesses on a geologic time scale (non-renewable).

Renewability is a relative concept, since it depends on how quickly a material or energy is used compared to the speed at which it is generated. Wood, for instance, can be a renewable resource, if the rate of harvesting is matched with the regeneration rate. In contrast fossil fuels and most mineral resources are not renewable. Even though they are being constantly regenerated their rate of use is much faster than the regeneration rate. In Figure 11 the emergy flow N is from non-renewable storage. E is the emergy from renewable processes and short term storages.

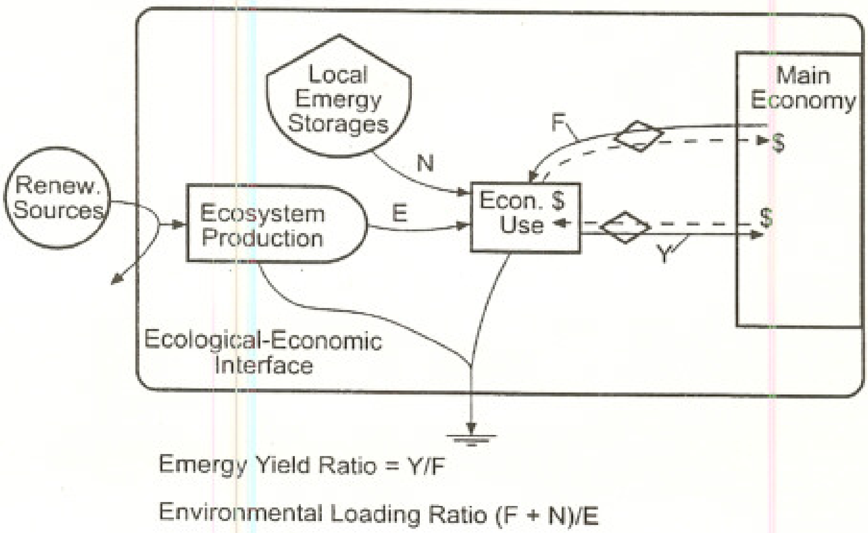


Figure 11: Systems diagram of the interface between ecosystems and economy, showing the flows of money, environmental contributions, and indices.

Agroecosystems are examples of the ecological-economic interface. Table 4 summarises emergy evaluations of thirteen crop systems in Italy. The emergy yield ratio (defined in Figure 11) measures the contribution to the economy beyond the emergy required to process it. The values between 1.1 and 2.2 are much less than those for primary energy sources such as fuels and electricity. The environmental loading ratio (defined in Figure 11) measures the economic empower impact on the local environmental processes. Fruit trees and vineyards had the greatest environmental impact. However, these values were less than average ratios within the United States.

7.2 Evaluating environmental contributions

All processes require material and energy inputs. The systems diagram of an economic use interface in Figure 11 is aggregated to show three inputs: (N) the use of non-renewal storages; (E) the use of renewable product of environment; and (F) the purchased items that 'feedback' (F) from the larger economy for the processing. The purchased items include human labour and services plus purchased non-renewable inputs brought in from other areas like minerals, and fuels, and renewable environmental inputs from other areas.

Examples are soils and water reservoirs. These have high emergy values because it can take hundreds of years to make 1 cm of topsoil (Pimentel, et al., 1995). Many environmental inputs are involved in collecting the waters used to cool power plants (Brown and Ulgiati, 1999).

Other environmental services are provided by the environment in absorbing and recycling waste products. They are often not accounted for because they are free.

Table 4: Indices for agro-ecosystems of Italy

Agro-ecosystem	Solar Transformity (E4sej/j)	Emergy-Yield ratio	Environmental loading ratio
Rice	5.58E+04	1.62	1.77
Forage	6.33E+04	2.20	0.94
Corn	7.74E+04	1.76	3.00
Sunflower	9.25E+04	2.18	1.96
Soybeans	9.33E+04	2.16	1.65
Wheat	1.00E+04	1.62	1.77
Sugar beet	1.05E+05	1.33	5.18
Rapeseed	1.05E+05	2.26	1.78
Fruits	2.16E+05	1.16	6.78
Oranges and Lemons	2.46E+05	1.15	7.26
Vineyard	3.02E+05	1.23	4.60
Olive	4.02E+05	1.35	3.10
Almonds	7.37E+05	1.42	2.59
Nation-wide crop production	9.14E+04	1.51	2.11

(Modified from Ulgiati et al., 1993)

When the environment becomes overloaded, the costs are recognised when the free service from the environment has to be replaced by technology. For production of by-products to be balanced with the environment's ability to absorb and recycle them, an adequate support area is necessary. When the environment is accounted for, performance of a production process is more time and location dependent, as it should be. In essence, by accounting for the 'load' on the environment and providing a support region for environmental recycle of by-products, a carrying capacity for economic uses of the environment can be determined.

7.3 Carrying capacity for economic investments

One theory for determining carrying capacity is that the scale or intensity of development in relation to its environment may be critical in predicting its effect and ultimately its sustainability (Brown et al. 1995, Ulgiati et al. 1995, Brown and Ulgiati 1997). Large-scale developments can be integrated into the environment, if there is sufficient regional support area to balance their effect. Much like the ecological concept of carrying capacity, where differing environments require different aerial extent of photosynthetic production for support of a given biomass of animals, environmental carrying capacity for economic investments depends on the area of 'support' over which a development's effect can be integrated. As the intensity of development increases (and therefore its consumption of resources and environmental impacts increase), the area of natural undeveloped environment required for its support must increase. All other things being equal, the more intense a development, the greater the area of environment necessary to balance it.

When environmental services are accounted for, materials and non-renewable energy inputs no longer appear to be the only important inputs. The ability of the environment to absorb impacts and recycle material by-products assumes a larger role in a process's sustainability. If the goal is to avoid changes of the environmental physio-chemical characteristics over time, the only way without increased investments in abatement technology is to expand the spatial scale of the process's supporting environment. By doing this, a strong constraint is placed on the size of the economic process allowed for a given area according to the carrying capacity of the local environment. Procedures and examples are given elsewhere (Ulgiati and Brown, 1999).

8. Time dimension for energy systems

Humans zoom up and down scales mentally when they consider policy decisions, but usually with verbal models that are not quantitative and cause semantic confusion. Energy systems concepts provide a pulsing paradigm for the time dimension of ecosystems and general systems designs for dynamic computer simulation.

8.1 Pulsing paradigm

By now enough knowledge has been accumulated in most fields to conclude that what is normally sustainable is a sequence of repeating pulses. At larger scales pulses are more widely separated but sharper. Current research seeks reasons – evidences that self-organising systems can increase their performance, maximising empower by pulsing. The reason pulsing is adaptive has to do with optimal loading of autocatalytic transformation processes. A simple steady state system of production and consumption may not transform as much as repeating surges of production and consumption. For whatever reasons the normal pulsing pattern is repetitive and oscillatory (Figure 12). Chaotic patterns may be a special pulsing design for maximising energy transformations.

Like the textbook prey-predator model, pulsing develops with a producer-consumer pair, in which a slow accumulation of one storage is followed by a frenzied consumption and momentary storage of high transformity structure and feedback actions. Self organisation reinforces those pairs that set up pulses, since more work is done by those pathway designs.

Like other autocatalytic units connected in series, information systems may also develop frenzied pulses. For example, if there is a source of species, biodiversity (information storage) may pulse as it draws emergy from accumulations of biomass (Figure 12). This is a way of looking at the increase of diversity in ecosystem succession.

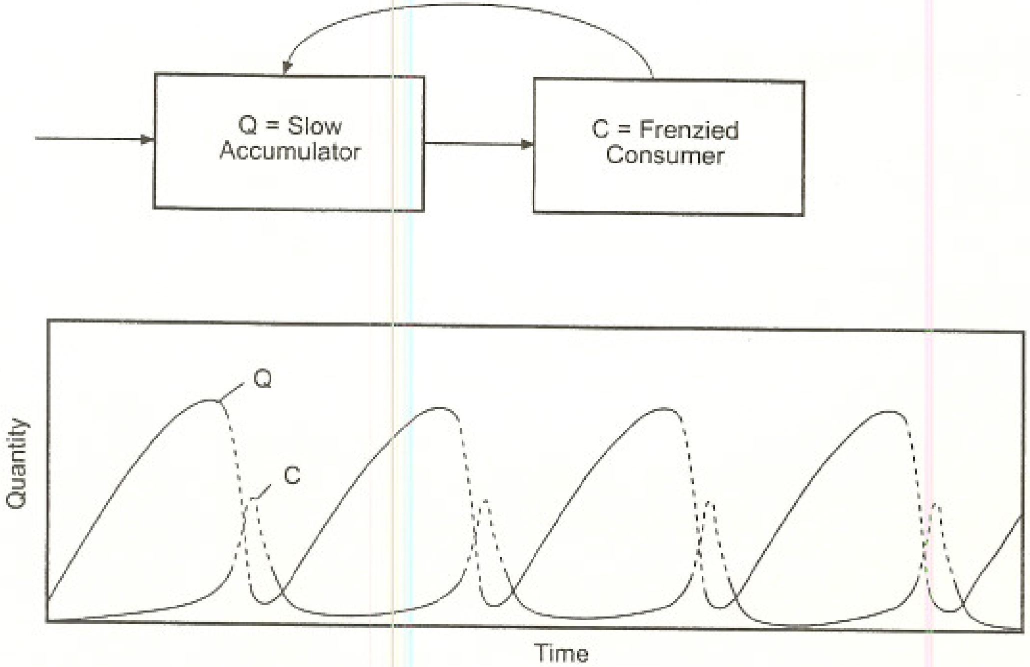


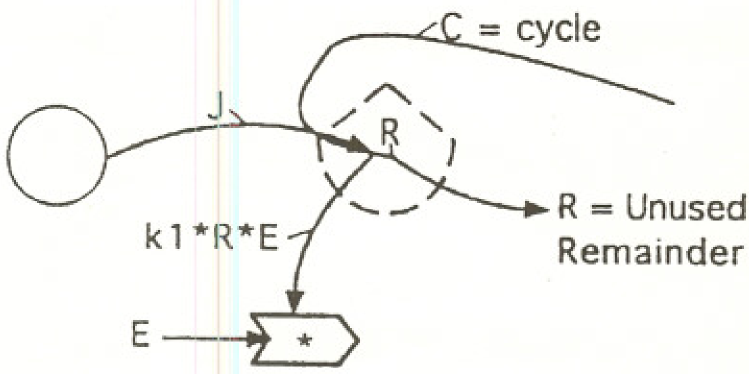
Figure 12: Pulsing pairs that dominate self organisation one each scale of size and time

8.2 Steady state aggregation of the small scale components

When a window of study is selected, scales of territory and oscillation are selected also. For example, if the view of an ecosystem selected is on the scale of hectares and years, small fast processes of photosynthesis, microbial bursts, and daily weather oscillations need to be aggregated, but not eliminated. What is relevant for the diagrams and for calculations is the running average effect of these fast processes on the larger scale of interest. As part of the aggregation process, the small, fast, and high energy inputs from the left can be included in the system diagram with a symbol (and mathematical characteristics) that aggregates the very fast, fine detail oscillations into a production function appropriate for the larger scale model. In other words, steady state of small scale inputs is a useful aggregation artefact by the beholder who is considering a larger scale.

8.3 Flow junction modelling of the small scale

While simulating a system on a time and space scale appropriate to the window of interest (days and years), it is a useless distraction to be simulating the tiny physiological parts of the ecosystem that fill and discharge in seconds. For example, simulating light-chlorophyll dynamics in a forest model wastes computer time and adds numbing complexity. In Figure 13 a flow is shown as the sum of inputs minus outputs with the remainder passing out of the system or into another storage. The limiting factor-type equation that results from this configuration is very similar to one that comes from setting the derivative of a storage equation to zero. Professor Katherine Ewel of the University of Florida found this configuration a way to input sunlight in analogue computer simulations of forests. Where small nutrient storages in oligotrophic lake models in Euler integration tend to go into errors of artificial chaos, they can be replaced with the configuration in Figure 13 which shows the nutrient flows without a storage. The computer output provides a running average of the flows that would exist with the storages in the real world. The flow junction is a way to keep models appropriate and understandable.



$$R = J + C - K1*R*E$$

$$R = (J + C)/(1 + K1*N)$$

Figure 13: Flow junction mechanism for contributions from a smaller scale than the primary window interest

8.4 Input pulses from larger scales

At the upper end of the systems window and its diagram are the pulses coming from the large scale. The larger scale includes the window of interest plus a much larger area in which it is embedded. In other words, pulses come from the surrounding system. These pulses are so infrequent that they appear on the ecosystem scale as catastrophe s such as hurricanes, earthquakes, and economic depressions. Ecosystems and their models appropriately respond by repairing, restoring, and repeating succession. However, these pulses from the large scale are just as regular and recurring as pulses of the smaller scale. Examinations of ecosystems in the field and their modelling need to consider repeating destruction and the repair mechanisms that make the system adaptive. The transformity of large scale pulses is great, and the best adapted systems derive useful emergy. Ecosystems strategy may be to resist small storms but to guide the destruction by large storms into patterns that add structure and favour rapid re-growth.

8.5 Pulses of global scale

The global ecosystem uses the main environmental systems of the atmosphere, ocean, and earth processes. Although it has mostly been studied with separate disciplines (meteorology, oceanography, geology), the geobiosphere is a highly integrated single system. Appropriate diagramming requires all the main processes of each as necessary to the others. When diagrammed in this way, flows are co-products and have the same empower. Increasingly, historical research in geology is finding large pulses in the earth systems. The energy systems theory suggests a means for calculating transformity and determining the scale of phenomena driving these pulses. The largest pulses may be those in evolutionary information processing or continent formation.

8.6 The pulse of the civilised human economy

One of the global pulses underway is the human economy accelerated in the last two centuries into a surge of civilisation achievement based on previous accumulation of fossil fuel and other slowly renewable resources. This global pulse is one of the large scale 'catastrophic' inputs to smaller ecosystems.

Human society adapting to the capitalistic patterns that maximise empower during rapid growth is certainly unprepared for the different type of system that will be required as the peak of the fuel-economic pulse is passed. It may be possible to rapidly change our priorities and ethics from the growth regime to one we hopefully designate 'The Prosperous Way down'. This will require reduction of population, selection of what is worth saving, increased co-operation, efficiency, and sharing of products and effort.

8.7 Selecting shared information to carry to the next pulse

To have a long existence in a global environment for the long range, humanity and its civilised information must pulse when resource accumulations permit and shift to a low emergy regime between.

In ecosystems we have two precedents to study: (a) the system that comes down in a crash as in fire and restarts, and (b) systems that have a smooth program of adapting to the winter and re-emerging in the summer. In both instances the future is based on information reserves in the larger surrounding system.

Information is increasingly shared globally through television and the internet. Global sharing makes some information of large scale and long duration. However, large scale information will have its own pulses – which we call information storms. To make civilisation sustainable in the long run through periods of pulsing and decent, perhaps we need to understand and manage information storms better. Through selection of what is worth sharing, perhaps a core of the civilisation can be placed in long term memory during periods of coming down for expanded use during the up cycles. Should we worry about these information storms, their creation and spread and the effects they have on human emotions and societies behaviour?

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