Citation: Brown, M.T. and S. Ulgiati, 2004. Emergy, transformity and ecosystem health. In S.E. Jorgensen et.al. (eds) *Handbook of Ecological Indicators for Assessment of Ecosystem Health.* Elsevier. New York.

Emergy, Transformity, and Ecosystem Health

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1. Introduction

In this chapter, ecosystems are summarized as energetic systems and ecosystem health is discussed in relation to changes in structure, organization and functional capacity as explained by changes in emergy, empower, and transformity. The living and non-living parts and processes of the environment as they operate together are commonly called ecosystems. Examples are forests, wetlands, lakes, prairies, and coral reefs. Ecosystems circulate materials, transform energy, support populations, join components in network interactions, organize hierarchies and spatial centers, evolve and replicate information, and maintain structure in pulsing oscillations. Energy drives all these processes and energetic principles explain much of what is observed.

The living parts of ecosystems are interconnected, each receiving energy and materials from the other, interacting through feedback mechanisms to self-organize in space, time, and connectivity. Processes of energy transformation throughout the ecosystem build order, cycle materials, sustain information, degrading energy in the process. The parts are organized in an energy hierarchy as shown in aggregated form in Figure 1. As energy flows from driving energy sources on the right to higher and higher order ecosystem components it is transformed from sunlight to plant biomass, to 1st level consumers, to second level and so forth. At each transformation second law losses decrease the available energy but the "quality" of energy remaining is increased.

2. A Systems View of Ecosystem Health

Conceptually, ecosystem health is related to integrity and sustainability. A healthy ecosystem is one that maintains both system structure and function in the presence of stress. Vigor, resilience and organization have been suggested as appropriate criteria for judging ecosystem health. Leopold (1949) referred to health of the "land organism" as "the capacity for internal self-renewal". Others have suggested that "Health is an idea that transcends scientific definition. It contains values, which are not amenable to scientific methods of exploration but are no less important or necessary because of that." (Ehrenfeld, 1993). Ecosystem health may be related to the totality of ecosystem structure and function and may only be understood within that framework.

The condition of landscapes and the ecosystems within them is strongly related to levels of human activity. Human-dominated activities and especially the intensity of land uses can affect ecosystems through direct, secondary, and cumulative impacts. Most landscapes are composed of patches of developed land and patches of wild ecosystems. While not directly converted, wild ecosystems very often experience cumulative secondary impacts that originate in developed areas and that spread outward into surrounding and adjacent undeveloped lands. The more developed a landscape, the greater the intensity of impacts. The systems diagram in Figure 2 illustrates some of the impacts originating in developed lands that are experienced by surrounding and adjacent wild ecosystems. They come in the form of air- and water-born pollutants, physical damage, changes in the suite of environmental conditions (like changes in groundwater levels or increased flooding), or combinations of all of them. Pathways from the developed lands module on the right carry nutrients and toxins that affect surface and ground water which in turn negatively affect terrestrial and marine and aquatic systems. Other pathways interact directly with the biomass and species of wild ecosystems decreasing viability and quantity of each. Pathways that affect the inflow and outflow of surface and groundwater may alter hydrologic conditions, which in turn, may negatively affect ecological systems. All these pathways of interaction affect ecosystem health.

3. Emergy, Transformity, and Hierarchy

Given next are definitions and a brief conceptual framework of Emergy Synthesis theory (Odum, 1996) and Systems Ecology (Odum, 1983) that form the basis for understanding ecological systems within the context of ecosystem health.

3.1 Emergy and transformity: concepts and definitions

That different forms of energy have different "qualities" is evident from their abilities to do work. While it is true that all energy can be converted to heat, it is not true that one form of energy is substitutable for another in all situations. For instance, plants cannot substitute fossil fuel for sunlight in photosynthetic production, nor can humans substitute sunlight energy for food or water. It should be obvious that the quality that makes an energy flow usable by one set of transformation processes makes it unusable for another set. Thus quality is related to form of energy and to its concentration; where higher quality is somewhat synonymous with higher concentration of energy and results in greater flexibility. So wood is more concentrated than detritus, coal more concentrated than wood, and electricity more concentrated than coal.

The concept of emergy accounts for the environmental services supporting process as well as for their convergence through a chain of energy and matter transformations in both space and time. By definition, emergy is the amount of energy of one type (usually solar) that is directly or indirectly required to provide a given flow or storage of energy or matter. The units of emergy are emjoules (abbreviated eJ) to distinguish them from energy joules (abbreviated J). Solar emergy is expressed in solar emergy joules (seJ, or solar emjoules). The flow of emergy is empower, in units of emjoules per time. Solar empower is solar emjoules per time (e.g., seJ/sec).

When the emergy required to make something is expressed as a ratio to the available energy of the product, the resulting ratio is called a transformity[1]. The solar emergy required to produce a unit flow or storage of available energy is called solar transformity and is expressed in solar emergy joules per joule of output flow (seJ/J). The transformity of solar radiation is assumed equal to one (1.0 seJ/J). 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 (Odum, 1996). The total emergy driving the biosphere is the sum of solar radiation, deep heat, and tidal momentum and is about 15.83 E24 seJ/yr, based on a re-evaluation and subsequent recalculation of energy contributions done in the year 2000 (Odum et al., 2000).[2] . This total emergy is used as a driving

[1] The transformity was originally proposed as a measure of energy quality (Odum 1976) and referred to as the energy quality ratio and the energy transformation ratio, but it was renamed *transformity* in 1983 (Odum et al. 1983). The ratio of emergy to matter produced by a process (i.e. seJ/g) is termed specific emergy. The general term for transformities and specific emergy is emergy intensity.

[2] Prior to 2000, the total emergy contribution to the geobiosphere that was used in calculating emergy intensities was 9.44 E24 seJ/yr. The increase in global emergy reference base to 15.83 E24 seJ/yr changes all the emergy intensities

force for all main biosphere scale processes (winds, rains, ocean currents, and geologic cycles), because these processes and the products they produce are coupled and cannot be generated one without the other (Figure 3)

Table 1 lists transformities (seJ/J) and specific emergy (seJ/g) of some of the main flows of emergy driving ecological processes. Transformities and specific emergy given in the last column are ratios of the biosphere driving emergy in the 2^{nd} column to the annual production in the 3^{rd} column. Figure 3 shows in an aggregated way the emergy of the main biosphere flows that are, in turn, used to account for input flows to processes on smaller space-time scales, like processes in ecosystems as well as in human dominated systems (Ulgiati and Brown, 1999; Brown and Bardi, 2001; Brandt-Williams, 2002; Kangas, 2002). The total emergy driving a process becomes a measure of the self-organization activity of the surrounding environment, converging to make that process possible. It is a measure of the environmental work necessary to provide a given resource. For example, the organic matter in forest soil represents the convergence of solar energy, rain, and winds driving the work processes of the forest over many years that has resulted in layer upon layer of detritus that ever so slowly decomposes into a storage of soil organic matter. It represents part of the past and present ecosystem's work that was necessary to make it available.

Example transformities of main ecosystem components are given in Tables 2 and 3. Table 2 lists components and processes of terrestrial ecosystems giving several transformities for each. Within each category transformities vary almost one order of magnitude reflecting the differences in total driving energy of each ecosystem type. The table is arranged in increasing quality of products from gross production to peat. Transformities increase in like fashion. An energy transformation is a conversion of one kind of energy to another kind. As required by the second law, the input energies (sun, wind, rain, etc) with available potential to do work are partly degraded in the process of generating a lesser quantity of each output energy. With each successive step, a lesser amount of higher quality resources are developed.

When the output energy of a process is expressed as a percent of the input energy, an efficiency results. Lindeman (1942) efficiencies, in ecological systems, are an expression of the efficiency of transfer of energy between trophic levels. Table 3 lists transformities of trophic levels in the Prince William Sound of Alaska calculated from a food web and using Lindeman efficiencies of

which directly and indirectly were derived from the value of global annual empower. Thus, to be consistent and to allow comparison with older values, emergy intensities calculated prior to the year 2000 are multiplied by 1.68 (the ratio of 15.83/9.44).

about 10% (Brown et al. 1993). The transformity, which is a ratio of the emergy input to the available energy output, is an expression of quality of the output energy; for the higher the transformity, the more emergy is required to make it.

3.2 Hierarchy

A hierarchy is a form of organization resembling a pyramid where each level is subordinate to the one above it. Depending on how one views a hierarchy, it can be an organization whose components are arranged in levels from a top level (small in number, but large in influence) down to a bottom level (many in number, but small in influence). Or one can view a hierarchy from the bottom where one observes a partially-ordered structure of entities in which every entity but one is successor to at least one other entity; and every entity except the highest entity is a predecessor to at least one other. In general, in ecology we consider hierarchical organization to be a group of processes arranged in order of rank or class in which the nature of function at each higher level becomes more broadly embracing than at the lower level. Thus we often speak of food-chains as hierarchical in organization.

Most if not all systems form hierarchical energy transformation series, where 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 ones **(Figure 4)**. Energy is converged from lower to higher order processes, and with each transformation step, much energy loses its availability (a consequence of the 2nd Law of Thermodynamics), while only a small amount is passed along to the next step. In addition some energy is fed back reinforcing power flows up the hierarchy. Note in Figure 4 the reinforcing feedbacks by which each transformed power flow feeds backward so that its special properties can have amplifier actions.

3.3 Transformities and Hierarchy

Transformities are quality indicators, by virtue of the fact that they quantify the convergence of energy into products and account for the total amount of energy required to make something. Quality is a system property, which means that an "absolute" scale of quality cannot be made, nor can the usefulness of a measure of quality be assessed without first defining the structure and boundaries of the system. For instance, quality as synonymous with usefulness to the human economy is only one possible definition of quality, a “user based quality.” A second possibility of defining quality is one where quality increase with increases of input. That is, the more energy invested in something the higher its quality. We might describe this type of quality as “donor based quality”.

Self-organizing systems (be they the biosphere or an ecosystem) are organized with hierarchical levels (Figure 4) and each level is composed of many parallel processes. This leads to two other properties of quality: a) *Parallel quality,* and b) *Cross quality*. In the first kind, "**parallel quality**", quality is related to the efficiency of a process that produces a given flow of energy or matter within the same hierarchical level (comparison among units in the same hierarchical level in Figure 4). For any given ecological product (organic matter, wood, herbivore, carnivore etc) there are almost an infinite number of ways of producing it, depending on surrounding conditions. For example, the same tree species may have different gross production and yield different number and quality of fruit depending on climate, soil quality, rain, etc.. Individual processes have their own efficiency, and as a result the output has a distinct transformity. Quality as measured by transformity in this case relates to the emergy required to make like products under differing conditions and processes. Note in Table 2 where several transformities are given for each of the ecosystem products listed.

The second definition of quality, "**cross quality**", is related to the hierarchical organization of the system. In this case, transformity is used to compare components or outputs from the different levels of the hierarchy, accounting for the convergence of emergy at higher and higher levels (comparison of transformity between different hierarchical levels, in Figure 4). At higher levels, a larger convergence of inputs is required to support the component (a huge amount of grass is needed to support an herbivore, many kg of herbivore are required to support a predator, many villages to support a city, etc). Also, higher feedback and control ability characterize components at higher hierarchical levels, so that higher transformity is linked to higher control ability on lower levels. Therefore, higher transformity, as equated with higher level in the hierarchy, often means greater flexibility and is accompanied by greater spatial and temporal effect.

Figure 5 and Table 4 give energy and transformity values for an aggregated system diagram of Silver Springs, Florida. The data were taken from H.T. Odum's earlier studies on this ecosystem (Odum, 1957). Solar energy drives the system directly (i.e. through photosynthesis) and indirectly trough landscape processes that develop aquifer storages, which provide the spring run kinetic energy. Vegetation in the spring run use solar energy and capitalize on the kinetic energy of the spring which brings a constant supply of nutrients. Products of photosynthesis are consumed directly by herbivores and also deposited in detritus. Herbivores are consumed by carnivores who are, in turn, consumed by top carnivores. With each step in the food chain, energy is degraded.

3.4 Transformity and efficiency

Transformities can sometimes play the role of efficiency indicators and sometimes the role of hierarchical position indicator. This is completely true in systems selected under maximum power principle constraints (Lotka, 1922a, 1922b, and Odum, 1983) and is therefore true in untouched and healthy ecosystems. Things are different in an ecosystem stressed by an excess of outside pressure. Relations among components are likely to change, some component may also disappear and the whole hierarchy be altered. The efficiency of given processes may change (they may decrease or ncrease) and some patterns of hierarchical control of higher to lower levels may diminish or disappear due to a simplified structure of the system. These performance changes translate into different values of the transformities, the variations of which become clear measures of lost or decreased system integrity.

When an ecological network is expressed as a series of energy flows and transformation steps where the transformation steps are represented as Lindeman efficiencies, the resulting transformities represent trophic convergence and a measure of the amount of solar energy required to produce each level in the hierarchy

4 Emergy, Transformity and Biodiversity

In practice, the conservation of biodiversity suggests sustaining the diversity of species in ecosystems as we plan human activities that affect ecosystem health. Biodiversity has no single standard definition. Generally speaking, biodiversity is a *measure of the relative diversity among organisms present in different ecosystems*. 'Diversity' in this case includes diversity within species (i.e., genetic diversity), among species, and among ecosystems. Another definition, is simply the *totality of genes, species, and ecosystems of a region*. Three levels of biodiversity have been recognized:

- genetic diversity - diversity of genes within a species.
- species diversity - diversity among species
- ecosystem diversity - diversity among ecosystem

A fourth level of biodiversity, cultural diversity, has also been recognized.

A main problem with quantifying biodiversity, especially in light of the definition above, is that there is no overall measure of biodiversity since diversity at various levels of an ecological hierarchy cannot be summed. If they were summed, bacteria and other small animals and plants, would dominate the resulting diversity to the total neglect of the larger species. It therefore may be possible to develop a quantitative evaluation of total biodiversity within regions or ecosystems by weighting biodiversity at each hierarchical level by typical trophic level transformities (see, for instance Table 5). In this way quantitative measures of biodiversity can be compared and changes resulting from species loss can be scaled based on transformities. A more realistic picture of total biodiversity may emerge and allow quantitative comparison of losses and gains that result from changes in ecological health.

5. Emergy and information

Ecosystems create, store and cycle information. The cycles of material, driven by energy are also cycles of information. Ecosystems, driven by a spectrum of input resources generate information accordingly and store it in different ways (seeds, structure, biodiversity). The emergy cost of the generated information can be measured by a transformity value and may be a measure of healthy ecosystem dynamics. Odum (1996) suggested transformities for various categories of information within ecosystems given in Table 5. In healthy ecosystems (as well as in healthy human-dominated systems such as a good University) suitable emergy input flows contribute to generating, copying, storing and disseminating information. In stressed ecosystems such as those where some simplification occurs due to improper loading from outside, the cycle of information is broken or impaired. In this case, the ecosystem exhibits a loss of information, which may manifest itself in simplification of structural complexity, losses of diversity, or decreases in genetic diversity (reduced reproduction).

There are two different concepts of information shown in Table 6. The first aspect refers to the emergy required to maintain information, as in the maintenance of DNA in leaves (i.e., copying), and the maintenance of information of the population of trees (Emergy in seed DNA which is the storing and disseminating information). The second concept is related to generating new information. When a species must be generated anew the costs are associated with developing one from existing information sources such as trees within the same forest. However, the emergy required to generate biodiversity at the global scale, that is to generate all species anew, required billions of years and a huge amount of total emergy. Table 6 provides very average data for tropical forest ecosystems and of course represents only "order of magnitude" estimates of the costs of information generation, copying, storing, testing and disseminating.

6. Measuring Changes in Ecosystem Health

Changes in ecosystem health can result from alterations in driving energy signature, or inflows of a high quality stressor such as pollutants, or unsustainable activity like over harvesting. In each case there is a consequent change in the pattern of energy flows supporting organization. An energy signature (see Figure 6) could change, resulting in ripples that could propagate through the ecosystem. If the change in signature is outside the normal range of fluctuations in the driving energy pattern, the effect is a change in the flows of energy and material throughout the ecosystem. Significant change in system organization might be interpreted as changes in ecosystem health. In general, chemicals, including metals, pollutants and toxins have high transformity (see Table 7) and as a result of an excess concentration, they are capable of instigating significant changes in ecosystem processes, which often result in declines in ecosystem health. As transformities (emergy intensities) increase their potential effect within ecosystem increases. Effects can be both positive and negative. Transformity does not suggest the outcome that might result from the interaction of a stressor within an ecosystem, only that with high transformity, the effect is greater.

The ultimate effect of a pollutant or toxin is not only related to its transformity, but more importantly to its concentration or empower density (emergy per unit area per unit time, i.e. seJ/m2*day) in the ecosystem. Where empower density of a stressor is significantly higher than the average empower density of the ecosystem it is released into, one can expect significant changes in ecosystem function. For instance because of the very high transformities of most metals like those at the bottom of Table 7, their concentrations need only be in the parts per billion range to still have empower densities greater than most natural ecosystems. For instance, using the transformity of mercury in Table 7, and the exergy of mercury (Szargut et al. 1988), one can convert the transformity to a specific emergy of 3.7 E17 sej/g. Using this specific emergy, and a mercury concentration of 0.001 ppb (the level the EPA considers to have chronic effects on aquatic life) the emergy density of the mercury in a lake would be 3.7 E12 sej/m^2. This emergy density is about 2 orders of magnitude greater than the empower of renewable sources driving the lake ecosystem. Genoni, et al (2003) measured concentrations of 25 different elements in trophic compartments and in the physical environment of the Steina River in Germany (Table 6). They calculated transformities of each element based on global emergy supporting river ecosystem, which cycles the elements and their Gibbs energy. They suggested that the tendency to bioaccumulate was related to transformity of the elements and the transformity of accumulating compartments (i.e. metals and heavy elements accumulated in high transformity compartments).

Empower density has been used as a predictor of impact of human dominated activities on ecosystems. In recent studies of the Florida, USA, landscape Brown and Vivas (2004) showed strong correlations between empower density of urban and agricultural land uses with declines in wetland ecosystem health and pollutant loads in streams. Table 8 shows general empower densities of urban and agricultural land uses with natural wildlands for comparison. The empower densities of urban and agricultural land uses are from 2 to 4 orders of magnitude greater than the empower density of the natural environment.

A change in ecosystem health is manifested in changes in structural and functional relationships within the system of interest (region, landscape, ecosystem). Often the signs are subtle enough that change is difficult to detect. In other circumstances indicators are not sensitive enough to detect change or to discern changes in health from “normal variability”. Network analysis of the flows of emergy on pathways of ecological systems may add insight into changes in ecosystem health. Using the data from Silver Springs in Figure 5, a network analysis of changes in emergy flows and cycling that results from removing the top carnivores (Table 9) shows changes in overall cycling emergy of about 15% at the top end of the food chain and diminishing effect cascading back downward toward the bottom. The analysis uses a matrix technique to assign emergy to pathways and includes cycling so that feedbacks within the system are accounted for. Evaluation of the changes in pathway emergy may provide a tool that can help in measuring changes in overall ecosystem health with alterations of components or elimination of trophic levels within the system.

7. Restoring ecosystem health

Restoration of ecosystems falls within the sphere of ecological engineering. Ecological engineering is the design and management of self-organizing ecosystems that integrate human society with its natural environment for the benefit of both. The restoration of damaged ecosystems, while resulting in benefits for humanity (increased ecological services) is also necessary to maintain landscape scale information cycles and ultimately biodiversity. The value of active restoration can be measured as the decrease in the time required to restore ecosystem functions to levels characteristic of levels prior to disturbance. The graph in Figure 7 illustrates the concept of a net benefit from ecological restoration. The difference between the upper and lower lines in the graph is the benefit of restoration. If the benefit is divided by the costs of restoration a benefit/cost ratio results.

Stressed or damaged ecosystems may be rejuvenated or restored by removal of stresses or in the case of significant losses by re-construction. Table 10 gives data for the construction of a forested wetland system in Florida. The data are given for a 50-year time period assuming that 50 years are required to develop a relatively mature forested wetland. While the inputs of non-renewable and human dominated resources are significant, over the 50 year time frame of the restoration effort the renewable emergy dominates.

Summary and Conclusions

Emergy and transformity are useful measures that may be applied to concepts of ecosystem health. Transformity measures the convergence of biosphere work into processes and products of ecosystems and as such offers the opportunity to scale ecosystem and their parts based on the energy required to develop and maintain them. Ecosystems are composed of physical structure (i.e., wood, biomass, detritus, animal tissue, etc) and information found in both its genetic makeup as well as relationships and connections between individuals and groups of individuals. Declines in ecosystem health are manifested in changes in the quality and quantity of relationships and connections between individuals. Stressors may change driving energies pathways, and connections,

When one component in a system is affected, the energy and matter flows in the whole system change, which may translate into declines in ecosystem health. We suggest in this chapter, that changes in ecosystem structure and functions are reflected in changes of emergy flows and the corresponding transformities of system components. We suggest that there may be a relationship between the empower density of urban and agricultural lands and their effects on ecosystem health. The effect of a stressor may be predicted by its empower density. Changes in ecosystem structure translate into changes in pathway empower and thus quantifying changes on networks may provide quantitative evaluation of changes in ecosystem health.

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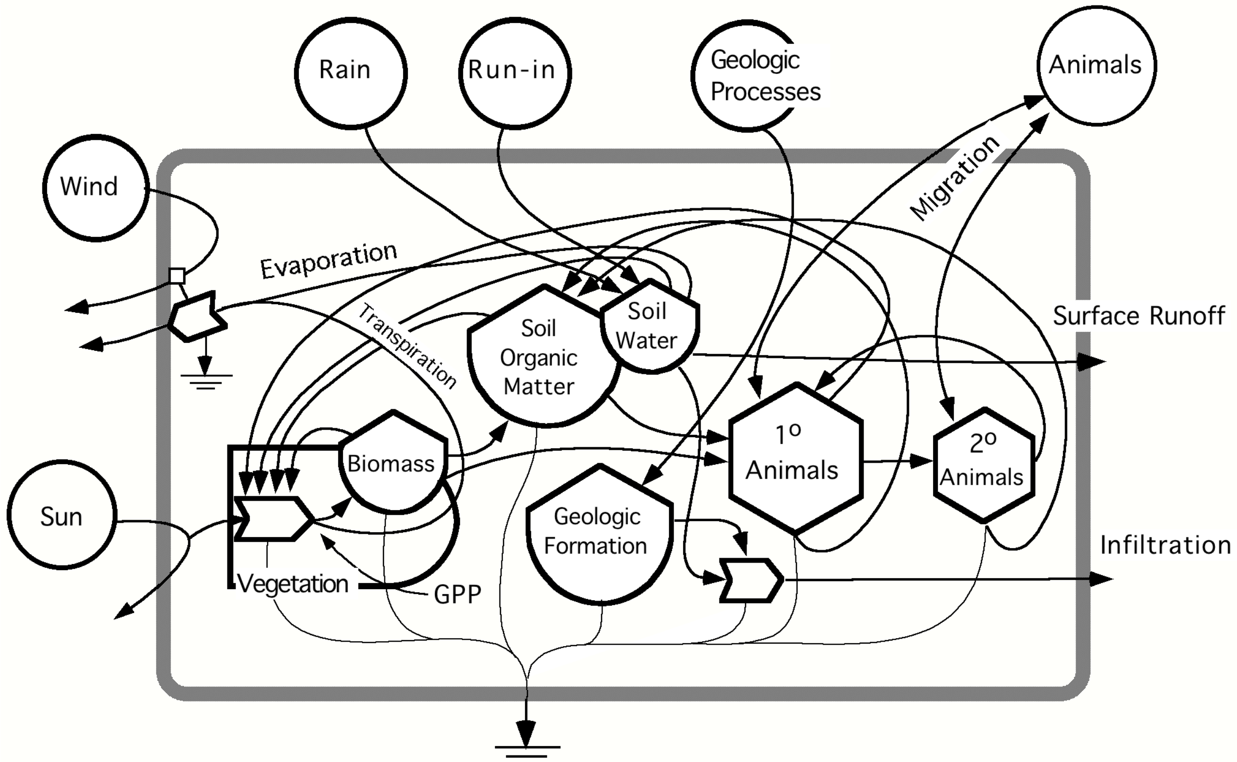

Figure 1 Generic ecosystem diagram showing driving energies, production, cycling, and the hierarchy of ecological components.

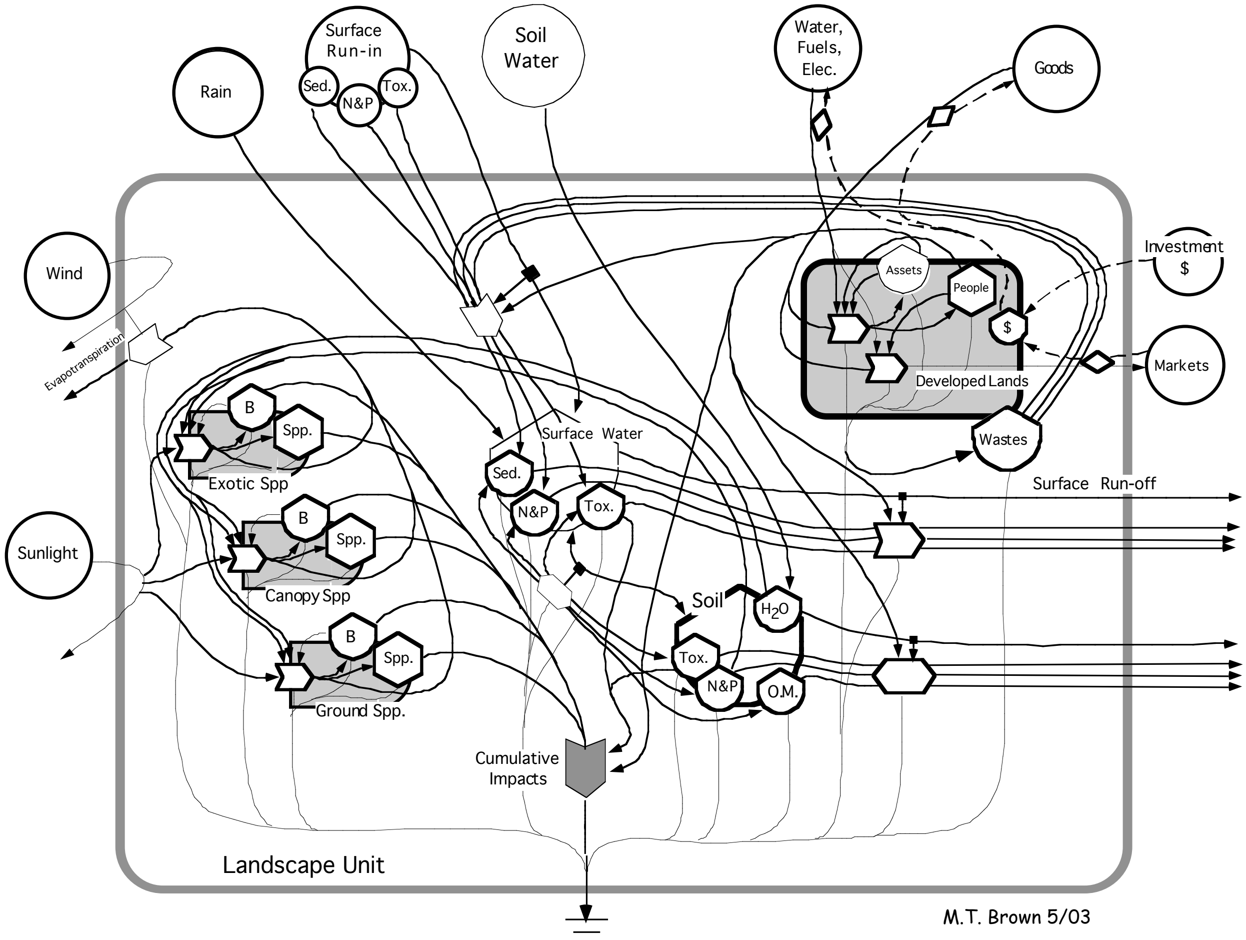

Figure 2. Landscape unit showing the effects of human activities on ecosystem structure and functions. The more intense the development, the larger the effects. B = biomass, Spp = species, Sed = sediments, N & P = nitrogen and phosphorus, Tox. = toxins, O.M. = organic matter

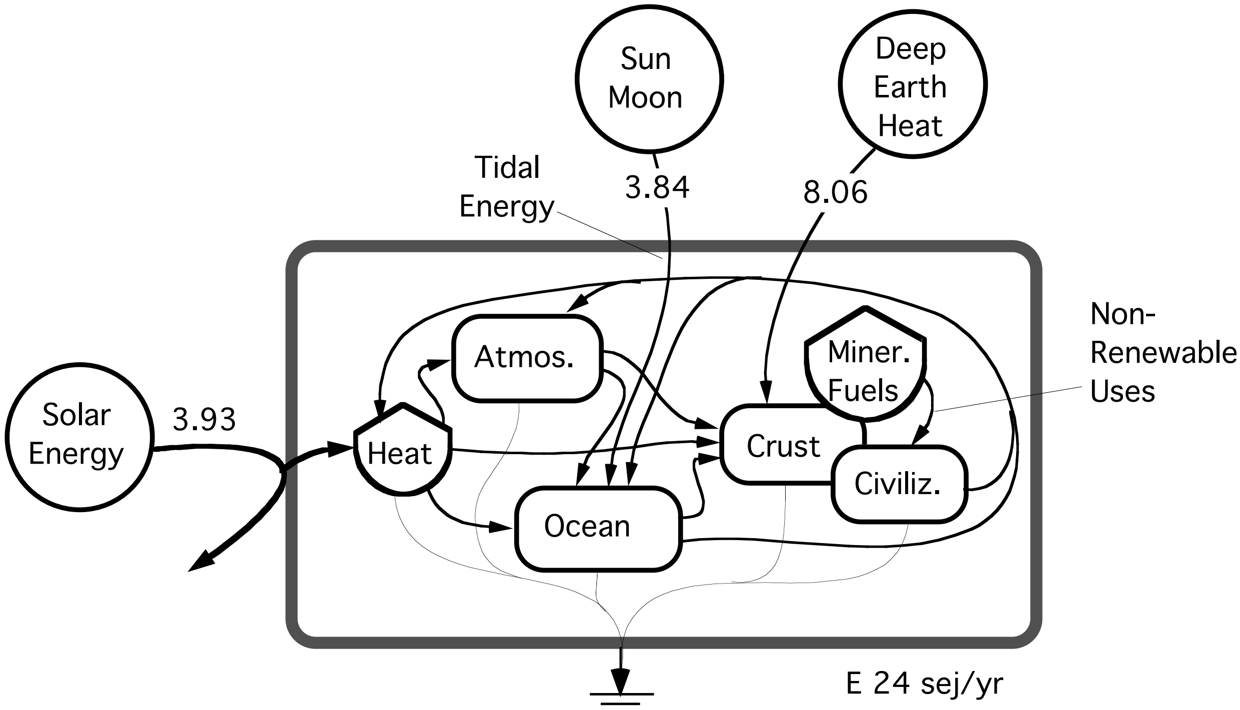

Figure 3. The main components of the biogeosphere showing the driving energies and the interconnected cycling of energy and matter. The total emergy driving the biogeosphere is the sum of solar, tidal and deep heat sources totaling 15.83 E24 seJ/yr

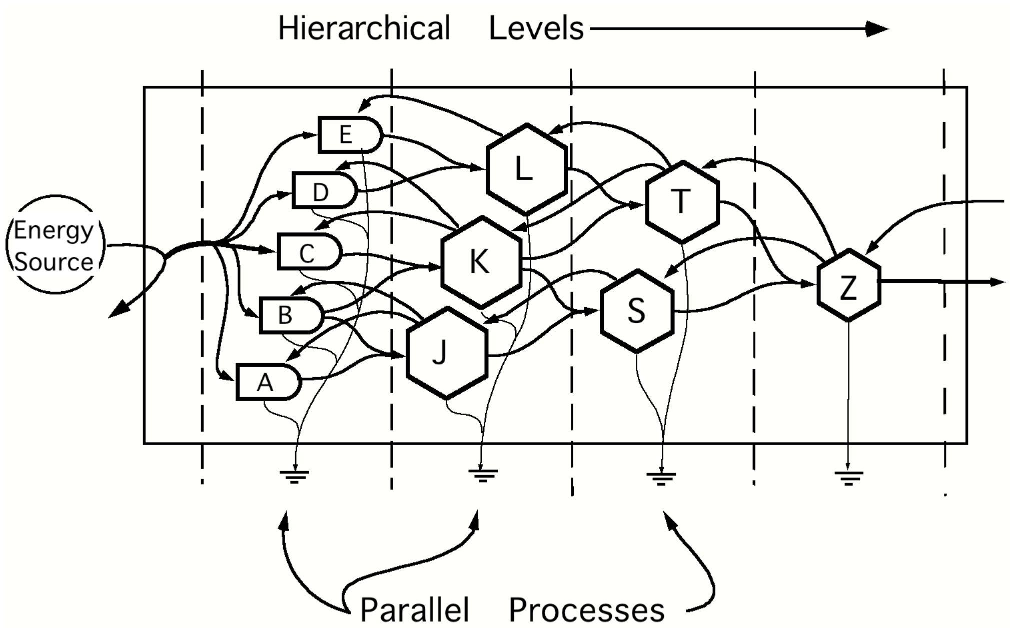

Figure 4. Diagram of the organization of systems showing the convergence of energy and matter into higher and higher levels via parallel and hierarchical processes.

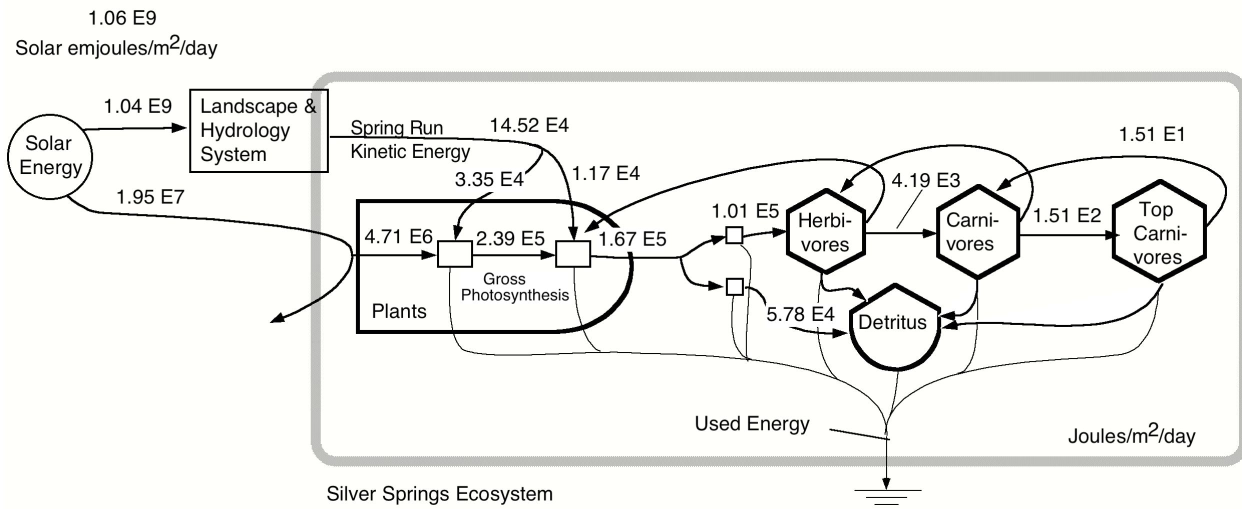

Figure 5. Aggregated systems diagram of the ecosystem at Silver Springs, Florida, showing decreasing energy with each level in the metabolic chain (after Odum, 2004). Table 5 gives the transformities that result from the transformations at each level.

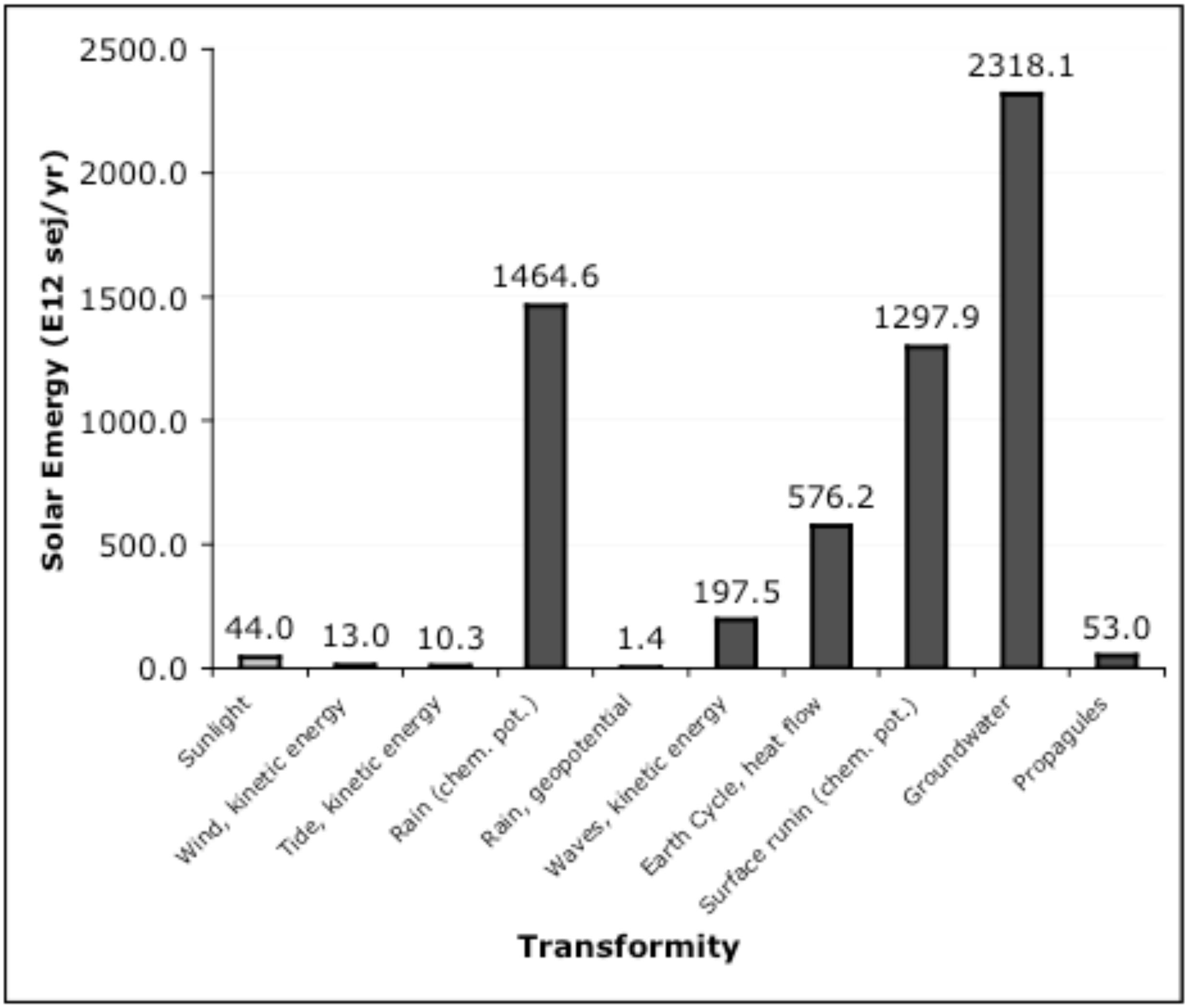

Figure 6. Emergy signature of driving energies for 1 hectare of typical mangrove ecosystem in Florida

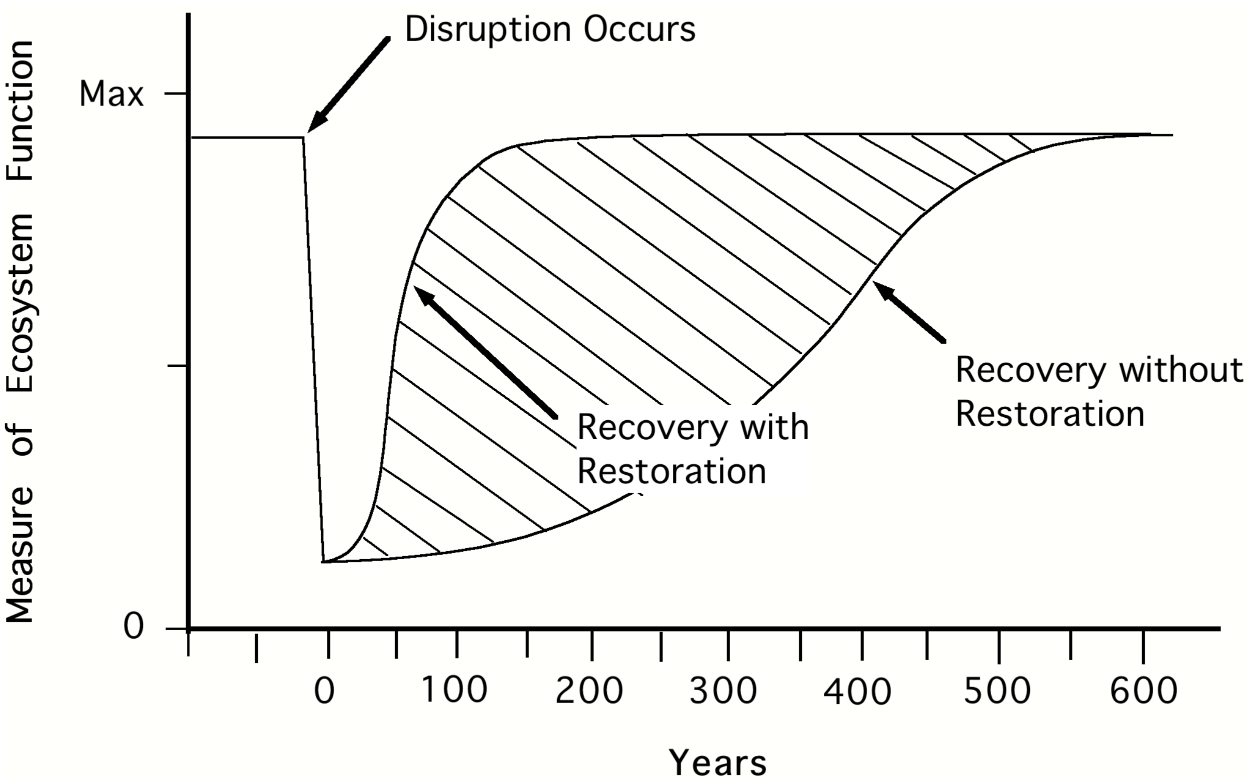

Figure 7. Graph illustrating the net benefit from ecological restoration. The net benefits can be calculated as the difference between recovery of ecosystem function with and without restoration efforts

Table 1. Emergy of Products of the Global Energy System (after Odum et. al 2000)

Product and Units	Emergy* E24 seJ/yr	Production units/yr	Emergy/Unit
Global latent heat, J	15.83	1.26 E24	1.3 E1 seJ/J
Global wind circulation, J	15.83	6.45 E21	2.5 E3 sej/J
Hurricane, J	15.83	6.10 E20	2.6 E4 seJ/J
Global rain on land, g	15.83	1.09 E20	1.5 E5 sej/g
Global rain on land (chem. pot.), J	15.83	5.19 E20	3.1 E4 seJ/J
Average river flow, g	15.83	3.96 E19	4.0 E5 sej/g
Average river geopotential, J	15.83	3.40 E20	4.7 E4 seJ/J
Average river chem. potential, J	15.83	1.96 E20	8.1 E4 seJ/J
Average waves at the shore, J	15.83	3.10 E20	5.1 E4 seJ/J
Average ocean current, J	15.83	8.60 E17	1.8 E7 seJ/J

* Main empower of inputs to the geobiospheric system from Figure 1 not including non-renewable consumption (fossil fuel and mineral use).

Table 2. Summary of transformities in terrestrial ecosystems.

Ecosystem	Transformity (seJ/J)	Reference
Gross primary production		
Subtropical mixed hardwood forest, Florida	1.03E+03	Orrel, 1998
Subtropical forest, Florida	1.13E+03	Orrel, 1998
Tropical dry savanna, Venezuela	3.15E+03	Prado-Jutar & Brown, 1997
Salt marsh, Florida	3.56E+03	Odum, 1996
Subtropical depressional forested wetland, Florida	7.04E+03	Bardi & Brown, 2001
Subtropical shrub-scrub wetland, Florida	7.14E+03	Bardi & Brown, 2001
Subtropical herbaceous wetland, Florida	7.24E+03	Bardi & Brown, 2001
Floodplain forest, Florida	9.16E+03	Weber, 1996
Net primary production		
Subtropical mixed hardwood forest, Florida	2.59E+03	Orrel, 1998
Subtropical forest, Florida	2.84E+03	Orrel, 1998
Temperate forest, North Carolina (Quercus spp)	7.88E+03	Tilley, 1999
Tropical dry savanna, Venezuela	1.67E+04	Prado-Jutar & Brown, 1997
Subtropical shrub-scrub wetland, Florida	4.05E+04	Bardi & Brown, 2001
Subtropical depressional forested wetland, Florida	5.29E+04	Bardi & Brown, 2001
Subtropical herbaceous wetland, Florida	6.19E+04	Bardi & Brown, 2001
Biomass		
Subtropical mixed hardwood forest, Florida	9.23E+03	Orrel, 1998
Salt marsh, Florida	1.17E+04	Odum, 1996
Tropical dry savanna, Venezuela	1.77E+04	Prado-Jutar & Brown, 1997
Subtropical forest, Florida	1.79E+04	Orrel, 1998
Tropical mangrove, Ecuador	2.47E+04	Odum & Arding, 1991
Subtropical shrub-scrub wetland, Florida	6.91E+04	Bardi & Brown, 2001
Subtropical depressional forested wetland, Florida	7.32E+04	Bardi & Brown, 2001
Subtropical herbaceous wetland, Florida	7.34E+04	Bardi & Brown, 2001
Wood		
Boreal silviculture, Sweden (Picea aibes, Pinus silvestris)	8.27E+03	Doherty, 1995
Subtropical silviculture, Florida (Pinus elliotti)	9.78E+03	Doherty, 1995
Subtropical plantation, Florida (Eucalyptus & Malaleuca spp.)	1.89E+04	Doherty, 1995
Temperate forest, North Carolina (Quercus spp)	2.68E+04	Tilley, 1999
Peat		
Salt marsh, Florida	5.89E+03	Odum, 1996
Subtropical depressional forested wetland	2.52E+05	Bardi & Brown, 2001
Subtropical shrub-scrub wetland	2.87E+05	Bardi & Brown, 2001
Subtropical wetland	3.09E+05	Bardi & Brown, 2001

Table 3. Summary of transformities in a marine ecosystem, Prince William Sound, Alaska (after Brown et al., 1993)**.**

Item	Transformity (seJ/J)
Phytoplankton	1.84E+04
Zooplankton	1.68E+05
Small nekton (molluskans, artropods, small fishes)	1.84E+06
Small nekton predators (fish)	1.63E+07
Mammals (seal, porpoise, belukha whale, etc)	6.42E+07
Apex predators (killer whale)	2.85E+08

Table 4. Solar transformities of ecosystem components of the Silver Springs.

Item	Transformity (seJ/J)
Solar Energy	1
Kinetic energy of spring flow	7170
Gross plant production	1620
Net plant production	4660
Detritus	6600
Herbivores	127000
Carnivores	4090000
Top carnivores	40600000

Table 5. Transformities of information in forest components and the emergy to generate global biodiversity (after Odum, 1996 and Ager, 1965)

Item	Solar transformity	Units
Forest scale		
DNA in leaves	1.2E+07	seJ/J
DNA in seeds	1.9E+09	seJ/J
DNA in species	1.2E+12	seJ/J
Generate a new species	8.0E+15	seJ/J
Global scale		
Generate global biodiversity	2.1E+25	seJ/species

Table 6. Number of species and average transformities of generalized compartments in the Everglades cypress ecosystem.

Compartment	No. Species*	Avg. Transformity
Bacteria[a]	?	1-10
Primary Producers[b]	250(est)	3.39E+04
Invertebrates	48	3.24E+05
Fishes	24	9.87E+05
Amphibians	14	1.16E+06
Mammals	20	3.35E+06
Reptiles	19	3.42E+06
Birds	59	3.76E+06

* after Ulanowicz, et al. (2001)

a – Jorgensen, Odum and Brown (2004)

b – Lanen et al. , (2003)

Table 7. Transformities of selected metals as global flows to atmosphere and storages within a river ecosystem

	Annual releases to atmosphere[a] (seJ/J)	River ecosystem[b] (seJ/J)
Aluminium	9.65E+06	3.30E+07
Iron	8.46E+07	6.19E+07
Chromium	2.59E+10	1.99E+10
Arsenic	8.56E+11	--
Lead	2.39E+12	3.59E+10
Cadmium	1.52E+13	8.78E+10
Mercury	6.85E+14	--

a - Not including human release

b - Genoni et al. 2003

Table 8. Empower density of selected land use categories (after Brown and Vivas, 2004)

Land Use	Empower Density (E14 sej/ha/yr)
Natural land / open water	7.0
Silviculture and pasture	10 - 25
High intensity pasture and agriculture	26 - 100
Residential and recreational uses	1000 - 3500
Commercial, transport, and light industrial	3700 - 5200
High intensity residential, commercial and business	8000 - 30000

Table 9. The effect of changes in system organization resulting from loss of top carnivore (Silver Springs, Florida data).

Item	Transformity (seJ/J)	Pathway emergy with top carn.[a] (seJ/m^2/day)	Pathway emergy without top carn.[b] (seJ/m^2/day)	Percent Change
Solar Energy	1	--NC--	--NC--	--NC--
Kinetic energy of spring flow	7170	--NC--	--NC--	--NC--
Gross plant production	1620	3.87E+08	3.84E+08	0.8%
Net plant production	4660	4.71E+08	4.68E+08	0.6%
Detritus	6600	6.67E+08	6.58E+08	1.4%
Herbivores	127000	5.32E+08	5.20E+08	2.3%
Carnivores	4090000	6.13E+08	5.20E+08	15.2%
Top carnivores	40600000	6.13E+08	0	100.0%

a.- Emergy on pathways of the system depicted in Figure 5. Emergy is calculated using a network analysis method (Odum, 2002)

b.- Emergy on pathways of the system depicted in Figure 5 when the top carnivore is excluded. Emergy is calculated using a network analysis method (Odum, 2002)

Table 10. Emergy costs for restoration of forested wetland in Florida (after Bardi, 2001)

Item	Data*	Units	Unit Emergy Values (sej/unit)	Emergy (E15 sej)
Environmental Flows				
Sunlight	4.2E+13	J/yr	1	2.10
Wind	3.0E+09	J/yr	2.5E+03	0.38
Rain, chemical potential	6.4E+10	J/yr	3.1E+04	97.60
				97.70
Construction flows				
Planting material	8.4E+07	J	6.7E+04	0.01
Services	8.7E+02	$	1.7E+12	1.48
Fertilizer	6.7E+03	g	4.7E+09	0.03
Services	1.0E+02	$	1.7E+12	0.17
Labor (unskilled)	3.1E+07	J	4.2E+07	1.30
Labor (skilled)	5.4E+07	J	1.2E+08	6.61
Services	4.1E+03	$	1.7E+12	7.01
				16.61
Management				
Chemicals (herbicides)	1.9E+04	g	2.5E+10	0.47
Labor (unskilled)	2.3E+07	J	4.2E+07	0.96
Labor(skilled)	4.6E+07	J	1.2E+08	5.63
				7.06

* based on assumption of 50 year recovery time.