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Editorial

Scales of ecological engineering

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Ecological engineering operates in those scales of size and time where most people do not believe there are many scientific principles. Because humans are in this scale, they see so much detail that they can not see the organization and often seek non-scientific theories for what happens. Others, including me, believe that all scales of size and time operate according to the same common designs with common principles. By this view, the noisy detail we see around us is the trial and error process of finding what works best, and what works best can be found from scientific principles. Trial and error efforts to find the maximum performance are aided by variation and choices provided by the dynamic oscillations of the smaller scales.

Horgan (1995) quotes many scientists who believe some scales have more complexity than others. My view is that all scales have the same complexity, but that humans perceive less as they look towards smaller or larger scales than their own realm. Does the ratio of variance to the mean tend to be constant? Progress in science has been faster at the scales where overview models were encouraged because the complexity was less visible. Mathematical models of ecosystems started with plankton ecosystems where it was easier to see less and think simple as compared to forests where the complexity was visible and intimidating.

Fig. 1 shows a typical graph of replacement time and territory of the type now common in all sciences. If ecological engineering is defined as the management of systems of human and environmental self-design, it can be seen to be with environmental science in the territory-time window at the interface between ecosystems and human society.

Filg. 2 shows the scales of size and time in an energy systems diagram where components are arranged from left to right in order of their territory-turnover time. In this particular aggregation the design of each scale is the same, and the inter-level

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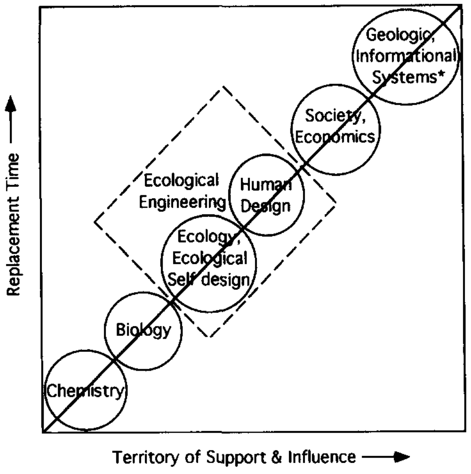


*Global and regional systems based on widely shared genetic and cultural information

Fig. 1. Window of ecological engineering in a graph of replacement time and territory.

linkages are similar, including reinforcement feedback loops of service acting as multipliers. Each level is reinforced by interaction with the level below and above.

Readers might ask what is the difference between the terms "*environmental management*" and "*ecological engineering*"? Environmental management often means humans making the environment to suit their wishes. "Ecological engineering" can be defined as light management that joins human design and environmental self-design so that they are mutually symbiotic. Well known examples from Florida are the recycling of nutritive wastewaters to swamps, the use of solid waste to fertilize forests, and using enhanced succession to restore wetlands after mining.

On both sides of the ecological engineering window (Figs. 1 and 2) are fields that deny there are any scientific organizational principles on the environmental scale. Adjacent on the smaller scale (left of window in Fig. 1) is ecology. Possibly the majority of ecologists of the current period moved their interest to smaller scales, many denying that there was any principle in the ecological organization of the environment other than the free struggle for existence of separate populations. The majority of these people do not believe there is an ecosystem, much less any larger scale principles regulating landscapes. Like biologists and chemists below them in the scale, they believe "basic" means to look to smaller parts and processes and that everything in the scale above their interest is mere application. People with this view try to manage environment as "applied ecology," which has as its main principle to leave it to the struggling organisms. These views (individualistic paradigm) could be called "small scale anarchy."

Adjacent to ecological engineering on the scale larger than environment is society, its institutions, and its popular concept for operating this scale, economics. Most economists do not believe there are any scientific principles governing the organization of society and environment other than human choices expressed through markets and willingness

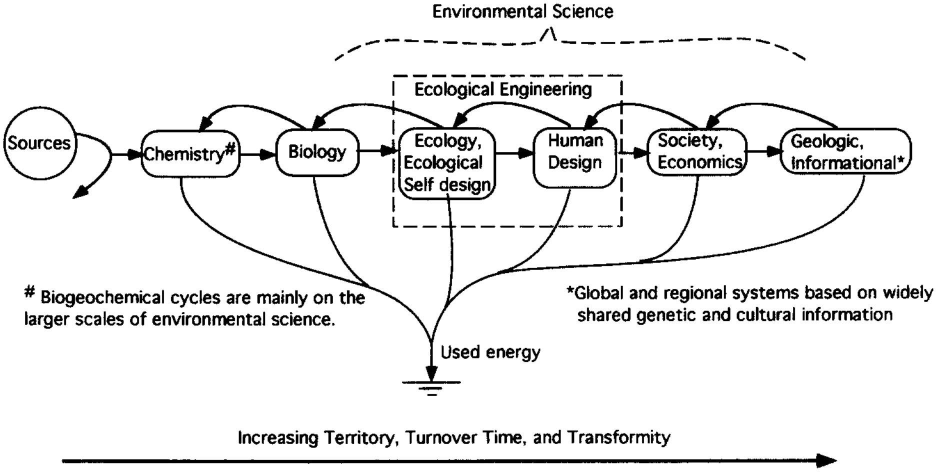


Fig. 2. Window of ecological engineering in an energy systems diagram in which units are left to right in order of turnover time, territory and transformity.

to pay. Coming out of social science with strong elements of humanism, mainstream economics believes in whatever patterns emerge from human choice. These views of environment could be described as "large scale anarchy." People with these views, including a good part of society, would do cost benefit analysis to determine what is constructed and its environmental relationship – even though money is only paid to people with little relation to real wealth of the environment and its contribution.

In contrast, our general systems view sees the window of environmental science and its managerial component, ecological engineering, as following the same organizational principles as other scales of the universe. What is observed is based on the same scientific principles controlling other scales, principles involving the self-organization of energy, matter, and information into network designs that prevail because they do more self-reinforcing.

In Table 1 are some of the common designs which seem to occur in all systems from

Table 1
Designs of self organization-at all scales [a]

(1) Autocatalytic reinforcement (feedbacks that multiply).
(2) Material recycle (also a reinforcement).
(3) Pulsing growth, alternating with intensive consumption later due to growth at the next scale.
(4) Delay in reinforcement allows competition, advantage to first units established, and dominance during the growth phase.
(5) What is sustainable is a long-run average, consisting of the pulsing of each scale driven by the oscillatory coupling with the next.
(6) Percent variation, and percent of phenomena causally determined by scientific relationships, is similar at all scales, including the scale of human society and environment.

[a] Consistent with the hypothesis that self-organization develops maximum power (Hall, 1995).

molecules to the stars. We have offered two books – *Systems Ecology* (Odum, 1983, Odum, 1994) and *Ecological Microcosms* (Beyers and Odum, 1993) – with evidence for the generality of these designs in all systems, especially ecosystems.

Most people are not listening, because their faiths are elsewhere. Many scientists dare not consider a paradigm for nature with more organized systems views lest they have to abandon life-long premises for their careers. The unwillingness to consider macro-scale science for macro-scale design leaves environment and its management in the hands of adversarial extremism and political expediency. Conflict is severe between those with concepts from the small scale anarchy of ecology and those with concepts from the large scale anarchy of economics.

By and large, engineers tried to stay out of the arguments by dealing only with technology and construction. What mix of construction and ecosystem organization the landscape should have was left to "public process." But when short-term economic development caused construction and technology to change the environment, engineers were blamed for the missing interface designs.

Many will agree with Malone (1994) who summarizes the poor state of affairs in the use of science in environmental management. Malone cites a new report of the National Academy that reviews case histories where there was polarization and poor communication between science and economic and social forces affecting management. A larger view of technology and environment as a single system with principles is required (ecological engineering). Defining those principles will require a marriage between systems ecology and environmental engineering. First, both scientists and managers have to recognize that there are principles of organization on this scale.

1. Up and down scale views of environmental modeling

Very different views of environmental models are held by those dedicated to smaller scale disciplines and those who study and manage a larger scale. People who study the phenomena of their favorite scale of interest expect these pieces to make the next level of size-time understandable when put together, hopefully by some giant computer. They see modelling as putting together small scale pieces. They regard this as mere application and not their responsibility. This is a bottom up modelling attitude. Examples may be found in the attitude of biochemists to organismal science, in the attitude of organismal scientists to ecology, and in the attitude of small scale ecologists to the environmental scale scientists.

Those dedicated to scales larger than environment expect models of environment to be highly aggregated, emphasizing the economics and needs of the larger society, with some inclusion of energy and materials that feed the economy, but with a minimum of ecological components. Those of a larger scale have a top down attitude to environmental models.

As the diagrams (Figs. 1 and 2) suggest, the appropriate modelling for ecological engineering is in the scale in between. Much of the detail of scales above and below has to be aggregated because they are not important on this time scale. However, the main driving forces (sources of energy, materials, information and money) and the mechanisms dominating this scale have to be included. The designs that emerge at all scales

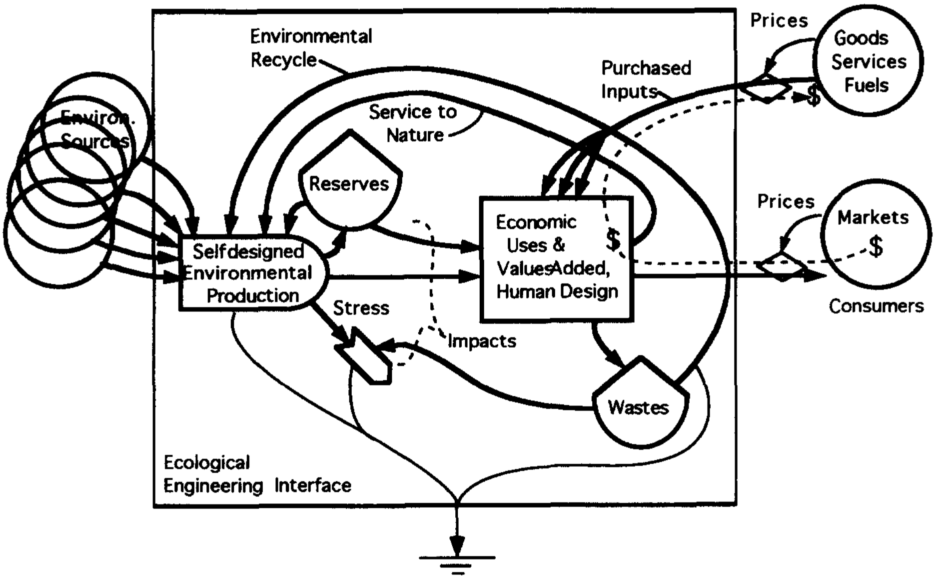


Fig. 3. Energy systems diagram of main components and design features of an ecological engineering system (from Ecological Engineering Lecture, National Research Council, May 1993).

should be sought at the start (Table 1). If something turns out to have an effect of 5% or less, it should be aggregated in overview models for environmental understanding and management and not included separately.

Fig. 3 suggests some main generic features of Ecological Engineering systems. As in other diagrams using these notations, scales of increasing replacement time, territory of support and influence, and transformity increase from left to right. Notice the technology, the recycle, the mutual reinforcements and the economic interface.

2. Example of competing views of scale, mesocosm Biosphere 2

Tragic confusion resulted from the many scales with which managers, generalists, scientists, and especially journalists viewed the magnificently innovative construction and operation of Biosphere 2 Oracle, in Arizona, USA (Nelson et al., 1993). From my view I saw many earnest people, contributing in unique special ways, being torn apart by the conflict over what the scale of ecological engineering of a mesocosm should be.

The big Biosphere 2 system was set up by 1992, seeded, and operated with reasonable sensors of overall function. The system behaved in its first 2 years much like the earth (Biosphere 1) in the interplay of plants, soil, gases, and carbonates, each stimulating the other. The main features of what happened to gases can be accounted for in a top-down systems model (Fig. 4). The self-organizational process was a beautiful living model with which to study aspects of the larger earth by comparison.

Because of initial large storages of organic matter in the starting soils, respiration was large, generating excess carbon dioxide, much of it going into the carbonates (in desert soils, in the sea biome, and in the concrete). Because the plant density was not heavy enough to balance respiration with photosynthesis, the carbon dioxide binding into carbonates put more system oxygen into storage (the O_2 in CO_2) than was coming out. Simple models developed during the first year (Beyers and Odum, 1993) were able to show the linkage of oxygen and carbonates.

That the limestone-carbonate system is so interdependent with oxygen is an important insight about the paleobiogeochemistry of the earth. On our planet, excess consumption of fuels is making excess carbon dioxide that goes into carbonate buffering, pulling oxygen down. In the big earth, however, the system has already self-organized for billions of years, and may already have the appropriate storages for responding to such pulses with long range homeostasis.

Philosophically, managers of Biosphere 2 had a large scale view related to Gaia mechanisms and self-organization. But at the same time, they believed it was possible to plant and manage smaller scale biomes inside by controlling the local microclimates (rain forest, savannah, desert, coral-reef ocean). Thus, management was on two scales. The mesocosm demonstrated a principle we think we see in microcosms, that the larger scale dynamics forces the small scale to fit, while becoming symbiotically based on the small scale. The system as a whole, with high carbon dioxide, tends to stimulate net-producing plant species, those that can best convert carbon dioxide into net organic gains (C-4 plants). But for persons trying to micromanage for mature biomes (perhaps too soon), these were weeds to be eliminated.

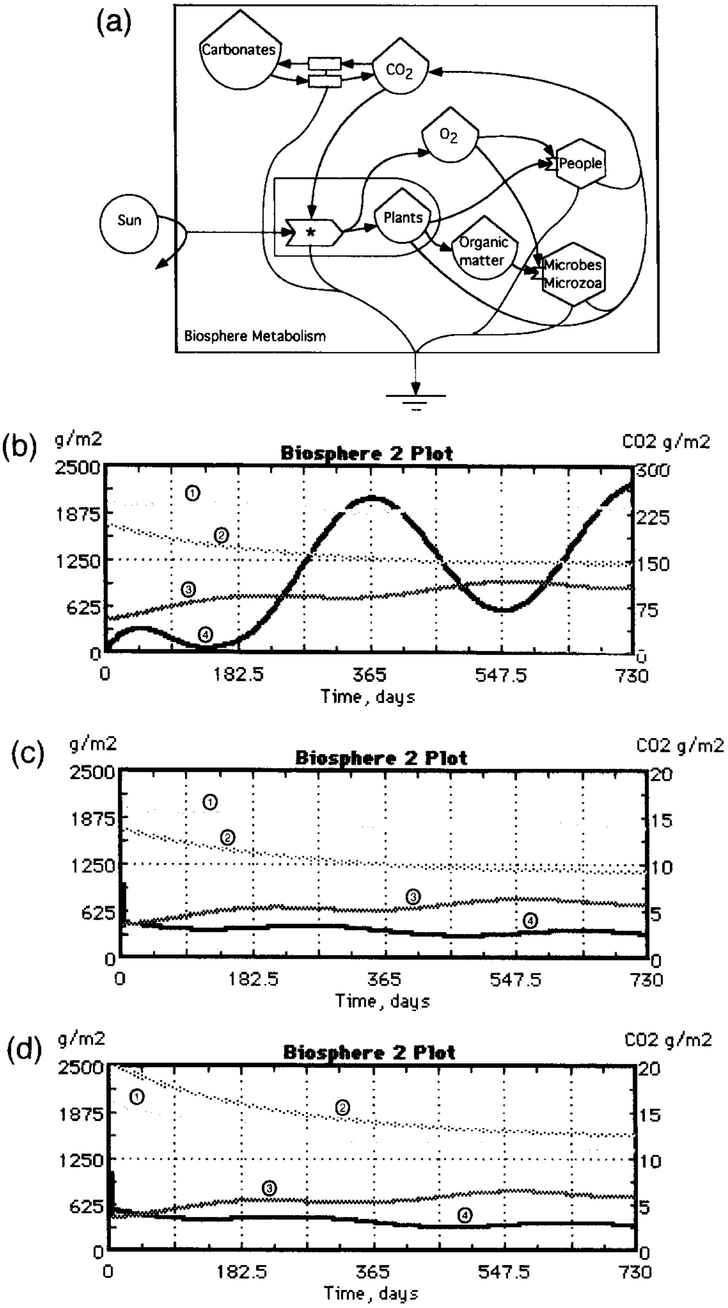
Since the initial high content of soil organic matter made respiration exceed photosynthesis, Biosphere 2 was not unlike the earth biosphere where organic consumption by fossil fuels exceeds planetary photosynthesis. With gaseous carbon dioxide increasing, the managerial action was to remove the excess with sodium hydroxide, which also removed the system's oxygen. Oxygen had to added from a tank truck outside.

Our simulation models (Engel, 1994) show that removing excess carbon dioxide and organic carbon moves the system toward a more stable balance of production and consumption. A newsletter from the new management indicates a continuation of this policy.

Good ecological engineering involves incremental changes to fit technological operation to the self-organizing biota. The management process during 1992–1993 using data to develop theory, test it with simulation, and apply corrective actions was in the best scientific tradition. Yet some journalists crucified the management in the public press, treating the project as if it was an Olympic contest to see how much could be done without opening the doors.

Like their readers, many journalists believe that human society may successfully design nature to fit economic aspirations. What Biosphere 2 showed, in a short time, is

Fig. 4. Simplified simulation model of metabolic concepts in Biosphere 2. (a) energy systems diagram of a highly aggregated, overview simulation model of metabolism in Biosphere 2; (b) simulation with ordinary initial stocks of organic matter and without buffering carbonates; (c) simulation as in (b) with large carbonate buffer added producing a gaseous steady state; (d) simulation as in (c) with larger initial stocks of organic matter causing oxygen to decrease. (SIM-BIO2 using EXTEND–Odum and Odum, 1994.) Numbers on lines: 1, oxygen; 2, dead biomass; 3, plants; 4, carbon dioxide.


(a)
Carbonates
CO2
O2
People
Sun
*
Plants
Organic matter
Microbes Microzoa
Biosphere Metabolism
(b)
Biosphere 2 Plot
g/m2
CO2 g/m2
2500
1875
1250
625
0
300
225
150
75
0
①
②
③
④
0
182.5
365
547.5
730
Time, days
(c)
Biosphere 2 Plot
g/m2
CO2 g/m2
2500
1875
1250
625
0
20
15
10
5
0
①
②
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0
182.5
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Time, days
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Biosphere 2 Plot
g/m2
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182.5
365
547.5
730
Time, days

the lesson that our global human society is learning more slowly with Biosphere 1 that humans have to fit their behvaior into a closed ecosystem (Fig. 4).

2.1. Scale of view

A discipline can be defined as a set of people studying the same scale of science with shared models of performance. However, those dedicated to one scale should not be intolerant of the science of other scales, or paradigms in which they may not believe. The way a group of scientists hold to a paradigm is not unlike faith in religion. Individuals feel pressured to conform lest they be ostracized for heresy and their research proposals for funding be rejected. In its early days, the National Science Foundation in the United States looked for new concepts, whereas sometimes now its referee system is a means for rejecting ideas outside of the paradigm of a subculture.

The present system of funding science is hampered by having dogma affecting decisions according to each narrow scale. There is little mechanism to insure a broader consideration. A much better system would have referees facing an author or proposer so that new views can be explained, misunderstandings avoided, and emotional reactions kept in scrutiny. Referees close to proposed work should make comments and criticisms, but recommendations and decisions should be made by a third party, who is not in competition with the proposer. A system that uses anonymous referees may be unconstitutional.

The original management of Biosphere 2 was regarded by many scientists as untrained for lack of formal degrees, even though they had engaged in a preparatory study program for a decade, interacting with international community of scientists including the Russians involved with closed systems. The history of science has many examples, where people of atypical background open science in new directions, in this case implementing mesocosm organization and ecological engineering with fresh hypotheses.

When journalists asked establishment scientists, most of whom were small scale (chemists, biologists, population ecologists), they got back the small scale dogma that system-scale experiments are not science. Some people with this level of interest recommended Biosphere 2 be used as they have used growth chambers for 60 years to study small things with many replications, relate trees to carbon dioxide, study species dynamics, etc. How do you explain to people whose lives have been dedicated to organismic or population scale that what is more important on an ecological mesocosm scale is the whole self-organizing process. The real world of Biosphere 1 and Biosphere 2 has several scales of size all interacting together: light fields, biodiversity, water regime, biogeochemical cycles, nested oscillations, genetic and ecological information processing selecting special abilities of different species to adapt and be reinforced?

A very destructive practice in science occurs when a scientist knowledgeable about science of scale A selects (in ignorance) a specialist dedicated to science of scale B as competent to judge work in a third scale C. The microbiologist writing a column on Biosphere 2 in *Science* honestly believed that the only first class basic science for Biosphere 2 would be studying small scale microscale mechanisms. A priori, all scales of science may be of equal importance, but there have been large research funds for the small scale, and very little for experiments at a large enough scale to be relevant to the global atmosphere.

Experiments inside to understand how parts are contributing to the whole are appropriate, but studying small scale phenomena for their inherent interest probably belong elsewhere. Experiments on the small scale often isolate these parts from the ecosystem complexity. However, experiments with whole systems and ecological engineering keep all the complexity operating, changing only the items whose effect is to be tested.

There is no sure way to test theories and models of mesoscale self-organization except by seeding and running mesoscale systems. Science at one scale cannot validate that at the next scale. Models are not enough if they cannot be iteratively tuned with the real world system. Perez et al. (1991), studying effects of a toxic substance on microcosms of three scales of size, concluded that the chemical action was dependent on scale.

Engel (1994) compared scales of aggregation in simulating the gaseous balance in Biosphere 2. First he simulated each of the six biomes (desert, ocean, rainforest,

Table 2

Plant species diversity counts from Bisophere 2, Nov. 9, 1993 [a] (H.T. Odum, Victor Engel and E.C. Odum)

Rain forest
Individuals per species in rank order:
528,200,145,46,19,10,10,10,9,8,8,8,7,7,6,5,5,4,4,3,3,3,3,2,2,2,2,2,2,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1
45 species found counting 1106 individuals
On log plot, 44 species per 1000 individuals

Lower Savannah
Individuals per species in rank order:
720,169,164,150,68,50,27,18,16,14,11,9,7,7,5,5,4,4,3,3,3,3,3,2,2,2,2,2,2,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1
46 species found counting 1490 individuals
On semi-log plot, 39 species per 1000 individuals

Desert area
Individuals per species in rank order:
215,150,139,138,125,60,30,30,20,15,15,13,12,6,5,5,5,5,5,5,4,4,4,4,4,4,3,3,3,3,3,2,2,2,2,2,2,2,2,2,2,2,2,1,1,
1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1
68 species in 1074 individuals counted
On semi-log plot, 68 species per 1000 individuals

Agricultural area
Individuals per species (including weeds) in rank order:
86,53,53,30,26,23,14,13,10,8,8,7,5,5,4,3,2,2,2,2,2,2,1,1,1,1,1
27 species in 416 individuals counted
On semi-log plot, 30 species per 1000 individuals

[a] Two indices: rank order and species per 1000 individuals counted. A useful index of species diversity is the number of species found when 1000 individuals are counted in a transect. A graph of species found as a function of the logarithm of the number of individuals counted tends to be nearly straight. If less than or more than 1000 are counted, the line between starting point:(1,1) and the number counted on the semi-log graph can be used to find the species per thousand. Data on individuals per species given below can be used to plot a rank-order graph, another way of showing diversity. Dr. Tony Burgess helped with identifying species.

savannah, wetland and agroecosystem) with a separate model. Next each of these were inter-connected to form a complex larger model of the whole system. For comparison a much aggregated minimodel of the whole Biosphere 2 was simulated. Although results were similar, the more complex model was better for the longer scale of time of seasons, whereas the minimodel was ok for diurnal change.

A day's examination of the ecosystem in Biosphere 2, after 26 months of self-organization, provided a few data in Table 2, showing features of self-organization in progress:

(1) Spectral reflectance measurements of vegetation inside Biosphere 2 (with a Li-Cor spectral radiometer) showed that the vegetation that was predominating growth had small infra-red reflectance. Perhaps absorbing more of the near infra-red insolation is adaptive in a chamber with half the normal light and high humidities, making transpiration more difficult. The self-organizing system appeared to be reinforcing the species that collect more energy (maximum power principle).

(2) Species diversity of plants was approaching normal biodiversity. (The biomes were started with more diversity of plant species than is normal for this much area.)

(3) In the absence of much insect biodiversity, generalist species, a cockroach and an ant species, prevailed in all the biomes, a phenomenon commonly observed with self-organization on islands where one species occupies many niches. Leaf holes, an index of insect herbivory, was much less than normal.

(4) An even simpler overview model than those by Engel (1994) was simulated for perspectives and principles using programed blocks for EXTEND™ (Imagine That, Inc., San Jose, CA). Results (Fig. 4) showed that the observed successional trend (carbon dioxide absorption by carbonates and high net production of "weed species vegetation") if allowed to continue, was in a direction that would eventually generate enough gross production to match respiration of the soil, which was gradually declining (Odum and Odum, 1994).

Thus, the self-organizational development of a human life support was successfully underway. Gaseous balance in small, high-organic-soil type terrestrial microcosms, with 0.1 m^2 area, required a day. Biosphere 2, with 100000 times larger area, might be expected to take longer.

Perhaps it is time to honor the first team whose originality started the great experiment of Biosphere 2? Next we should back the second team to stay the course, continuing this ecological engineering mission to investigate what is required for high biodiversity and life support for humans? The smaller, faster Biosphere 2 is a good model for studying the biogeochemical dynamics of our earth? It would be a shame if interests in the smaller scale divert this opportunity to understand what a large-scale system does adapting to a continuing regime.

3. Ecological engineering and the scales of pulsing

In all the scales of the known universe, from atomic processes to the stars, pulsing oscillations appear to be the norm. Like the over-simple prey-predator type oscillator model, pulsing alternation of production and consumption is becoming recognized by more and more people as a general paradigm (Fig. 5). Pulsing involves units with

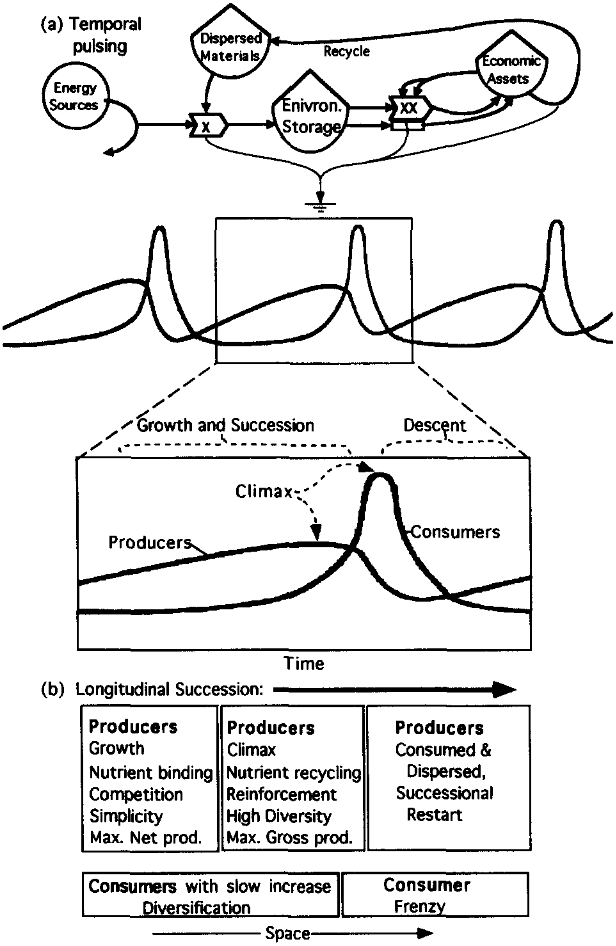

Fig. 5. Minimodel simulation of pulsing alternation of production and consumption useful for defining stages in a pulsing paradigm (consumption incudes autocatalytic secondary production). (a) Patterns with time; (b) temporal pattern laid out horizontally as longitudinal succession.

production and consumption on two or more scales of time and space. In previous efforts to explain their prevalence, the pulsing designs were explained as maximizing performance in the long range average (Odum, 1983, Odum, 1994, Odum, 1996; Beyers and Odum, 1993; Odum et al., 1995). The idea is that better loading of energy transformations occurs in pulsing cycles than in stable steady states. The maximum empower principle explains that reinforcement of patterns that maximize power (such as pulsing) prevail because they have more resources to transform and more efficiency in use.

The question here is whether pulsing patterns should be expected and programmed to get maximum performance in ecological engineering. In a minimodel of production, consumption and recycle, the pulsing is determined by the turnover time of the larger scale unit. From Figs. 1 and 2, it may be common for the human technology to be on a larger scale of time and space (with slower percent depreciation) than the components of the environmental system with which its oscillation is coupled. Examples are aquaculture, waste processing systems, Biosphere 2, and salt manufacture from brine ponds.

In microcosms and mesocosms, the walls of the container may block out the coupling of the next larger system, and with it the larger scale pulsing. It may be that mesocosms intended to give information about the un-contained real world should be supplied long-period pulses appropriate to the size of the next scale.

4. Pulsing in longitudinal succession

Already familiar, in ecologically engineered wetland systems receiving nutrient wastes, are areas of low diversity – net-producing plants that appear to be in arrested succession. Examples are areas where nutrient waters are inflowing, dominated by cattails and water hyacinths. Some waste recycling subsystems within Biosphere 2 are based on this property. How can ecosystems of arrested succession make sense with the concept that pulsing maximizes performance? First, look at the pattern of pulsed succession with time, which was generated by a relevant minimodel (Fig. 5a). Then, consider the possibility that the pattern of stages in time can be laid out in space where waters renew inputs and carry out the products (Fig. 5b). The following stages in time may be laid out in space.

- *Stage 1.* Colonization and maximum growth rate, competitive exclusion, net production, maximum power achieved by the first and fastest overgrowing others.
- *Stage 2.* Efficiency development, symbiotic division of labor, more recycling and gross production, maximum power achieved by reinforcement of resource procurement and efficient transformations.
- *Stage 3.* The climax (maximum) storages of structure and diversity are pulled down by consumption-destruction coming from the next larger scale.

Should spatial organization of scales be a stabilization technique for ecological engineering? Is a lateral organization of scales generally found in environmental systems receiving resource flows? Will longitudinal organization of scales be found in mesocosms of the future?

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