The design of Living Technologies for waste treatment

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Abstract

This article elucidates the emerging principles required for the design of task-oriented mesocosms. Twelve key factors are discussed including mineral diversity, nutrient reservoirs, steep gradients, high exchange rates, periodic and random pulses, cellular design and mesocosm structure, sub-ecosystems, microbial communities, photosynthetic bases, animal diversity biological exchanges beyond the mesocosm, and mesocosm/macrocosm relationships. The fields of ecological design and engineering are developing efficient Living Technologies for environmental repair, waste treatment, food production and infra-structure integration.

A living machine for the treatment of sewage and the production of fish and horticultural products, operational since 1989, produces high quality water irrespective of season or input variation. BOD5, COD, TSS, nitrification, phosphorus uptake, metals sequestering and coliform reduction data depict a robust, self-organizing technology capable of handling the mixed waste stream of a New England industrial city.

Keywords: Aquaculture; Ecological design; Environmental repair; Mesocosm; Sewage Treatment; solar Aquatics; Nitrogen and phosphorus control; Metal retention

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1.Introduction

Ecological engineering is an emerging field capable of addressing a broad range of issues. It will influence the future of waste treatment, environmental restoration and remediation, food production, fuel generation, architecture and the design of human settlements. Ecology is the long-term intellectual foundation for the development of new technologies to support society.

The workings and architecture of complex natural systems offer a blueprint for technological designs. This article elucidates some of these principles and applies them to the design of mesocosms for the purification of wastes. These principles represent the cumulative experience of over 25 years of designing and testing integrated Living Technologies based upon an ecosystem approach (Todd and Todd, 1980, 1984, 1994).

It should be noted that ecological engineering is scarcely three decades old. Attempts to codify design principles as yet must be tentative. As a discipline, ecological engineering was formalized only in the past few years. Mitsch and Jørgensen (1989) edited the first college text. Two years later it was followed by the publication of the first international symposium proceedings (Etnier and Guterstam, 1991). The journal Ecological Engineering was first published in 1992. Despite its newness however, it is evident that ecological engineering has the potential to transform radically the infra-structures underlying contemporary societies and bring them into greater balance with the natural world.

The terms, ecological technology, living technology or living machine are used here interchangeably. Ecological technologies have attributes that separate them from conventional technologies. Mitsch (1993) defined ecological technologies as being unique in that they apply in their design a wide range of selected life forms which, in new settings, have the ability co-design with the engineer. He wrote "Ecological engineers participate in ecosystem design by providing choices of initial species as well as the starting conditions; nature does the rest". This view represents a fundamental shift in thinking about the relationship of humans with other forms of life in a technological setting.

H.T. Odum (1971), the father of ecological engineering, articulated the need to view species, nature and technology in a radically new way. He stated: "The inventory of species of the earth is really an immense bin of parts available to the ecological engineer. A species evolved to play one role may be used for a different purpose in a different kind of network as long as its maintenance flows are satisfied."

The art and science of re-creating models of natural systems in laboratory settings has advanced immeasurably our knowledge of ecological engineering. Adey and Loveland (1991) have been at the leading edge of this effort. Their emphasis has been to build microcosms and mesocosms, such as mangroves or tidal pools, that are replicas of living systems. To support the intensive care of complex systems housed in small physical spaces they have developed energy intensive ecological support technologies including algal scrubbers. Adapting ecological processes into confined spaces had led to technological innovation of a high order.

Within the last couple of years practitioners in ecology, design and the fields of complexity and chaos dynamics have begun to communicate to their shared benefit. This exchange is beginning to influence ecological engineering. Kauffman (1993) has studied how self-organization, ranging in scale from the molecular level to large ecosystems, is generated in nature. He has proposed an explanation of why self-organization and design occur in nature and why it is possible to use these attributes in technological settings. Further, he has attempted to elucidate what propels a living system towards the edge of chaos or a balanced state. This addresses the question of why a living machine works. The process involves establishing diverse life forms in new combinations of species within artificial settings for specific processes, such as water purification. Kauffman has developed a theory of criticality. Organic forms may reach a state of supracriticality and in that state literally invent new molecular combinations or species arrangements. He suggests that diverse ecosystems may have this property of supracriticality. Subcritical systems lack adaptiveness because they lack the critical diversity or the ability to support this diversity. According to Kauffman, life at the level of the individual, from bacteria to higher organisms, is subcritical, poised on the edge between the two criticalities. The question posed by complexity theory for ecological designers is how can Living Technologies be developed that are supracritical, capable of self-design, self-regulation and invention, to carry our specific function.

Kauffman (1993) and Kinsinger et al. (1991) argue that complex ecological systems with diverse enzymatic pathways and complex surfaces for the exchanges of gases and nutrients, such as are found in the micro-anatomy of plants, will enable the ecological engineer to design technologies with the potential of several orders of magnitude greater efficiency than contemporary mechanical and chemical technologies. If they are correct, it is an opportunity for ecologists and engineers to collaborate in a significant enterprise. It may be possible to reduce pollution and its negative impact on the environment to a small fraction of existing levels)Todd and Todd, 1995). Ecological engineers are conceiving, designing and engineering "zero" emission industrial zones in a number of cities (Pauli, 1995).

2.The design of Living Technologies

A number of principles guide us in the design of Living Machines. Many have been discovered through trial and error. We have built dozens of systems over several decades for producing foods, treating wastes, and generating fuels as well as integrating all of these functions. Other principles have been gleaned from the scientific efforts and the experience of others. The process to date has not been systematic or highly codified. It has involved the study of a range of disciplines from the material sciences to the workings of ancient systems of food culture. Knowledge and information thus garnered has been organized to fit within an ecological framework. Natural history provides the raw material in the search for assemblies of species adapted to the constraints of a proposed living technology. At this stage in its development ecological engineering is a science and practice of assembly – the gathering of disparate bits of knowledge which are recombined to create new technological forms.

Ecological engineering has another challenge. It must protect natural ecosystems from alien organisms contained in Living Technologies. Our practice has been to use either organisms prevalent in the region, or species which cannot survive beyond the confines of the given mesocosm. In temperate regions, such as New England, we may use tropical plants and animals to perform functions that render the living technology economically viable. These same species would perish during the cooler seasons if they were to escape.

Twelve criteria enter into the design of Living Technologies. From our experience with food culture and waste treatment, all of these must be incorporated into the systems if they are to be optimized. An analysis of the relative importance of each of these criteria is beyond the scope of this paper.

2.1.Mineral diversity

Brady (1990) argues that the biological richness of the earth is a result of the complexity and diversity of its mineral foundations. In areas of similar climate and weather patterns it is the underlying bedrock that creates ecological differences. Biological responsiveness is determined, in large measure, by the rocks and minerals that make up the parent materials of soils. In mineral-rich zones, life can be extraordinarily abundant.

There are entire food chains based upon autotrophic bacteria that derive food and energy from inorganic mineral sources (Margulis and Schwartz, 1988). They are comprised of chemosynthetic and photosynthetic bacteria which can directly exploit mineral diversity, thereby providing the foundation for ecological diversity. In one experiment carried out over 6 years with 36 sealed and illuminated microcosms two-thirds of the systems died out. Those that succeeded were dominated by autotrophic bacteria in a mineral-rich environment. Heterotrophic bacteria populations represented only 1-10% of the remaining biomass (Lapo, 1987).

In designing Living Machines, mineral diversity should include igneous, sedimentary and metamorphic rocks. With a rich mineral base they should support a wide variety of biological combinations and give the systems greater capacity to self-design and optimize. Lowenstam (1984) has shown that species diversity may be partly mineral-based. Bacteria use carbonate, phosphate, iron oxide, manganese oxide and sulfide minerals in metabolizing. Some minerals, of which iron is a relevant example, provide the foundations for complex biological chemistry and play key roles in enzymatic systems and with, myoglobin and hemoglobin, as oxygen-carrying proteins in the blood (Silver, 1993).

Mineral diversity can assist in the formation of diverse mineral/organic compounds called colloids. Colloids, being clay and humus particles of extremely small size, regulate the exchange of ions between soils, water, bacteria and higher plants. Brady (1990) considers colloid-based ion exchange exceeded only by photosynthesis and respiration in importance.

In Living Machines we use finely ground rock powders which are quickly incorporated into biological systems. Agricultural and forestry researchers have found that powders sieved through 200 mesh screens (0.125 mm) are incorporated into soil metabolism within weeks, whereas materials sieved through 100 mesh screens (0.25 mm) are incorporated on a time scale measured in months (Campe, 1993). In a recent experiment we have digested 19,000 m3 of bottom sediments in a polluted 4 ha pond with the application of 7200 kg of rock powders from glacial materials. They were used in combination with a floating living machine through which 750 m3 of pond water circulated daily (Todd and Josephson, 1994).

2.2.Nutrient reservoirs

While mineral diversity provides the long-term foundation for nutrient diversity, in the near term microorganisms and plants require nutrients in an available form. If carbon is recalcitrant, or phosphorus in n insoluble state, or the NPK ratios are out of balance, or trace elements are missing, the ecosystems can become impoverished. For example, if an appropriate inorganic carbon source is not available to the nitrifying bacteria, the degradation of nitrogenous waste products is reduced and toxic levels of ammonia can increase. This can lead to biological impoverishment with the system and the shut down of other critical biochemical pathways. Nutrient deficiencies are particularly common in biological systems treating food and industrial wastes. These waste streams need to be blended with other types of waste or the imbalances should be corrected with fertilizers. As a general rule, we prefer to use organic and rock-based amendments to correct imbalances and kelp meal for trace minerals and potassium. Highly soluble forms of fertilizers are used sparingly to compensate for short-term upsets in high rate waste treatment systems.

In sewage treatment systems that vary from a carbon/nitrogen/phosphorus ratio of 100:5:1 (with carbon measured as BOD) process rates can drop dramatically (Gray, 1989). The flora of waste purification systems can be completely altered by trace mineral imbalances (Curds and Hawkes, 1983).

2.3.Steep gradients

Steep gradients are used to increase the diversity of internal processes and the multiplicity of pathways within a living machine. by steep gradient we mean an abrupt or rapid change, as measured in time or space, in the basic underlying attributes or properties of the subsystems. For example, a waste stream can benefit from passing through a series of stages that have different oxygen regimes, redox potentials, pH, temperature, humic and ligand or metal-related states. These subsystems, which have their own distinct communities of organisms, often gain by being connected with a number of feedback loops. A small percentage of the flow is recycled back upstream to earlier subsystems.

Gradients play critical roles in the dynamics of natural systems. In lakes and ponds the greatest shifts in redox occur at the steep interface between the mainly liquid water column and the denser sediments. Reduction processes of biochemical origin are active in the mud and at the mud/water interface. These conditions set the stage for highly reactive processes (Hutchinson, 1957).

Jørgensen (1989) employs gradient shifts in ecological engineering in natural systems. When the redox is low enough to cause hydrogen sulfide to form, he treats polluted lakes with forced aeration, or with the addition of nitrates. The literature from the study of paddy agriculture is relevant to the design o Living Technologies. Moderate reducing conditions enhance rice growth and yields whereas intense reducing conditions produce substances that are either toxic to plants or require a significant amount of the plant's energy to overcome the stress. Patrick (1994) found that iron compounds are key redox elements in regulating paddy soils and health.

The ecological designer should consider using diverse humic materials in various subsystems to produce gradients. This will result in an increase in biochemical interactions. Wakesman (1952) describes how these materials determine the nature of microbial populations, absorb toxic materials, supply catalytic agents and deliver trace minerals to higher plants. Humic materials, in combination with iron compounds, have been used for phosphorus reduction in natural systems waste treatment (Reed et al., 1995),

2.4.High exchange rates

One design objective of the ecological engineer is to maximize the surface area of living material to which a waste stream is exposed. The challenge is to create surfaces and associated communities that are not disrupted by strong currents and turbulence yet do not impede flows. One aproacy is to grow floating aquatic plants on the water surface and, with aeration, to create upwellings that pass large volumes through the root mass and associated biological communities. The root complexes provide massive surface areas for microbial communities. The surface area of roots available to microorganisms in several order of magnitude greater than that of manufactured substitute surfaces (Kinsinger et al., 1991).

Higher exchange rates over diverse biological surfaces can be achieved with ecological beds. These have been used in pond restoration experiment mentioned previously (Todd and Josephson, 1994) and in our Living Machines for sewage treatment in Frederick, Maryland and San Francisco, California (Todd and Josephson, 1995). The ecological fluidized bed is a technological development a step beyond the trickling filters or conventional biofilters used in intensive closed system aquaculture. Water circulates within the fluidized bed at up to three orders of magnitude greater than the system's throughput. The medium, whether plastic or of mineral origin, must have a specific gravity approaching 1 so that the medium will be buoyant or capable of being readily re-suspended. Such a medium, particularly when rough-surfaced or porous, can support a diverse microbial and benthic communities including snails and freshwater clams. Zooplankton proliferate in the interstitial spaces. A wide variety of wet tolerant tree and emergent aquatic and semi-aquatic plants are cultured on the surfaces of the ecological fluidized beds. The root zones provide additional surface areas for gas and nutrient exchange. Fluidized beds with high exchange rates can host concurrently benthos, plankton, small fish, and higher plants in highly dynamic communities. Nitrification as well as some denitrification can occur within the same internal recycle loop due to the abrupt oxygen gradients and the presence of endogenous organic carbon in the beds.

2.5.Periodic and random pulsed exchanges

Margalef (1968) in his classic text, Perspectives in Ecological Theory, pointed out the significance of regular or periodic influences, as well as random-seeming events, in shaping the structure and response capacity of ecosystems. He stated "Direct reaction of organisms to environmental change is most useful if the environment is being altered in an unpredictable way… One can say that the ecosystem has "learned" the changes in the environment, so that before it takes place, the ecosystem is prepared for it, as it happens with yearly rhythms. Thus the impact of the change, and the new information, are much less".

Odum (1971) applied pulses in ecological engineering. He wrote: "By creating a pulse, perhaps by controlling the water table or by covering plants with black plastic and introducing new plantings to accelerate the self design, a simpler system with a large net yield may replace the complex one with many low yields".

It has been our approach to perturb newly developing mesocosms after the initial seedings using abnormal changes in the light regime, flow and supplemental aeration. In this way the Living Technologies become robust enough in ecological terms to survive the inevitable failure of some of the system's external hardware and software.

2.6.Cellular design and the structure of mesocosms

Paturi (1976) argued that current technologies are adapted to neither human needs nor global ecology. For him industrial era design was badly flawed and he recommended looking to living organisms to provide the framework for design. Paturi was particularly inspired by the engineering employed by higher plants.

Cells being the building blocks of larger organisms are the starting point for design. A single living cell is engineered as a whole system, capable of division, replication, nutritio, synthesis of molecular materials, digestio, excretion and communication with adjacent cells. A cell can undertake specialized functions in an organ or organisms. An autonomous system, it is simultaneously interdependent with adjacent cells. By mimicking such attributes in the design of Living Technologies, ecological engineering would create technologies more efficient in their use of materials and energy (Todd and Todd, 1995).

Our mesocosms are cellular in design. In most cases they are covered with a transparent climatic envelope or greenhouse-like structures. The waste treatment systems are designed as multiple rows of "cells" connected together like beads on a string. The cells or tanks along each row differ in internal design and function. Recycling back up stream creates feedback loops. For reasons of technology validation we do not yet cross link the parallel rows. An optimized living machine would have an array of cross linkages in a variety of directions. Input and output from the system would remain the same.

Another advantage of cellular design is that a living technology can expand or contract depending upon need. To accomplish this more cells are added or subtracted. With cellular design technological improvements can be made without dismantling or decommissioning the whole system. Cellular design allows comparable technologies to be built at different scales, ranging from factory or neighborhood to a complete city.

2.7.Minimum number of subecosystems

A key issue in living machine design is the number of different kinds of subecosystems required to build a mesocosm that is a viable, self-designing and organizing system, capable of sustaining itself over time measured in years or decades. Mitsch and Jørgensen (1989) recognized the problem and proposed a general rule: "Ecosystems are coupled with other ecosystems. This coupling should be maintained wherever possible and ecosystems should not be isolated from their surroundings."

Unfortunately, most of the research on microcosms and semi-closed systems has not addressed the issue of the number of subsystems that are required in Living Technologies. Most of the work has involved the study of system dynamics, self-regulation and stability in single isolated aquaria or terraria. Adey and Loveland (1991) have addressed this issue in terms of balance. All the ecologically engineered systems they describe have at least two subecosystems. One is an algae growth chamber or algal scrubber that operates under intense light and acts as a control module. They define the ideal closed system as having three major components or subsystems. It consists of a sunlight-based, photosynthetically driven system that is connected to an animal consumer component, which is turn, is connected to a detritus/bacterial system.

Our experience supports the Adey and Loveland (1991) requirement of a minimum of three distinct subecosystems. We have found it is best to house the subsystems in distinct cells separated in space but connected by flows. In the early years we had worked with one- and two-cell systems for the intensive ecological culture of fishes but it proved impossible to maintain benthic communities and diverse zooplankton, and phytoplankton diversity was reduced to a dozen species or less (Todd and Todd, 1980). A two-cell system has been used successfully to degrade coal tar derivatives (PAHs) in toxic sediments. However, the cells were connected to each other and exchanged materials and biota for only minutes a day. The rest of the time they were kept isolated (Todd, 1992). Our educational Living Machines are now used in over half a dozen schools. They demonstrate primary production and food chain building in the first cell, consumption by half a dozen fish species in the second and, in the third, water transformation and purification in a paddy/marsh system. These Living Machines can range from three-cell systems to a 20-cell system that treats sewage in the central atrium of a school owned by the Toronto, Ontario, Board of Education (Todd, 1991). Comparable industrial and sewage treatment systems, currently operating in eight states, have a minimum of seven cells per treatment train.

We have learned that diversity of cell types produces Living Technologies that are more stable and robust. However, research is needed to determine the optimal number of distinct ecological subsystems. In waste treatment facilities cell diversity may be important to the reduction of toxins and the control of pathogens. As the technology of mesocosms evolves, more integration of waste streams with fuel production and food/fiber culture will result. As a rule, Living Technologies should have a minimum of three possibly four basic ecological components.

2.8.Microbial communities

That microbial communities are the foundation of Living Machines is obvious. What is less obvious, if the potential of ecological engineering is to be optimized is the diversity in communities of micro-organisms required. One school of thought in biology considers bacteria as ubiquitous organisms that organize life on the planet. Sonea and Panissett (1983) go further, suggesting that bacteria are organized, not as distinct species as is conventionally understood in biology, but as a unitary society of organisms with no analogous counterparts among other living organisms. Another school in microbiology maintains that bacteria species have highly specific nutritional and environmental requirements and the ubiquity principle, which may work over long-term time frames, is inappropriate to the design of Living Technologies (Ehrlich et al., 1989).

In waste or intensive aquaculture, for example, if conditions are not right for nitrifying bacteria, e.g. not enough calcium carbonate as a carbon source, then Nitrosomonas and Nitrobacter will functionally disappear from the system. The only quick way to re-establish nitrification is through correcting the calcium-carbonate deficiency and re-inoculating the system with culture of appropriate bacteria.

Bacterial communities remain a largely unexplored frontier in the design of Living Technologies. some 10,000 species have been named and described. Many important reactions are catalyzed only by bacteria. Margulis and Schwartz (1988) argue that the natural history and ecology of bacteria have been little studied and that we know little of their distribution and numbers. In our work with the degradation of coal tar derivatives (PAHs) we inoculated the treatment systems with microbial communities from such diverse locations as salt marshes, sewage plants and rotting railroad ties.

Although less diverse metabolically than bacteria, nucleated algae, water molds, slime molds, slime nets and protozoa are organisms with exceptionally diverse life histories and nutritional habits (Margulis and Schwartz, 1988). It has been shown that protozoans are important in removing coliform bacteria and pathogens from sewage (Pike and Carrington, 1979). They also serve to remove moribund bacteria and improve system efficiencies (Curds and Hawkes, 1975).

Fungi are key decomposers in ecological systems. It is estimated that there are about 100,000 species, many capable of excreting powerful enzymes. They can be as efficient as heterotrophic bacteria in the removal of organic matter from wastewater (Gray, 1989). Fungi tend to be more dominant in low pH and terrestrial soils than in aquatic environments. It may be that Living Technologies should incorporate soil-based acid sites linked to the main process cycles into their design.

2.9.Solar-based photosynthetic foundations

Ecological engineering was founded on a recognition of the role of sunlight and photosynthesis. By way of contrast, algae and higher plants are seen in civil engineering as nuisance organisms to be eliminated physically and chemically from the treatment process. Contemporary intensive aquaculture takes a similar view. The ecosystem-based solar aquaculture developed at the New Alchemy Institute in the 1970's and its successors constitute an exception to this trend (Todd and Todd, 1980, 1984, 1994) and (McLarney, 1987).

Algae-based waste treatment systems have been pioneered by Oswald (1988) and Lincoln and Earle (1990) in the US, Fallowfield and Garrett (1985) in the UK, Shelef et al. (1980) in Israel and a host of scientists in China and India (Ghosh, 1991). Floating higher aquatic plants are used in a variety of waste treatment approaches (Reddy and Smith, 1987). The use of emergent marsh plants and engineered marsh-based systems for waste treatment has gained prominence and technical sophistication over the last few decades (Reed et al., 1995).

Employing plant diversity can produce Living Technologies that require less energy, aeration and chemical management. Root zones are superb micro-sites for bacterial communities. We have observed enhanced nitrification in treatment cells covered with pennywort, Hydrocotyle umbellata, and water hyacinth, Eichhornia crassipes, as compared with comparable cells devoid of higher plants. Some plants sequester heavy metals. One species of mustard, Brassica juncea, has been found to remove metals from flowing waste streams, accumulating up to 60% of its dry weight as lead (Nanda Kumar et al., 1995). Metals can be recovered from harvested, dried and burned plants. Certain species of higher plants such as Mentha aquatica produce compounds or antibiotics that can kill certain human pathogens (Seidel, 1971).

There is economic potential in plants from Living Machines. Flowers, medical herbs and trees used in rhizofiltration in a waste treatment facility can subsequently be sold as byproducts. Our Frederick, Maryland living machine sewage treatment facility produces horticultural crops for the water gardening industry.

2.10. Animal diversity

The regulators, control agents and internal designers of ecosystems may be unusual and little appreciated organisms. Having built ecological microcosms and mesocosms for over 25 years, we are aware that organisms from every phylogenetic level have a role in the design of Living Technologies and in the reversal of pollution and environmental destruction. A search of the vast repository of life forms for species useful to ecological engineers is needed.

Odum (1971) spoke of the need to find control species, meaning those organisms capable of directing living processes towards such useful end points including foods, fuels, waste recovery, and environmental repair. The potential contributions of animals to Living Technologies is remarkable, yet their study has been badly neglected in Biology of Wastewater Treatment, mollusks are not mentioned (Gray, 1989) and in the two volume ecological Aspects of Used Water Treatment, snails are mentioned only once and referred to as nuisance organisms (Curds and Hawkes, 1975 and Curds and Hawkes, 1983).

We have found snails central to the functioning of Living Technologies. Pulmonate snails, including members of the Physidae Lymnaeidae and Planorbidae families feed on the slime and sludge communities. They thrive in zones where predators are lacking. Snails play a dominant role in sludge reduction, tank maintenance and ecological fluidized bed and marsh cleaning. Ram's horn snails of the family Planorbidae graze and control filamentous algae mats that would otherwise clog and reduce the effectiveness of the diverse fluidized bed communities. Some snails digest recalcitrant compounds. The salt marsh periwinkle, Littorina irrorata, produces enzymes that attack cellulose, pectin, xylan, bean gum, major polysaccharide classes, algae, fungi and animal tissues as well as 19 other enzymes interactive with carbohydrates, lipids and peptides (Barlocher et al., 1989). Snails can function as alarms in the Living Machines treating sewage. When a toxic load enters the Providence sewage treatment system for example the snails quickly leave the water column and move into the moist lower leaves of the floating plants above the water. Observing this behavior the operator then increases the rate of recycling clean water back upstream into the first cells. Performance losses are minimized as a consequence of the rapid behavioral response of the animal.

Virtually all phyla of animals in aquatic environments feed through some filtratio mechanism. Bivalves, algivorous fish, zooplankton, protists rotifers, insect larvae, sponges and others are in this functional category (Austin, 1995). They remove particles of roughly 0.1 µm to 50 µm from the water column. Bivalves are significant filterers. Mussels can retain suspended bacteria smaller than 1 µm. Efficiencies reach 100% for particles larger than 4 µm (Hawkins and Bayne, 1992). Individual freshwater clams of the genera Unio and Anodonta filter up to 40 1/day of water, extracting colloidal materials and other suspended organic and inorganic particles. Removal rates are 99.5% (Karnaukhov, 1979). Karnaukhov has proposed clam-based mesocosms and hatcheries for the treatment of polluted waters. In one experiment clams were used in a Russian river to reduce total suspended solid levels of 50 mg/1 to 0.2 mg/l.

Species of freshwater clams are becoming extinct. With complicated life cycles that often include stages in the gills of fish species intolerant of pollutio, they are especially threatened. In this century, 50% of the clam species have become extinct and two thirds of those remaining are listed as threatened (Pennack, 1978). Living Technologies need to be developed to culture threatened species. This applies to other animals as well. Recently, we built a living machine to support and breed a species of Lake Victoria cichlid, Oreochromis esculentus, now extinct in the wild.

Zooplankton can be employed to good effect in applied mesocosms. They feed upon particles 25 µm and smaller (Smith, 1993). Their nauplii or juvenilt stages graze sub µm sized particles (Turner and Tester, 1992). Since they can exchange the volume of a natural body of water several times per day it is difficult to overstate their importance in ecological engineering (Austin, 1995). In cells within the Living Machines, where fish predators are absent, their numbers are prodigious. We have found microcrustaceans throughout 3 m deep ecological fluidized beds comprised of 2 cm sized pumice rock in a prototype living technology that upgrades secondary sewage effluent to reusable quality water in San Francisco (Todd et al., 1995).

Insects play pivotal roles in Living Technologies. Removed from predators in ecologically engineered systems, they proliferate and impact significantly on the water. In our sewage treatment facilities chironomid larvae attach themselves to the walls of the aerated tanks, often in great numbers. McLarney (1987) developed mass culture methods for chironomids fed on dried sewage. His objective was to culture live foods for fish. Chironomid production levels were as high as 400 g m-2 day-1. Water quality improvement was an additional benefit.

Vertebrates play key roles in the functioning of Living Technologies. With an estimated 22,000 species, fishes are the most numerous and diverse of the vertebrates (Lagler et al., 1962). In diet, behavior, habitat and function fish are extraordinarily diverse. Filter and detritus feeding fish are common to all the continents. The filtration rate of algivorous fish may be five orders of magnitude greater than their volume every day (Gulati and Van Donk, 1989). In theory it is possible for the total volume of a fish pond to pass through algae-filtering fish on a daily basis. There are edible fish species like the Central American Characin, Brycon guatemalensis, that are capable of shredding and ingesting tough and woody materials (McLarney, 1973). We use members of the South American armored catfish family Plecostomidae to control sludge build up in waste treatment and food culture Living Technologies. Tilapia, Oreochromis spp., are used to harvest small plants like duckweed and aquatic ferns. The grass carp, Ctenopharyngodon idellus, recycles as variety of plant materials. In several Living Machines minnows, including the golden shiner, Notemigonus crysoleucas, and fathead minnow, Pimephales promelas, feed on organic debris and rotting aquatic vegetation. They breed among rafted higher plants grown on the surface of the water. Excess minnows are sold as bait fish. Research into the aquarium and ichthyological literature will be valuable to ecological engineers.

2.11.Biological exchanges beyond the mesocosm

To optimize their self-design and organization capacities a living technology may require gaseous, nutrient, mineral and biological linkages with larger natural systems. Odum (1971) was among the first to recognize that the ecology of invasions is relevant to the ecological designer. He wrote: "One of the means for developing stable new ecological designs for new environments is multiple seeding; many species are added to the new ambiance while conditions are maintained as they are likely to continue…the species go through a self-selection of loops, producing a stable metabolism and a complex network within a few weeks". Mitsch (1993) added: "The multiple seeding of species into ecologically engineered systems is one way to speed the selection process in their self organization or self design."

It is relevant to add that the seedings should come form distinct environments. As a general rule, we choose from a variety of natural, polluted and humanly managed systems ranging from waste treatment plants, to agriculturally impacted zones like feedlots and pig wallows. For aquatic mesocosms we select organisms from stream, pond and lake environments. It is valuable to return each season to these same environments for samples. Doing so will provide organisms adapted to seasonal differences.

An interesting experiment would entail linking a living machine to a natural ecosystem and exchange biological materials between the two. A sewage treatment facility for example could be connected with a nearby marsh or pond. A small percentage of the flow could be directed to the natural system which, in turn, could be linked back to the living technology. In this way the natural system would provide, on a periodic or a continuous basis, an influx of chemical and biological materials. The linkage would allow the natural water body to act as a refugia for the living technology, protecting it from toxic upsets or unnatural loadings.

2.12.Microcosm, mesocosms, macrocosm relationships

The most complete living system of which we are aware, the earth, should be the overriding basis for design. The study of the earth as a whole system is critical to the emergence of a science and practice of earth stewardship (Lovelock, 1988). An experiment such as the Biosphere 2 project in Arizona is an attempt to apply global system knowledge on a manageable scale (Allen, 1991). Our earliest work with mesosocms for the culture of foods was based upon applying what we knew about macro-systems on earth. These we grafted to concepts derived from ancient, culturally7-based notions of polyculture such as had been practiced by the Chinese for several millennia (McLarney and Todd, 1974). In these earliest mesocosms, which were housed in geodesic structures with transparent membranes, we simulated the planet having 70% of the interior space occupied by water and the remainder terrestrial. The structures were capable of engendering internal hydrologic cycles and climate regulation without mechanical air movement or supplemental heating in New England. A small amount of electrical or wind energy was used to create currents and upwellings. The aquatic and terrestrial components exchanged water and nutrients as well as biological materials. The food chains included fish, mollusks, greens vegetables and fruits grown in zones within the aquatic and terrestrial subsystems. Between 1971 and 1980, six 10 , diameter biodomes were built. One remains operational. Although the designs were somewhat crude, they worked well. Solar energy and ecologically engineered food webs produced abundant foods year round. No agricultural chemicals, including pesticides and fungicides, were used. That they performed so well may be because the designs were based on relationships and proportions derived from those of the biosphere.

The twentieth century has seen the development of high rate computation and electronics. The biological and ecological sciences have emerged as disciplines with complexity, exchange, symbiosis and highly dynamic states. The next step in the evolution of technology should be the application of this knowledge to ecological design and to Living Technologies that sustain the human community while supporting and enhancing the natural world. Ecological design will help create a symbiotic partnership between humanity and nature.

Visit this paper on-line at, http://home2.swipnet.se/~w-25860/icibs/todd

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