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Ecological Engineering 20 (2003) 339–361

ECOLOGICAL ENGINEERING

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Concepts and methods of ecological engineering

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Received 14 June 2002; accepted 4 August 2003

Abstract

Ecological engineering was defined as the practice of joining the economy of society to the environment symbiotically by fitting technological design with ecological *self design.* The boundary of ecological engineering systems includes the ecosystems that self organize to fit with technology, whereas environmental engineering designs normally stop at the end of the pipe. For example, the coastal marsh wildlife sanctuary at Port Aransas, Texas, developed when municipal wastewaters were released on bare sands. The energy hierarchy concept provides principles for planning spatial and temporal organization that can be sustained. Techniques of ecological engineering are given with examples that include maintaining biodiversity with multiple seeding, experimental mesocosms, enclosed systems with people like Biosphere 2, wetland filtration of heavy metals, overgrowth and climax ecosystems, longitudinal succession, exotics, domestication of ecosystems, closing material cycles, and controlling water with vegetation reflectance.

Keywords: Ecological engineering; Waste recycle; Self organization; Energy hierarchy; Emergy; Transformity; Emdollars; Maximum power

1. Introduction

The following commentary defines what *ecological engineering* is, explains some of its principles, and describes techniques of application with examples from the author's experience. Ecological engineering started as people recognized cooperative environmental interfaces. In 1957, we applied the name to the conscious use of ecosystem self design. By the 1990s the concepts were used worldwide with formation of an International Society of Ecological Engineering.

1.1. Definitions

Engineering is sometimes described as the study and practice of solving problems with technological designs. The sketch in Fig. 1a shows the environment and the economy coupled symbiotically by exchange of materials and services. Environmental engineering develops the technology for connecting society to the environment. But the technology is only half of the interface with environment. The other half of the interface is provided by the ecosystems as they *self organize* to adapt to the special conditions. Ecological engineering takes advantage of the ecosystems as they combine natural resources and outputs from the economy to generate useful work.

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0925-8574/$ – see front matter
doi:10.1016/j.ecoleng.2003.08.008

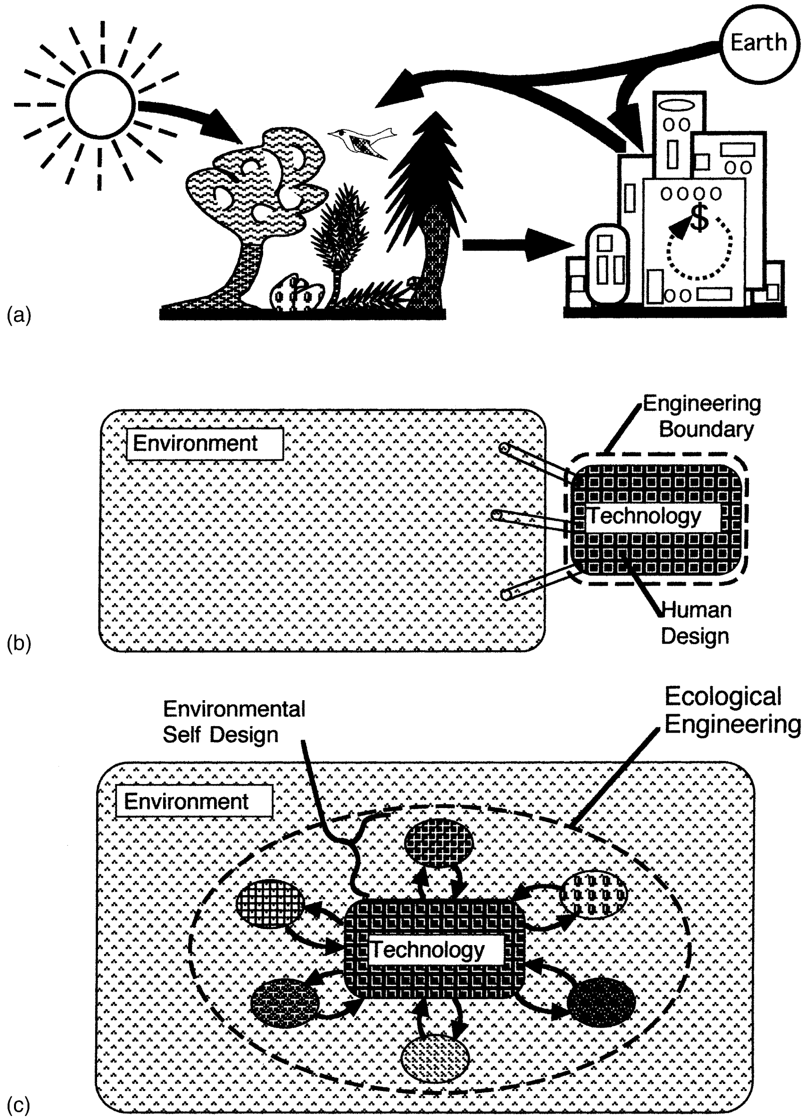

Fig. 1. Scale of ecological engineering, a larger realm than traditional environmental engineering. (a) Sketch of the unified system of environment and technology sometimes used as a logo for ecological engineering; (b) traditional boundary of environmental engineering designing; and (c) boundary of ecological engineering designing.

Ecological engineering is the study and practice of fitting environmental technology with ecosystems *self design* for maximum performance.

1.2. Scale of ecological engineering

By considering the ecosystems that surround the technology, ecological engineering uses a larger scale than typical environmental engineering. Fig. 1b shows environmental engineering at the edge of environmental technology, whereas Fig. 1c represents the larger boundary of ecological engineering that includes the free self adapting ecosystems.

Ecotechnology may not be a good synonym for ecological engineering because it seems to omit the ecosystem part. It is the self regulating processes of nature that make ecological self designs low energy, sustainable, inexpensive, and different.

Odum (2001a) quotes Z. Naveh using the term *techno-ecosystem* to represent the combined systems of technology and ecology, which is the realm of ecological engineering.

People of many backgrounds seek methods of managing environment for beneficial purposes. In some groups and journals, managing ecosystems for productivity and harmony with the economy is called *restoration*, which might imply going back to ecosystems before conditions were changed by economic development. For example, Middleton (1999) reviews restoration and management of wetlands and their adaptation to pulsing. Ecological engineering is a better word which welcomes the new ecosystems as well as old systems when they are necessary for maximum benefit.

1.3. An example, the Audubon sanctuary at Port Aransas, Texas

In 1954, the outer banks village of Port Aransas, Texas, had 500 residents increased by summer tourists. A sewage plant with primary and secondary treatment released its nutritive waste waters on the flat bare sands. Around the outfall, a pond and freshwater marsh developed and around that, salt adapted vegetation. By year 2000, the town had 5000 residents with many times that in summer. The outfall marshes had spread and attracted wildlife including alligators, turtles, and waterfowl (Fig. 2a). The area was adopted as an Audubon Wildlife sanctuary with boardwalk and tower added for observers (Fig. 2b). In this development, ecological engineering meant letting nature self organize a suitable tertiary treatment ecosystem and fitting human society to nature in a way that both prospered. An emergy evaluation found large net benefit (Odum et al., 1987).

2. Theoretical basis for ecological engineering

Although the interface ecosystems that develop are often unexpected surprises, the systems can be understood and sometimes predicted with the energy laws that control all systems. Whereas humans can make free choices, these theories claim that only those choices that fit the principles are sustained. In other words, the realm of ecological engineering is based on scientific principle, not free for any human choice. The reader is referred to publications elsewhere that justify these principles (Odum, 1971, 1975, 1983; Hall, 1995). The pertinent energy laws are reviewed briefly as follows:

2.1. Maximum power, fourth energy law

Well stated by Lotka (1922a,b), *system designs that prevail are those that maximize power*. For example, the marshes at Port Aransas organized to utilized the nutritive waters and sunlight to maximize photosynthetic productivity. Energy corollaries 1–5 are consequences of this law.

Corollary 1. Maximum power requires optimum efficiency. For any energy transformation, there is an optimum loading, and thus optimum efficiency that produces maximum power (Odum and Pinkteron, 1955). Systems organized to be more efficient or to go more rapidly, generate less power output. For example, self organizing plants adjust their green chlorophyll concentrations to maximize power.

Corollary 2. Energy transformations that prevail store energy that can reinforce their inputs by amplifying feedbacks and recycle. The output of energy transformations that prevail store and feed back their products to help maximize power. For example, algal populations reproduce and use the increased numbers to process more energy.

Corollary 3. Adapting to physiological stress reduces species diversity. Extremes and impacts that require physiological adaptation take priority over supporting species diversity. For example, ecosystems adapting to extremes of temperature or salinity have lower species variety. Networks may be simplified, causing energy to concentrate in fewer pathways. For example, fish production of a few species increased in hypersaline bays of Texas.

Corollary 4. Overgrowth prevails when resources are underutilized. The first priority for maximizing power is to transform energy into a form that can be stored and used to reinforce the capture of underutilized

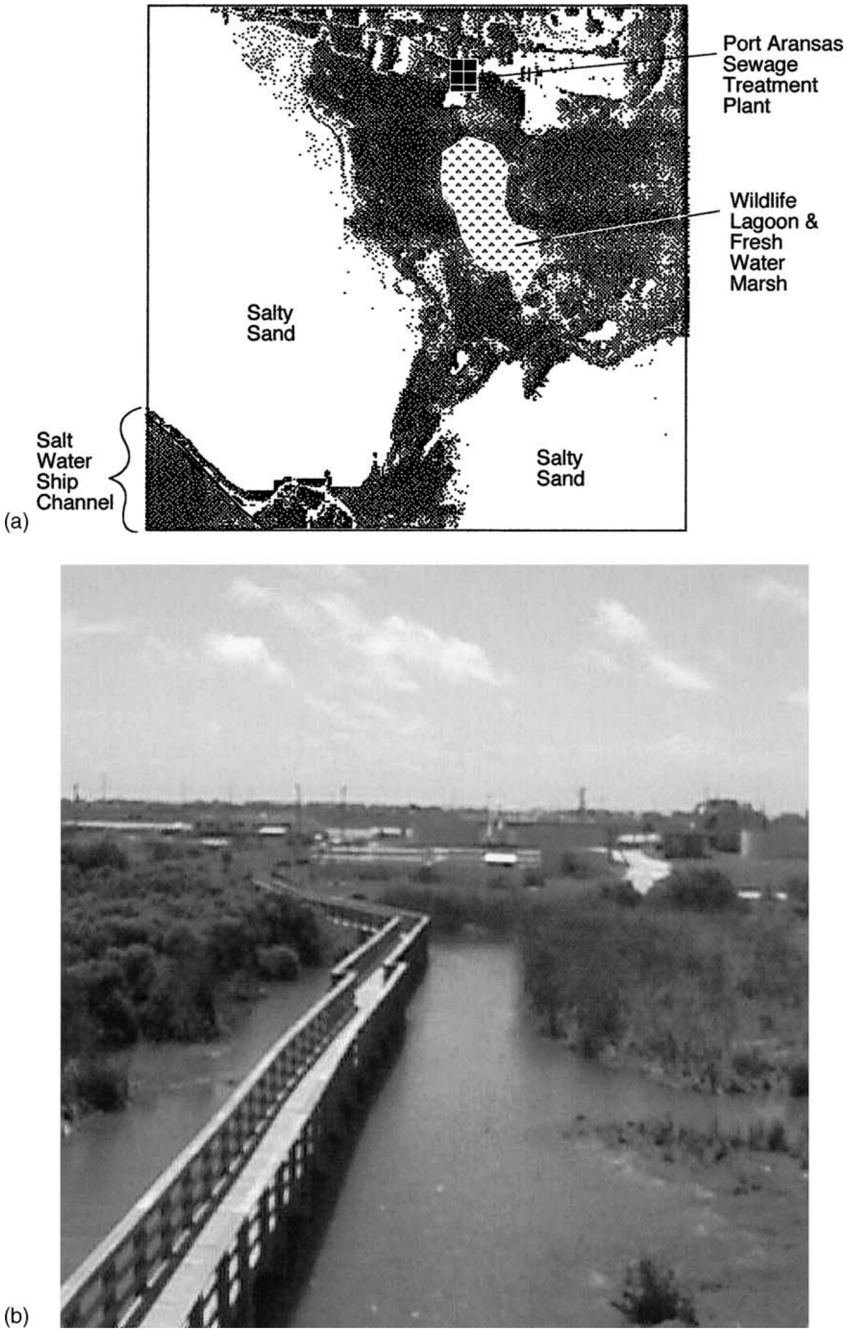

Fig. 2. The Audubon marshes at Port Aransas, Texas, an example of ecological engineering use of self organization. (a) Map view; and (b) view from tower.

energy. In this situation power is maximized by letting free competition select species that overgrow others, causing a low diversity, as suggested by Yount (1956). For example, low diversity blooms prevail with excess resources in wastes released from the economy.

Corollary 5. Maximum efficiency develops diversity and division of labor when resources are not in excess. The second priority for maximizing power prevails when there are no more unutilized resources. Efficiency is increased by development of high diversity and division of labor among species. For example, typical plant succession develops high diversity in situations where no new resources are being added.

The author recently published two models PIONINFO (Odum, 1999) and NUTRISPEC (Odum, 2000) that simulate the maximum power switch from overgrowth to climax diversity or back, depending on input resources. People with background in population ecology refer to growth and steady state using coefficients of growth models as R and K strategy, but this language is less appropriate for the scale of ecological engineering.

2.2. Energy hierarchy, a fifth energy law—a systems effect of the second law

A hierarchy is a design in which many units of one kind are required to support a few of another. According to the second law, all energy transformation works to convert many joules of available energy (exergy) of one kind to a few joules of another kind of energy. In self organization, all energy transformations form hierarchical chains, connecting each kind of energy to the next. For example, ecological systems form networks of energy transformation processes with their food chains. To illustrate energy transformation hierarchy, Fig. 3a simplifies the usual network by aggregating units as a straight chain. From left to right energy flow decreases, but the quality of transformed energy is often said to increase. The following properties (Odum, 1983) are revisited as consequences of the hierarchical self organization of energy (energy corollaries 6–12).

Corollary 6. Units are controlled and reinforced from downstream. Chains and networks that prevail feed back services and materials from downstream units that reinforce the source units upstream (Fig. 3a). For example, in the waste marshes in Fig. 2, the alligators by their physical work maintain a central pool of algal productivity. Also, nutrient materials from the plants consumed by animals recycle to stimulate plant growth again.

Corollary 7. The scale of energy transformations increases downstream. Energy centers are larger and have greater territory of support and influence with steps along the energy hierarchy (left to right in Fig. 3b). Transformed outputs have less energy, but by becoming concentrated can maximize their effect in feedback reinforcements. For example, the size and share of area increases along a food chain from algae to alligator.

Corollary 8. The quantity of storage increases with transformation steps, but the turnover time decreases. Although there is less energy flow at each transformation step, the amount of energy stored increases (Fig. 3c). In ecosystems, biomass storage increases along the food chain, which facilitates the use of small energies to have stronger feedback reinforcements. For example, the alligator with less total energy flow is able to control the whole pond. With less energy flow but greater storage, the turnover time and percent depreciation decreases.

Corollary 9. Pulses of accumulation and feedback increase upscale. On all scales, power is maximized by accumulating output in storages, which are later consumed in a pulse of feedback reinforcement. Although energy flow is less along the networks (to the right in Fig. 3d), the accumulation times are longer, so that the pulses are shorter and stronger with greater impact. For example, there are many small actions but fewer large impacts among storms, carnivores, and people. By the store-pulse sequence all systems can reinforce better than by steady state. However, any scale of pulsing can be averaged as if in steady state to simplify calculations on larger scales of time and space.

Corollary 10. Centers have high transformities and empower density. Energy transformations converge flows to centers with decreasing energy flow, but with an increase in spatial concentration of the emergy

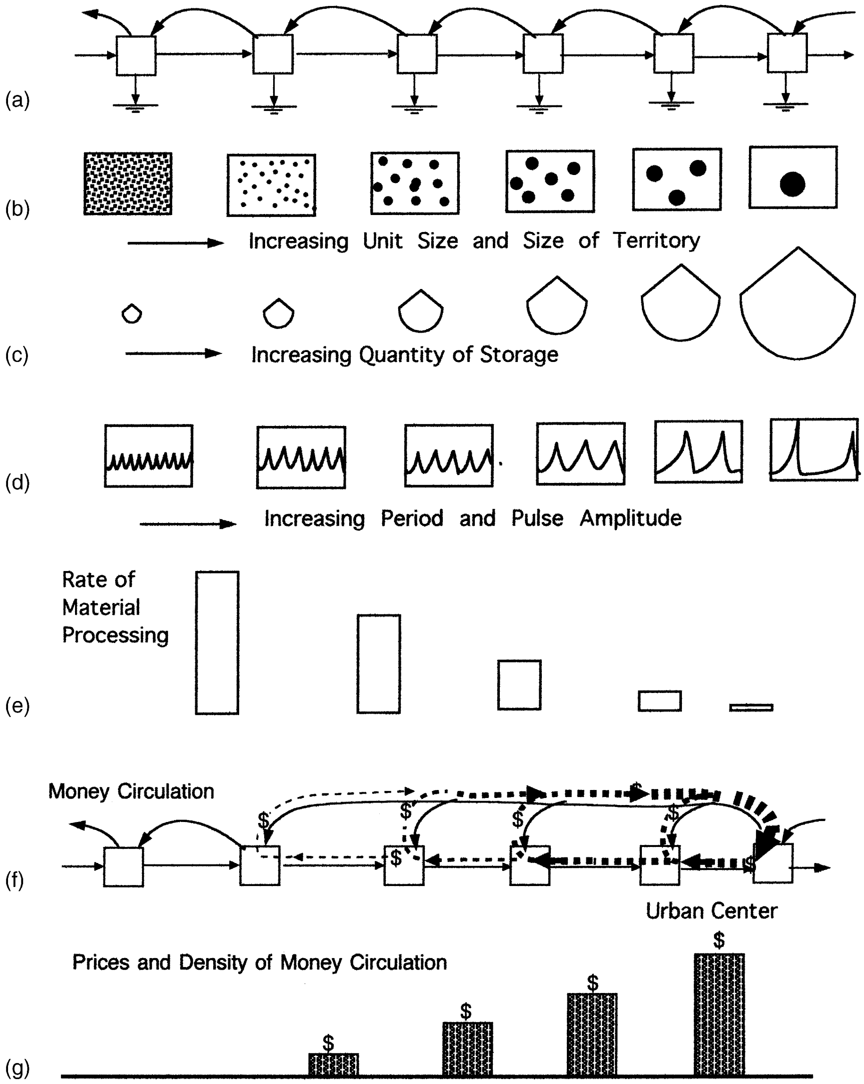

Fig. 3. Summary of the concept of energy hierarchy and the relationships with increasing scale. (a) Network aggregated as an energy transformation chain; (b) size of centers and their territories; (c) quantity stored and turnover time; (d) period of pulses and time between pulses; (e) rate of materials flow to centers; (f) pattern of money circulation; and (g) concentration of money circulation and prices.

(higher areal empower density). Concentrating emergy also increases transformities.

Corollary 11. Items of higher transformity have greater unit effect. Self organization of networks selects feedbacks with effects commensurate with their support. The more emergy an item receives the higher the transformity, and the more feedback effect is selected. For example, drugs with high levels of benefit or toxicity have high transformities (tobacco, cocaine).

Corollary 12. Material processing decreases with available energy. On every scale materials are incorporated and recycled, coupled to the transformations of available energy. Along the transformation chain (left to right in Fig. 3e) as energy flow decreases, the rate of material flow decreases, although the storages become more concentrated in centers (Odum, 2001a,b).

Corollary 13. Circulation of money is more concentrated in centers. Money circulates only among people and is not paid to environmental work processes. Money is a counter current to the series of energy transformations of the economy, becoming more concentrated along with the energy in urban and financial centers (Fig. 3f, Odum, 2001a,b). No money circulates in the realm of small scale processes. Prices rise along the chain (to the right in Fig. 3g).

Following the energy laws, successful ecological engineering joins systems of nature, which are usually the smaller scale networks on the left in Fig. 3, to the designs and uses of society, which are on a larger scale on the right. The energy hierarchy also provides quantitative measures to help people select alternatives that contribute most.

3. Emergy, emdollars, and transformity

Attempts over 150 years to use available energy as a general measure of work failed because energies of different kinds were regarded as equal. The energy hierarchy was not recognized. Now, energy of different kinds is put on a common basis by using *emergy (spelled with an "m") as the available energy of one kind used up directly and indirectly to generate a product or service* (Odum, 1988, 1996a,b)). It is a property that recalls the energy flows in network back to the left in Fig. 3. Units of emergy are *emjoules*, a numerical memory of past energy transformation. Along the simplified energy transformation steps in Fig. 3a, the emergy flows in from the left and is constant. (Rate of emergy flow is called *empower*.)

Emergy measures real wealth, which money buys. Calculating the emergy/money ratio of an economy puts the buying power of money on an emergy basis. Vice versa, the ratio can be used to estimate the economic equivalent of emergy. *Emdollars of something is the part of the gross economic product due to its emergy*. Emergy–emdollar evaluations have been widely used in ecological engineering to appropriately compare the contributions of the environment to those proposed from the economy so as to maximize both.

The quotient of *emergy flow divided by the energy flow is defined as transformity*, with the units emjoule per joule. For example, solar transformity has the units solar emjoules per joule. The transformity increases along energy transformation networks. Transformity marks the position of something in the universal energy hierarchy. An ecological engineering technique places processes and interfaces where transformities are compatible.

3.1. Mitigation with emdollars

In mitigation, developments are allowed in environmentally valuable areas if equivalent environmental protection is added to comparable areas elsewhere. Emergy–emdollar evaluation is the appropriate way to compare systems which need both environmental and economic inputs to be evaluated on a common basis. In Florida, wetlands mitigation is still done without a quantitative scientific basis, although emergy emdollars have been much discussed.

3.2. Economic matching which is sustainable

3.2.1. The investment ratio is the ratio of purchased emergy to free environmental emergy

To be sustainable, an ecological engineering interface should have an investment ratio similar or less than other environmental uses in the region. Systems with higher ratios are too costly to compete.

4. Methods and examples of ecological engineering

Next let us review some of the techniques of ecological engineering that are now widely applied. Examples are given from the author's experience. An extensive review of ecological microcosm research and their potential for space was published in an earlier book (Beyers and Odum, 1993).

4.1. Microcosms and multiple seeding

The self organizational principles and corollaries of maximum power seemed to explain the self organization observed in studies of energetics in Silver Springs and other ecosystems. In order to apply the experimental method, efforts were made in 1954 to

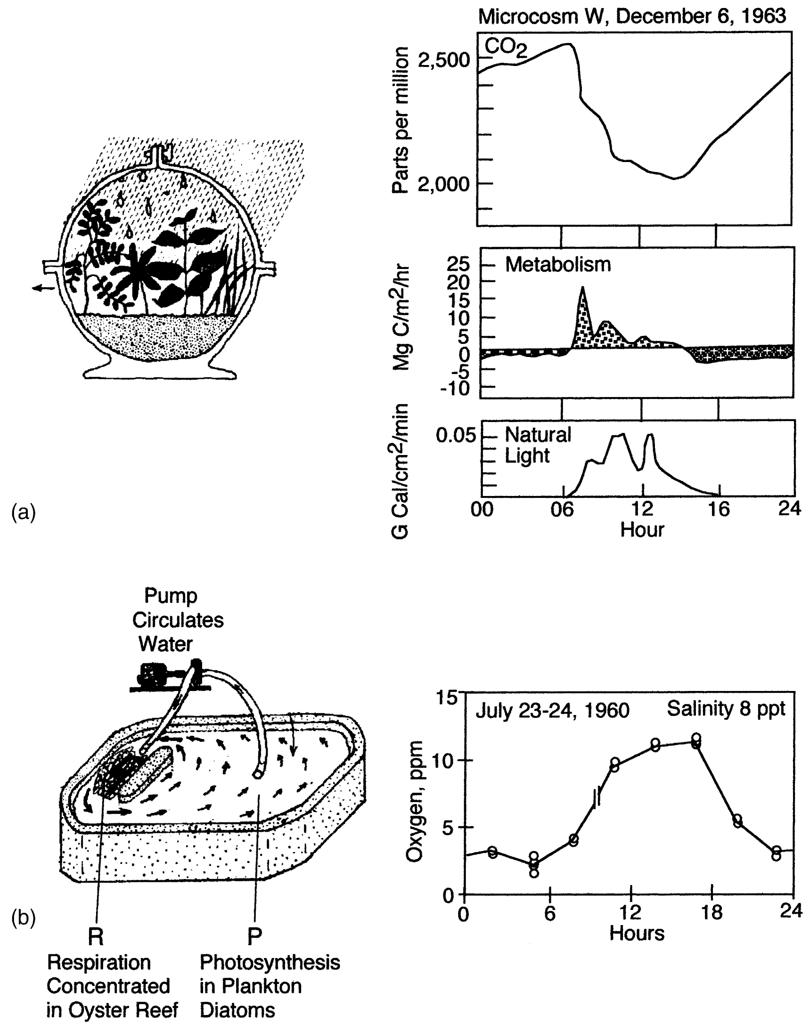

Fig. 4. Microcosms used for testing impacts on ecosystems. (a) Terrestrial microcosms started with rainforest soil, litter, and herbs and metabolism measured from diurnal variation of carbon dioxide. (b) Microcosm simulating the circulating animal reef-plankton ecosystem of South Texas, with metabolism indicated by diurnal variation in dissolved oxygen.

replicate ecosystems in miniature with experimental microcosms. Interesting complex ecosystems formed rapidly, rarely what was expected, depending on the species that had been introduced inadvertently or on purpose. With enclosed microcosms, it is easy to measure metabolism from observed changes of oxygen in the water or carbon dioxide in the atmosphere of terrestrial microcosms (Fig. 4a).

To generate duplicate microcosms and make happen-stance introductions less important, intense seeding of species was brought from appropriate wild environments so that the self organization could select optimum populations. Duplicate microcosms were usually different. If the duplicates were regularly mixed, then they became similar. Thus, the multiple seeding technique developed as a way to accelerate nature's adaptation. Multiple seeding was applied on the larger scale of ecological engineering as the first step in developing a new interface. The idea is to help nature find the competitive system, rather than trying to predict or chose in advance.

4.2. Microcosms for anticipating ecological engineering consequences

The microcosms were also seen as a way to anticipate ecological engineering designs that might follow if implemented on a larger scale. For example, the oyster reef mesocosms were able to duplicate the main features of the estuarine ecosystem and its response to added nutrient water (Fig. 4b). At a smaller scale than in nature, all the properties of size and time were to the left in Fig. 3. After extensive use of small microcosms, they were criticized as not able to show what was of importance on the large scale. The big animals and large scale pulses were absent. However, the results from microcosms can be multiplied by scale factors (turnover time, territory, and transformity) to infer the equivalent at the larger scale. More efforts were made to experiment with larger mesocosms, although the costs were greater. The book of papers edited by Gardner et al. (2001) compares properties of ecosystem with scale, including many new graphs that illustrate the energy hierarchy.

4.3. Achieving resilience with complexity

It was soon obvious from microcosm studies by many investigators that ecosystems developing after multiple seeding were relatively resilient and immune to disaster from changes in environmental condition or further species introductions. The small ecosystems were like the wild ones, using the diversity of their gene pool to stay adapted to various changes. For example, the terrestrial microcosms simulating the rainforest floor (Fig. 4a) were very resistant when exposed to gamma irradiation (Odum and Lugo, 1970).

4.4. Microcosms and mesocosms for space

The struggle within the National Aeronautics and Space Administration to find a more self supporting life support system for space that started in the 1950s seemed to be solved by the complex microecosystem demonstrations. Even though complex ecosystem life support was presented in NASA co-sponsored symposiums in 1962 (Taub, 1963a,b) and again in 1982, only pure cultures or limited species combinations were considered for space, and these were not stable. Even in year 2001 no complex microcosm had yet been tested in space.

4.5. Mesocosm life support for people and Biosphere 2

The concept of a self organized mesocosm that included people was offered in proposals to NASA for a ground test (Fig. 5a, Odum, 1971). Although these were not funded, a billionaire, Edward P. Bass, funded a highly original project led by John Allen, developing the 3-acre Biosphere 2 that used the multiple species complex ecosystem concept to support eight people for 2 years (Figs. 5b, c and 6a). The scientific results were the subject of a special issue of *Ecological Engineering* journal (Marino et al., 1999), documenting many insights about the earth (Biosphere 1) as well as showing what is required for space. Fig. 7b shows the near balance of production and consumption achieved by the self organization inside after 2 years. Fig. 7c shows the species survival in the self organization of the plants of the rainforest zone. Without normal rainforest insects and birds, normal pollination was missing, and species with strong asexual reproduction prevailed (Leigh, 1999).

4.6. Search for adapted ecosystems, examples of wetland filtration

Scanning environments in search of ecosystems that have adapted to economic inflows and impacts is an inexpensive way to find out what works. For example, treated sewage waters discharged into marsh-bordered tidal channels in Morehead City, NC, were observed with lush growths and abundant wildlife in 1960s. Measurements by Marshall (1970) confirmed the high productivity (Fig. 7). Similar discharges at Naples, Florida, examined by Sell (1977), showed increased productivity of mangroves.

Examination of wetlands receiving lead and zinc from mining for 400 years in Poland by Wojcik and Wojcik (2000) showed the long term ability of marshes for heavy metal removal (Fig. 8a). Lead from a battery recovery operation in Jackson County, Florida, was largely sequestered in cypress swamps (Odum et al., 2000a,b), which developed an interface ecosystem of floating plants (Fig. 8b). Examples in Fig. 7 are im-

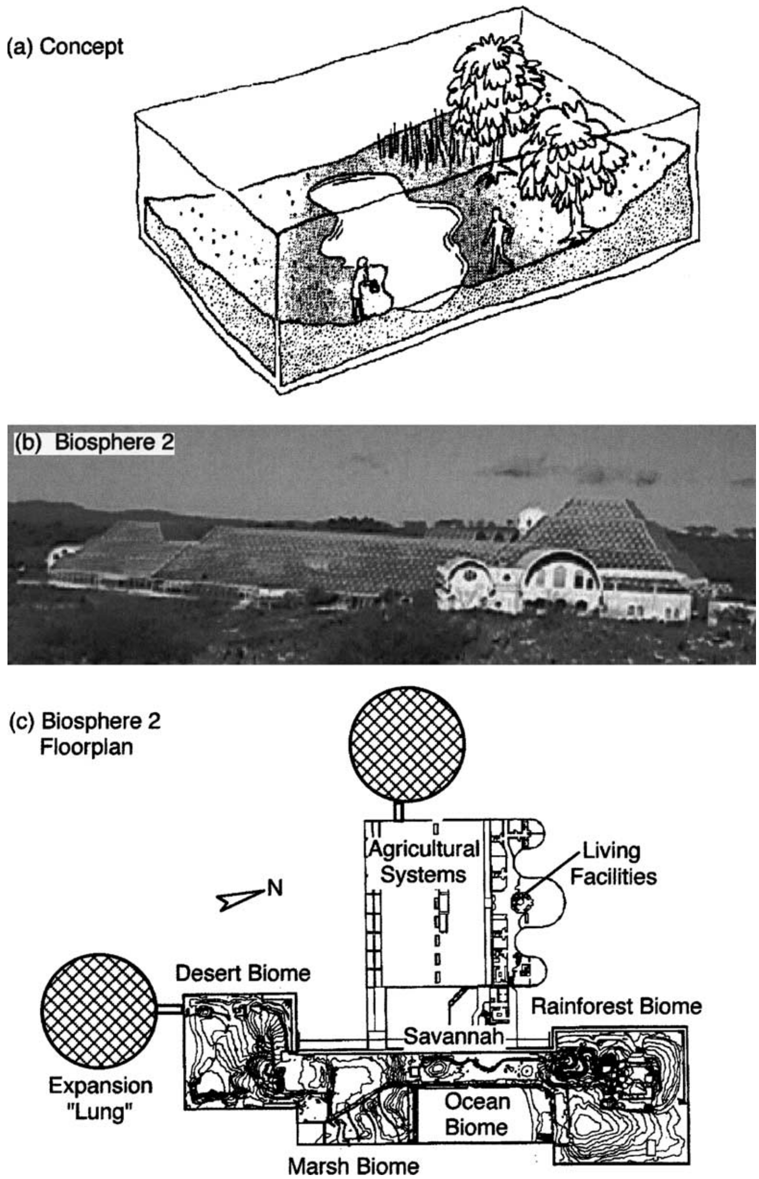

Fig. 5. Concept of enclosed ecosystem with multiple species to support people adopted in Biosphere 2. (a) Concept published in 1971; (b) view of Biosphere 2; and (c) floor plan of Biosphere 2.

portant in refuting those who claim wetland filtration is not sustainable.

4.7. Domestication of ecosystems

When a useful ecosystem interface is discovered, its conditions and species can be transplanted for use in new situations with similar conditions elsewhere. In this way, ecosystems are domesticated. This is not unlike the capture of the trickling filter and activated sludge ecosystems in the 19th century. Those ecosystems were enclosed in concrete boxes to become the mainstays of environmental engineering ever since. For the great variety of environmental conditions, a

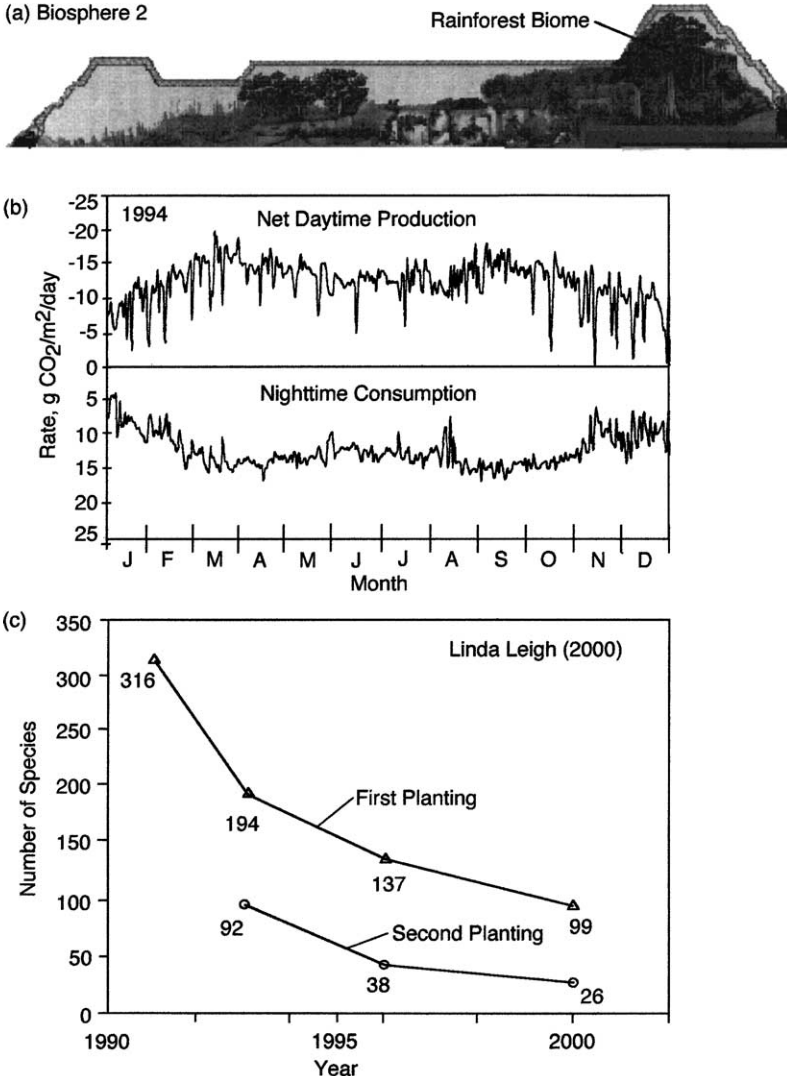

Fig. 6. Biosphere 2 and its metabolism and diversity in Biosphere 2. (a) Cross section view; (b) nearly balanced production and consumption after 2 years of self organization; and (c) diversity of plants after 7 years.

much larger repertoire of free ecosystems is available for ecological engineering use without the costs of concrete enclosures.

4.8. Ecological engineering of an estuarine wastewater ecosystem

In 1966–1970, a conscious test was made of the ability of multiple-seeding self organization to develop an estuarine ecosystem adapted to treated sewage wastewaters. In a project of the National Science Foundation and Sea Grant at the University of North Carolina, one set of ponds received saltwater and wastewater (Fig. 9), while the control set of ponds received saltwater and tap water. Whereas the control had plankton, invertebrate and fishes with normal variety and seasonal cycle, the new ecosystem that adapted to the wastewaters had intense *Monodus* bloom with ten times normal chlorophyll even in winter, wide oxygen range, blue–green benthic algae,

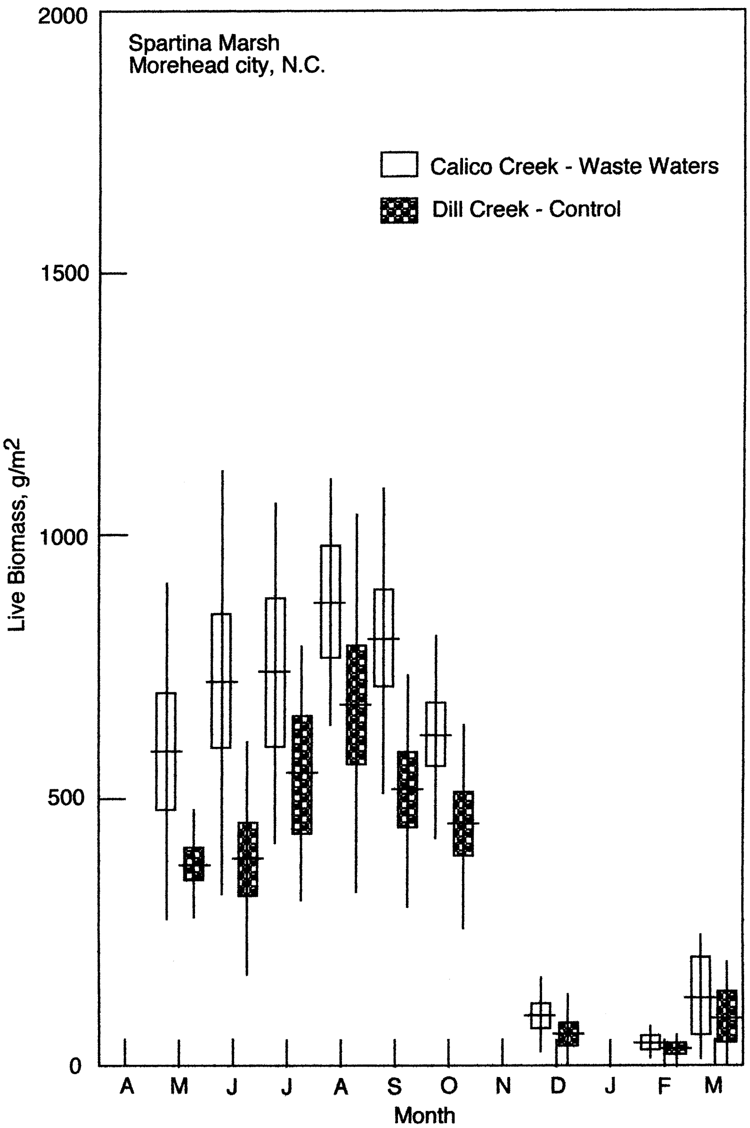

Fig. 7. Comparison of marsh productivity in marshes receiving municipal treated wastewaters at Morehead City, NC, compared with control marshes (Marshall, 1970).

low diversity of zooplankton, but good population of blue-crabs, bait-suitable top minnows, mullet, and dense lateral masses of *Spartina* facilitated by mud crabs. Fig. 10 shows the great differences in total metabolism between waste ponds and controls. The 3-year experiment gave early insights on the microbial bloom ecosystems that have since become widespread in estuaries (Odum et al., 1982; Odum, 1983).

4.9. Wetlands ecosystems for receiving wastewaters

In 1972, after a decade observing self-organizing wetlands doing filtration work, a national workshop was held at Gainesville under Rockefeller Foundation support, after which large projects were funded at the University of Florida, Michigan, and elsewhere.

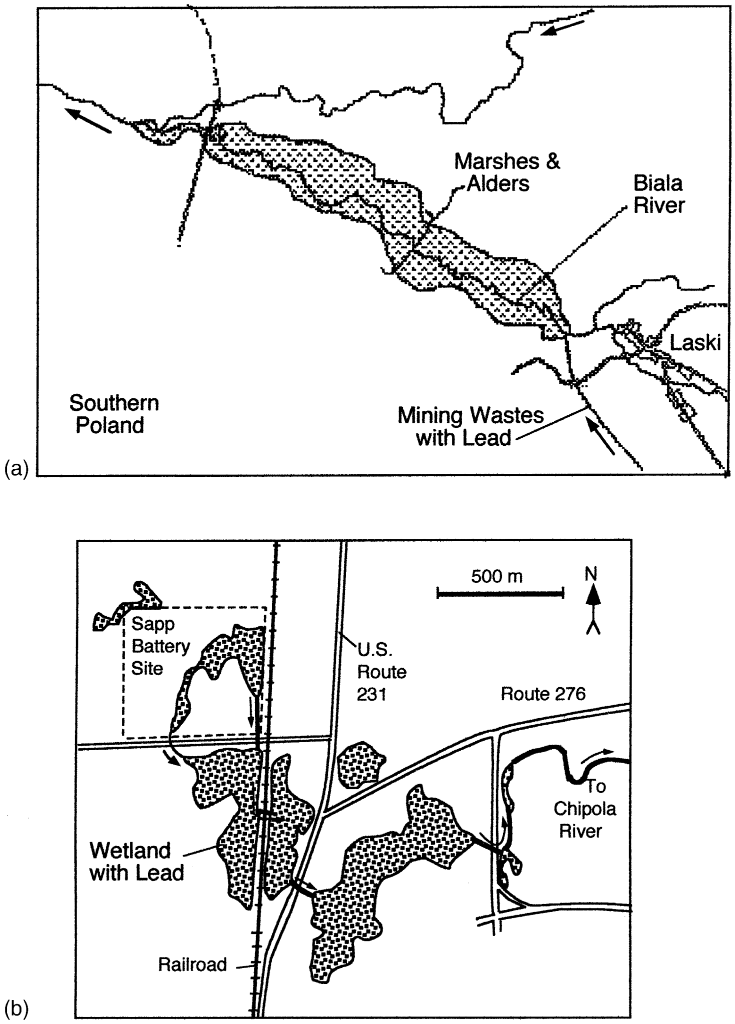

Fig. 8. Sites where self-organized wetland ecosystems were able to sequester large quantities of lead and zinc. (a) Biala River marshes of Poland; and (b) Sapp swamp in Florida.

The project at Gainesville established its Wetlands Center and evaluated many wetlands using municipal wastewaters, starting with cypress swamps. Results were shared at a Rockefeller symposium at Bellagio, Italy (Odum et al., 1977b). National Science Foundation circulated a training film. After the studies in Florida and many other places, the practice of arranging tertiary treatment with wetlands spread all over Florida and the rest of the world. Knowledge and ecological engineering guidelines on this was summarized by Kadlec and Knight (1996).

4.10. Ecosystem interface with dispersed solid waste

A main branch of environmental engineering manages high concentrations of solid wastes, land fills, gas production, groundwater toxicity, and other impacts. A different interface using ecological engineering principles was tested by shredding and dispersing the solid wastes over landscape as litter joining the natural forest litter. After covering bare land with 18 in. of shredded solid wastes, slash pine seedlings were planted by Smith (Jokela and Smith, 1990). Very high rates of forest growth resulted. After 20 years, the solid waste

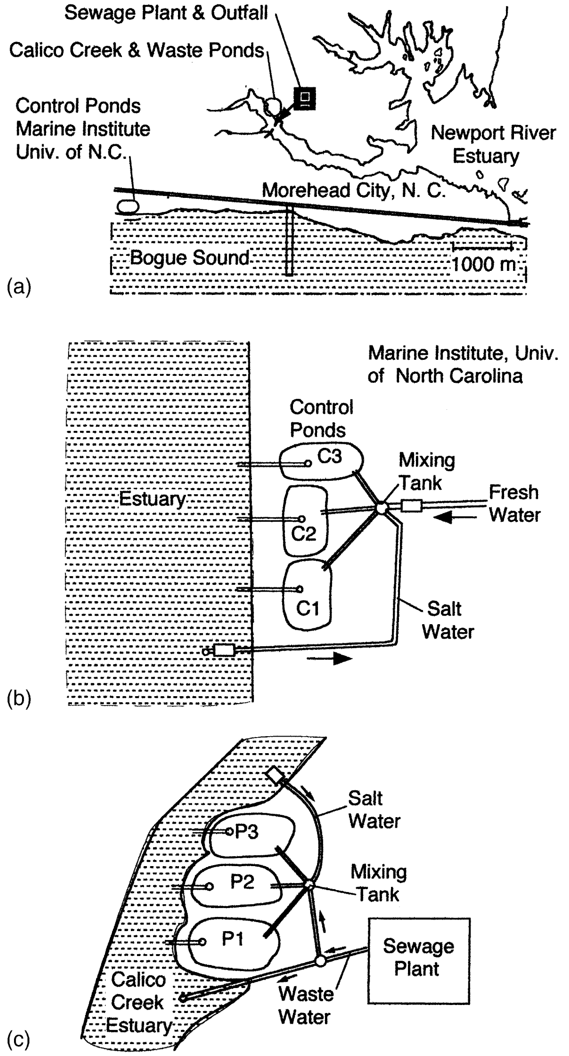

Fig. 9. Experimental and control ponds used to test self organization of an estuarine interface ecosystem adapted to municipal wastewaters. (a) Locations; (b) waste receiving ponds; and (c) control ponds.

forest looks like any other slash pine plantation in Florida, but one can find scattered bits of metal or rubber by digging in the soil profile. While on sabbatical at the LBJ school of Public Affairs in Texas, I raised the idea of solving solid waste by dispersed littering with Lady Bird Johnson, who led national initiatives against littering. It was not well received.

Along State Highway 100 between Palatka and Bunnell, Florida, is a business in which old cars are dumped into wetlands, and parts removed for sale. The used car dump is mostly hidden by the wetland trees. From what we know about wetlands absorbing and holding heavy metals (Odum et al., 2000a,b), this may not be a bad arrangement, a kind of ecological engineering.

4.11. Utilizing succession

The maximum power principle and its corollaries (above) explain the stages of ecological succession to be expected in situations based on their resources and seeding. Some kind of ecological succession was observed in most new microcosms and new interfaces. Succession from low to high diversity is typical of succession that starts on bare lands because initially there is unutilized energy (corollary 4).

Studies of regrowth after phosphate mining in Florida suggested that using self organizing ecosystems was the cheapest and fastest method of restoration. Ecological engineering of the interface between mining and the environment was accelerated by aiding the self organization of succession. Effects of landform, waters, nutrients, and seeding on mining reclamation has had extensive testing in central Florida (Brown and Tighe, 1991; Brown et al., 1992, 1997a,b, 2001; Erwin et al., 1997).

4.12. Arrested succession and thermal waters of power plants

Power plants and many other kinds of industries have irregular impacts on their environmental interface that make the ecosystems develop short term responses. Succession to larger components and diversity is arrested in earlier stages. For example, the on and off release of hot waters from power plants at Crystal River, Florida, developed an interface ecosystem displacing normal underwater grass flats with algae and other fast turnover producers and a lower productivity. However, emergy evaluation showed more benefit with the interface ecosystem than with the cooling towers and the impact of their manufacture (Kemp et al., 1977; Odum et al., 1977a).

4.13. Longitudinal succession and the everglades

Whereas succession is the sequence of stages of an ecosystem over time in one place, longitudinal

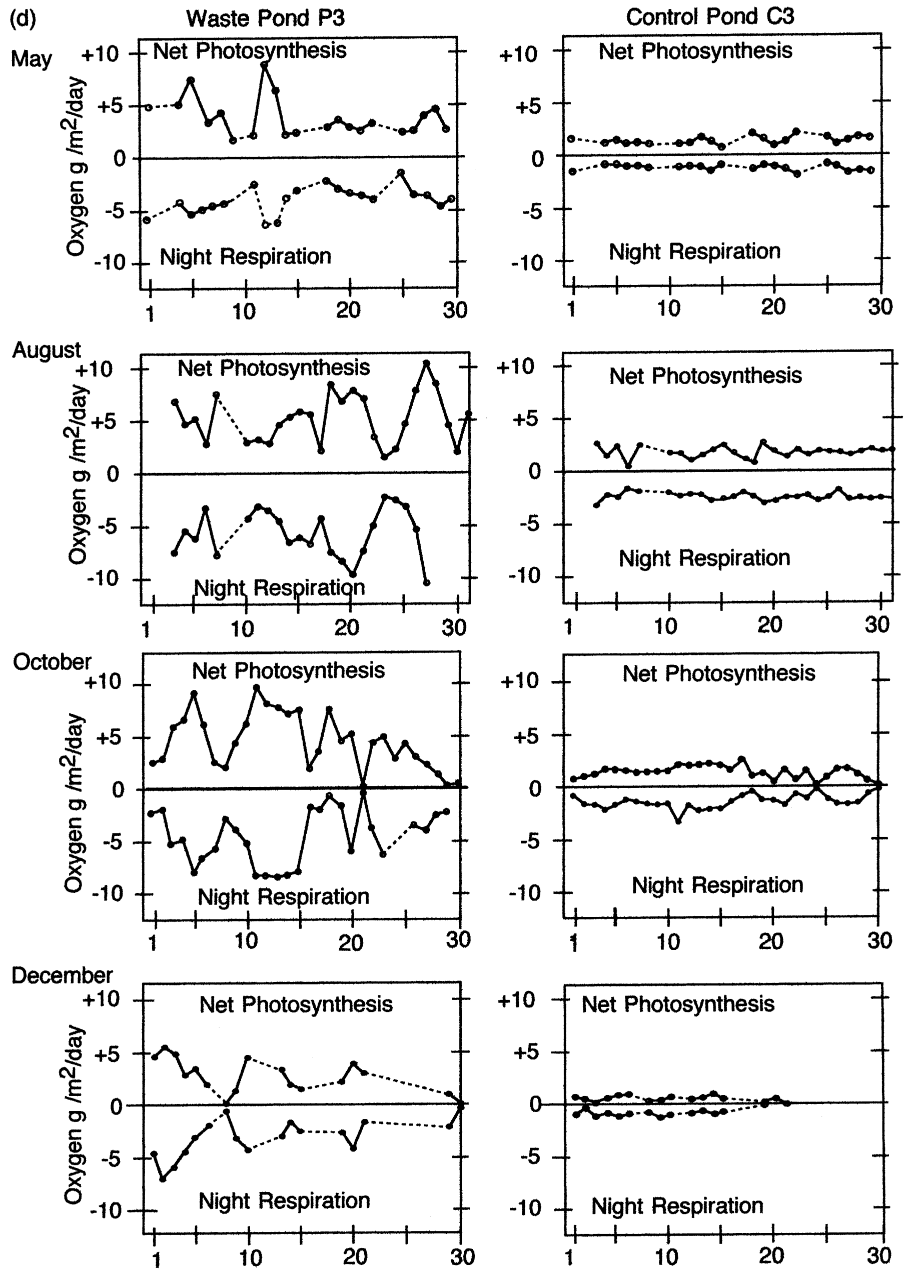

Fig. 10. Annual record of metabolism of estuarine ponds determined from the diurnal variation of dissolved oxygen.

succession is the somewhat similar series of stages that ecosystems develop in space in response to flowing resources. To succeed, projects which interface flowing waters with environment have to work with longitudinal succession, not try to omit or defeat its designs.

For example, in year 2002, some proposals for partial restoration of the Everglades of south Florida plan to retain the high nutrient muckland agriculture while restoring the low nutrient Everglades without the normal eutrophic stage in between to fix and de-

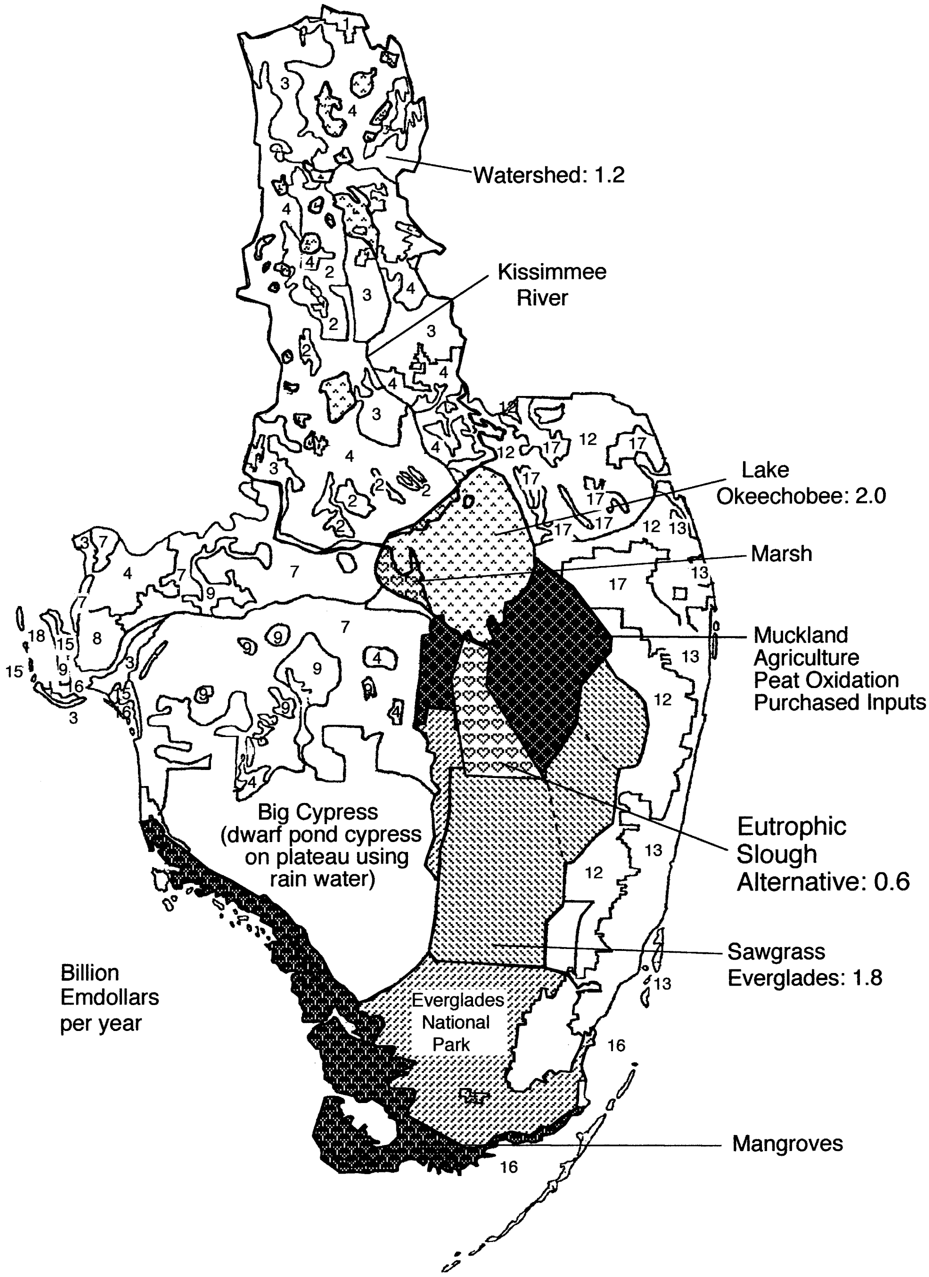

Fig. 11. An improved plan for using self organization of longitudinal succession for restoration of Everglades. Annual contribution of each area is given in emdollars.

posit nutrients as organic matter. Fig. 11 shows the Everglades and its connecting inflows and outflows. Water from the north in the Kissimmee River and smaller streams enters the lake, which discharges to agriculture and urban development. At times, excesses are wasted by pumping east and west into the sea. The restoration is intended to return more water to Everglades and Everglades National Park. Fig. 11

improves the present plan by restoring longitudinal succession with a eutrophic slough just south of Lake Okeechobee. This is sustainable, reduces costs, can accept nutrients from the surrounding agriculture, and generates more emdollars for South Florida. Each of the areas involved in the water flows was evaluated with annual emergy production and use and expressed in Fig. 11 as economic-equivalent emdollars.

4.14. *Water quantity management with wetland vegetation*

Studies in Florida found the vegetation of natural watersheds improving regional productivity by controlling evapotranspiration. Most of the headwaters of the small rivers of Florida originate in wetland plateaus where pond cypress is dominant, mainly receiving rain water (for example, Okefenokee Swamp with the

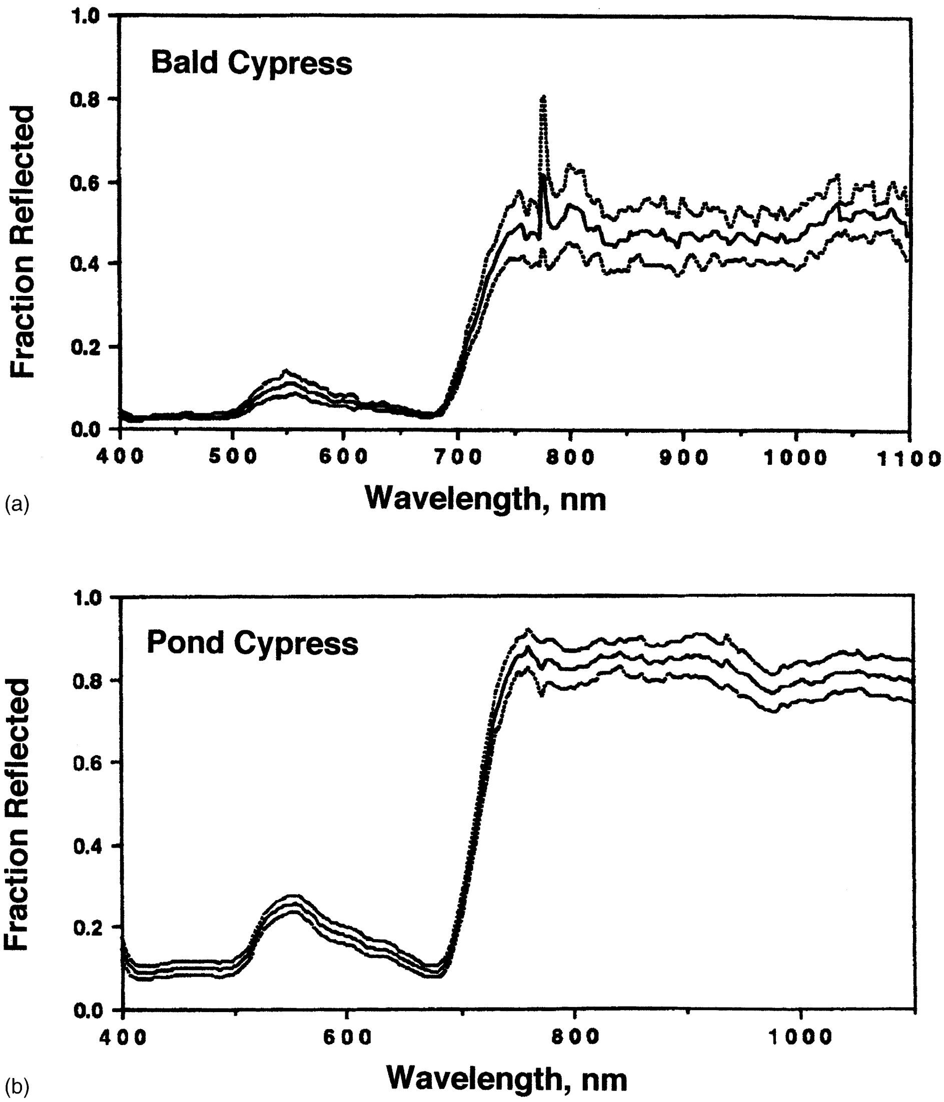

Fig. 12. Spectra of solar energy reflectance of cypress species in Florida, mean graphs with 95% confidence interval. (a) Faster growing bald cypress; and (b) water-saving pond cypress (McClanahan and Odum, 1991).

Suwannee River and the Big Cypress area of South Florida in Fig. 11). Bald cypress is mainly found in strands, stream margins and floodplains, where flowing waters bring nutrients for growth. As illustrated with Fig. 12, pond cypress reflects much of the near infrared solar energy, thus reducing its transpiration. With few nutrients and less transpiration, growth is slow but water is conserved as a headwater source for small rivers. Emergy–emdollar evaluation showed that retaining the peat base of the headwater swamp of the Santa Fe river was much more valuable than mining the peat as a fuel supplement (Odum, 1996a,b).

By controlling the species of wetland vegetation, waters may either be saved for regional productivity downstream, or used to increase forest production upstream. The Australian exotic *Melaleuca* is adapted to maximize transpiration and dries out lands where waters are intermittent. Ecological engineering of its areas needs a commercial use of *Melaleuca*, such as paper manufacture.

4.15. Ecological engineering of alternatives for pulp mill waters

Pulp–paper mills use large quantities of water and release wastewaters full of brown lignin, the peaty substance of tree trunks. Good ecological engineering should conserve and reuse waters, process lignin wastes for beneficial use, and protect open waters from these high concentrations. For example, four alternatives are shown for the pulp mill wastewaters at Perry, Florida, in Fig. 13. Wastes in 2002 pass down the small Fenholloway River that was declared an industrial river 50 years ago. Studies show that the toxicity and shading of the outflow eliminates the fertile seagrasses and their fisheries in that zone. As environmental agencies sought to eliminate wastes from the stream, a plan was considered to pump the wastes to the mouth of the river by pipe, which would make the estuarine impact worse. The Center for Wetlands at Florida proposed two better alternatives (Odum and Brown, 1997): One was to send waters to the coast in

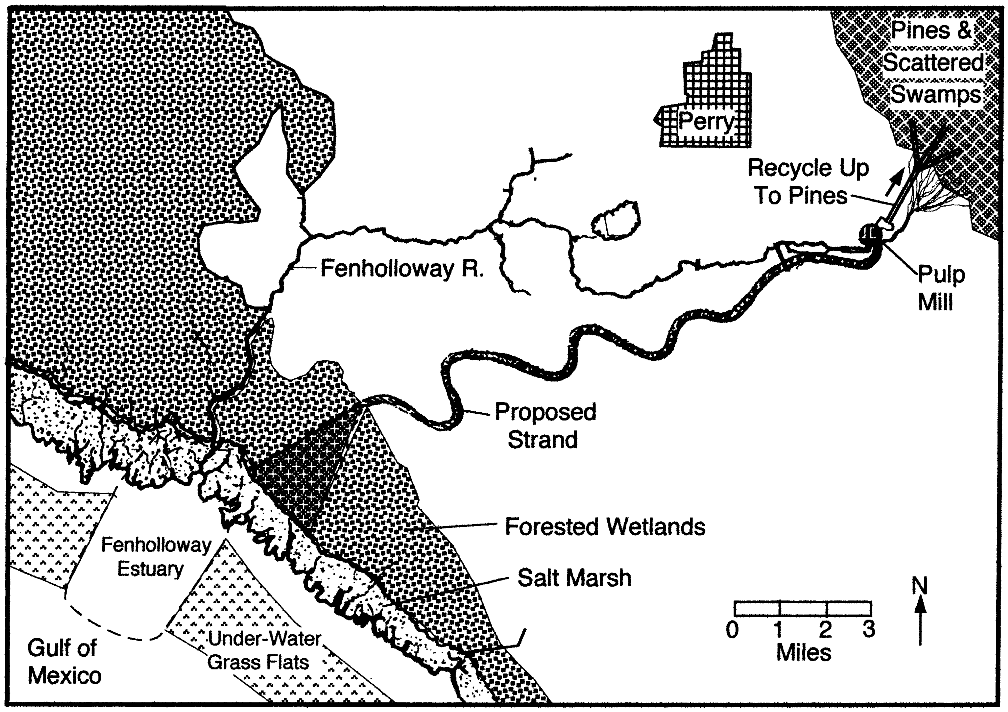

Fig. 13. Alternatives for pulp–paper mill interfaces with environment in the Fenholloway River watershed of Perry, Florida.

a strand (shallow slough full of wetland vegetation). The second was to pump the waters back into the small wetlands among the pines from which the trees were harvested. In both of these alternatives, waters would be filtered by wetlands and recharge groundwaters for further use. Wastewater lignin would mix with normal peat. Emergy–emdollar evaluation showed great economic advantages of these alternatives to the public, and in the long run to the industry.

4.16. Use of exotics

Nature's way of self organizing to new situations is to allow adapted species that are part of its gene pool to replace dominants not adapted to new conditions. Sometimes the species that become dominant are already present as minor constituents, and sometimes they come from other areas, in other words as exotics.

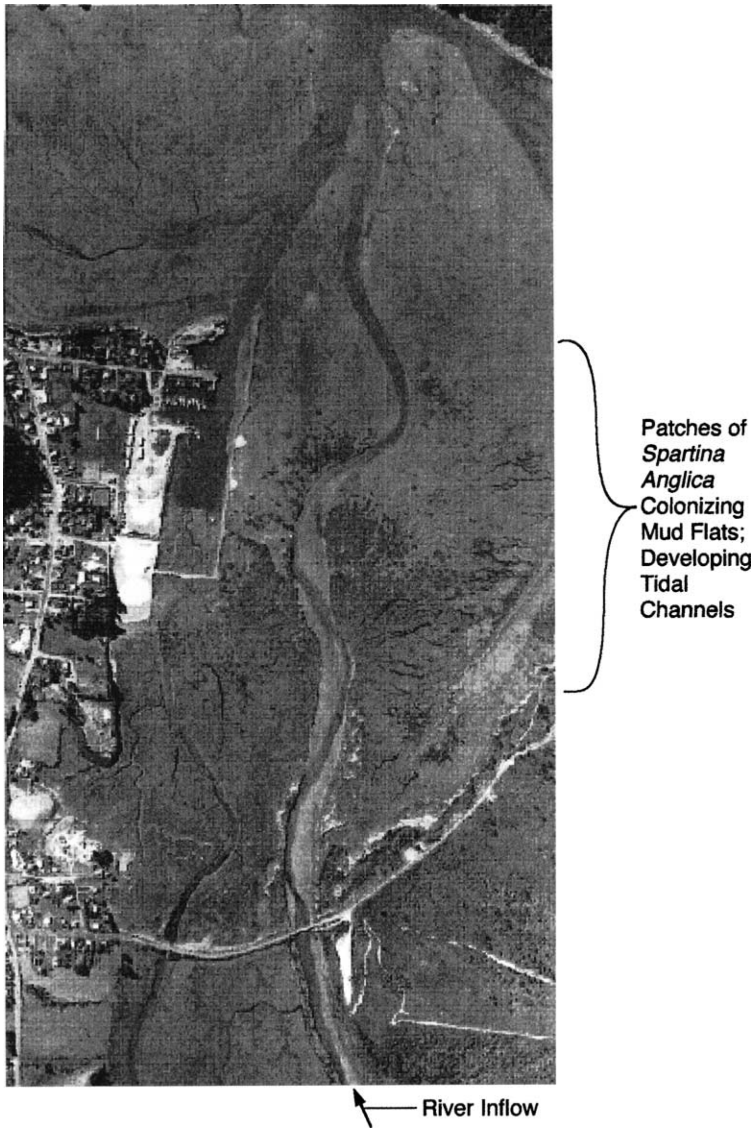

Fig. 14. Example of ecological engineering with exotics, the self organization of *Spartina anglica* colonizing mud flats in New Zealand.

Using exotics is controversial. Many organismic-oriented scientists think of exotics as the cause of ecosystem change, rather than as nature's appropriate response to new conditions. In continental areas of the world with large gene pools and without changed conditions, adding an exotic usually enriches its gene pool without much effect.

However, when the new situation has excess resources, there is low diversity overgrowth by the exotic. The energy corollary 4 (above) explains why attempts to remove such exotics are futile as long as there are inputs of excess resources. With new exotic plants, its normal animal and microbial associates and control agents may be missing. Consequently, the vegetation may be monolithic, and typical sequences of succession absent. In time, the system improves when controlling organisms are introduced or when complexity is developed with other self organization.

However, on isolated islands like Hawaii, only a few species were introduced over thousands of years before the development of the global economy. Consequently, these few species evolved as generalists able to occupy the many habitats, but not specialized for any one. Introducing more specialized mainland species to these islands displaces the native generalists, causing many extinctions. Costly efforts are required to preserve the original species in reserves in which exotics are removed as fast as they come in.

After multiple seeding of new situations, ecological engineering of interfaces will often find exotics dominant and useful in the cooperating ecosystems. However, ecological engineers should be legal, play safe, and avoid controversial publicity, by never importing exotics from another area.

4.17. *Mud flat colonizing by exotic Spartina anglica*

In temperate latitudes all over the world, the salt–marsh grass *Spartina anglica* is colonizing the areas of bare mud-flats. Fig. 14 shows the spread of the exotic grass at Havelock, New Zealand. Our studies there showed much increased productivity, increased nursery role for fishes and marsh birds, but a loss of habitat for sandpipers and shore birds (Knox et al., 2002; Odum et al., 1983). It fits the principle of self organization for maximum productivity. But why did not the earth spread or evolve better adapted plants in millions of years of ecosystem evolution earlier? The much feared role of global transportation and trade spreading exotics may actually be one of humanity's beneficial contributions by increasing the empower of the earth.

In western United States and New Zealand, the *Spartina anglica* invasion is regarded as bad, and efforts are made to kill the plants, but colonization is welcomed for its productivity and coastal protection in China. It is used to pasture horses in Wales.

Spartina anglica and the east coast *Spartina alterniflora* are both exotics on the west coast (California, Oregon, and Washington), the subject of the Washington Sea Grant program (Aberle, 1990)

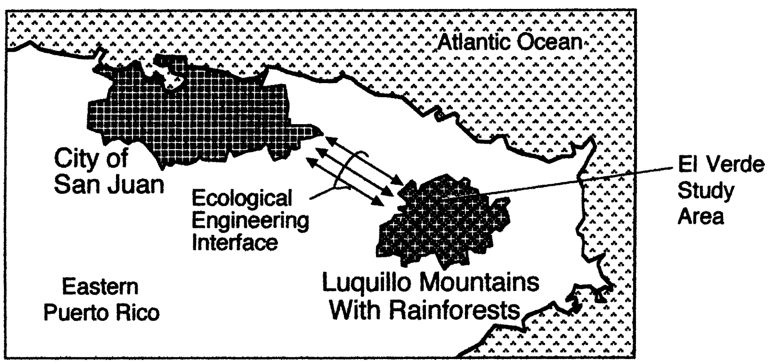

Fig. 15. Example of large scale ecological engineering, the coupling of the urban center of San Juan, Puerto Rico, with Luquillo Mountain Rainforests, a geobiological center.

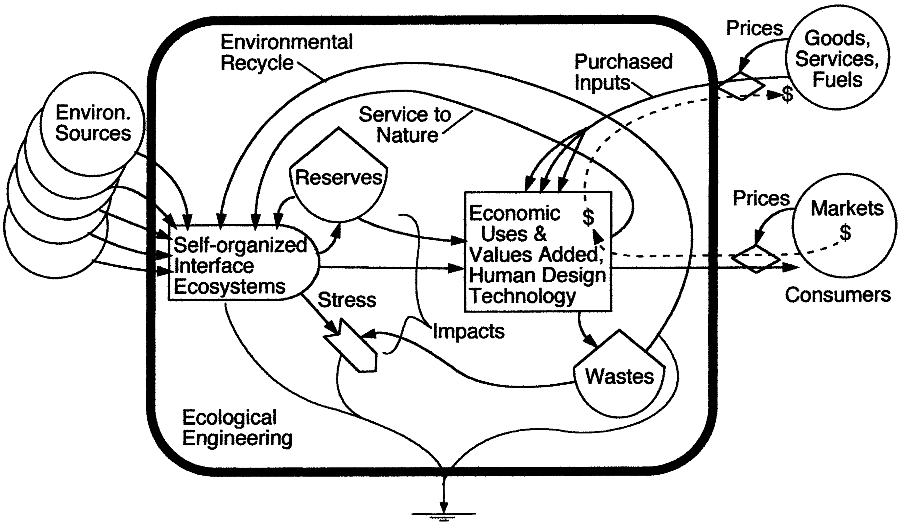

Fig. 16. Energy systems summary of ecological engineering interface of technology and ecosystems given at an ecological engineering workshop at the National Academy of Science.

4.18. Ecological engineering of biodiversity

Interface ecosystems can be managed for maximum biodiversity by eliminating excess resources, multiple seeding, and managing succession, as explained in corollary 5 above. New systems sometimes favor endangered species. For example, the pattern of golf courses and interfacing cypress swamps used as roughs at Naples, Florida, were populated by fox squirrels that were previously endangered in that region.

4.19. Interface of urban-environmental centers in Puerto Rico

The energy theory of hierarchical centers given earlier explains the self organization of human settlements in cities and the self organization of geological processes in mountain centers. Ecological engineering theory predicts the symbiotic coupling of energy concentrations of one scale with those of another. In eastern Puerto Rico, the intense concentration of empower and transformity in San Juan is only a few miles from the concentration of empower and high transformity in the Luquillo mountains (1333 m high) (Fig. 15). Many connections are emerging between these two centers including tourism, recreational living in second homes in the mountains, diversion of rainforest streams to the city, the spread of species adapting to human settlements, and the laws protecting the rainforest. This is large scale ecological engineering. Emergy evaluation can help select choices that maximize empower. For example, evaluation of six reforestation alterna-

Table 1
Ecological engineering techniques

Maximize diversity and complexity by multiple seeding.
To channel energy, reduce diversity by supplying excess raw materials or stress requiring physiological adaptation.
Include legal exotics in multiple seeding for self organization.
Match environment and technology so that there are reinforcing loops.
Plan for longitudinal succession in flowing water environments.
Return used groundwaters through wetlands to the ground.
Manage whole cycles of materials.
Control chemical ratios of inputs to control species associations.
Use mesocosms to anticipate large scale self organization.
Manage regional water with vegetation selected for reflectance.
Select alternatives with higher empower contributions.
Evaluate stored quantities with emergy and emdollars.
Place units and functions in the spatial hierarchy according to the appropriate empower density or transformity.
Estimate impacts from transformity.
Include purchased inputs according to the regional investment ratio.
Mitigate with emdollars.
Use transformities to scale results in microcosms to the larger scale.
Provide incentives for environmental management based on emdollar contributions.

tives showed the advantages of natural succession near old forests and exotic reforestation elsewhere (Odum et al., 2000a,b).

5. Summary

This introduction defined ecological engineering, stated energy principles that guide the self-organizing design of interface ecosystems, and suggests practical techniques with examples. Fig. 16 summarizes the interface of technology and ecosystems and the main pathways that interact to increase performance. Emergy, transformity, and emdollars are useful measures for evaluating the best alternatives. Some ecological engineering techniques are summarized in Table 1.

Acknowledgements

These comments introduced the first meeting of the American Ecological Engineering Society in Athens, Georgia, in April, 2001. Illustrations are from a book manuscript Environment Power and Society, second edition.

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