Energy Analysis and the Coupling of Man and Estuaries

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ABSTRACT / New concepts and insights concerning human and natural systems in the coastal zone are emerging from recent energy analysis and synthesis studies. By using new concepts for measuring the quality of energy, one can express the work of ecosystems and human economies in equivalent terms. From energy models and new energy quality evaluations, one can learn what kinds of coastal systems maximize power, are competitive, economically vital, and likely to have a survival advantage.

Energy analysis and synthesis is aided by energy circuit diagrams. Models of the coastal zone that emphasize the change in external driving functions related to world energy sources provide insights and some predictive abilities that are not found in economic studies, since money flows alone do not evaluate external driving energies. This paper suggests four procedures for coastal planning: 1) calculation of investment ratio in units of equal quality to determine which projects are economic in a broad sense, 2) development of energy signatures for coastal ecosystems, 3) determination of which interface ecosystems develop the best energy flows, and 4) development of regional models that include the main features of human and natural ecosystems.

Energy Quality Evaluations and the Investment Ratio

In this section, we discuss the theoretical concepts of energy quality and the investment ratio and give examples and case studies of energy quality calculations.

Energy quality theory provides a useful empirical way of tracking hidden energy contributions in complex webs. It is the principle that allows the flow of energy to be used to estimate ability to do work. Physics courses are often started with the statement that energy measures the ability to do work. If one compares energies of the same type, this is true; but if one compares energies of different types, Calories of heat equivalents do not measure ability to do work. Calories of dispersed, degraded heat cannot do any work. Confusion over the relative abilities of sunlight, coal, wind, water, and other energy sources to do work is clarified by expressing them all in equivalents of the same quality, such as coal equivalents (Kcal_{CE}) or fossil fuel equivalents (Kcal_{FFE}), which are used in this paper (Odum and Odum, 1976).

The flow of energy in chains of increasing quality is shown in Figure 1. Low quality energy in the form of sunlight, shown on the left, is transformed and concentrated through successive stages to high quality energy on the right. In this process of upgrading (where energy flows are from only one kind of low quality source) some energy is degraded and dispersed in unusable form. The energy so dispersed measures the work of upgrading if the system has been under competition and selection for effective conversion and elimination of waste. It takes many Calories of dilute energy to form one Calorie of concentrated energy, such as fossil fuel or electricity, which is required for complex work. If competition has produced the most effective conversion possible, the work of upgrading measures the increased cost of such conversion. An example is the conversion of coal to electricity, during which 3.6 Calories of coal are required, directly or indirectly through goods and services, to generate 1 Calorie of electricity. For its energy cost to be justified as a contribution to a system's maximum power, upgraded energy must interact with other parts of the energy network to stimulate at least as much energy income as the energy used in the conversion. High quality energy that does not interact to amplify low quality energy is wasted.

Figure 2a shows a generalized scheme of interaction and energy conversion, where I, the free outside energy flow, is amplified by the feedback loop F to give gross output P. The figure also gives definitions of net energy N and other ratios that characterize the energy conversion process (Odum, 1976).

KEY WORDS: Energy analysis, Estuaries, Coastal ecosystems, Energy quality evaluation, Florida regional studies, Energy models, Coupling, Environmental impact analysis

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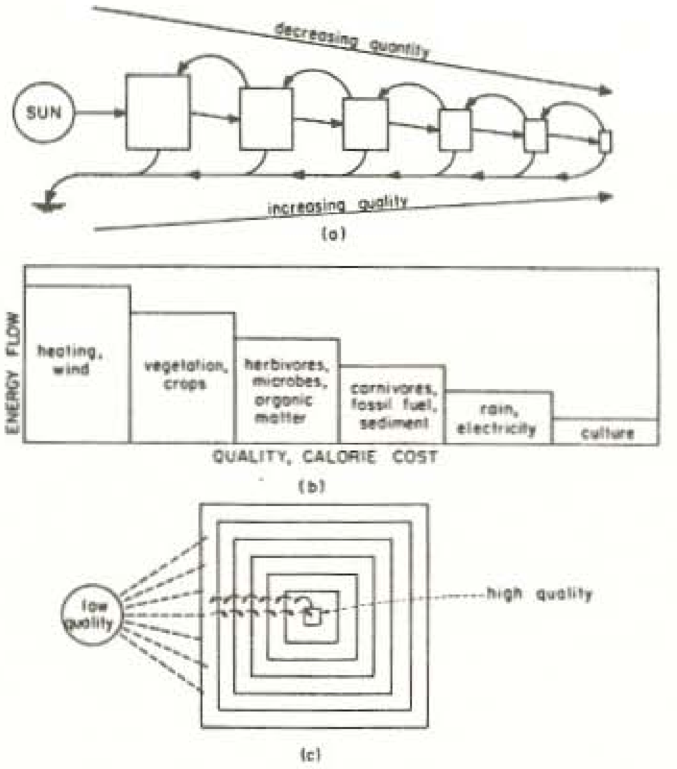


Fig. 1. Characteristic energy chains resulting from maximum power where energy is primarily from one source of low quality. (a) energy transformations; (b) power spectrum in heat equivalents; (c) areal view of energy chains where incoming energy is dilute dispersed low quality sunlight.

Examples of Energy Quality Evaluations

Tidal Energy. To observe the orders of magnitude for different energy flows, we have estimated in Figure 2b the costs of conversion for tidal energy at La Rance, France, where a 20-foot tide drives an electric power plant. Heat equivalents of energy flows are calculated first, including those used elsewhere in the economy to generate purchased goods and services. Purchased goods and services are expressed in coal equivalent Calories (Kcal_{CE}) and were estimated by converting their dollar costs into Calories at a rate of 25,000 Calories per dollar. Electricity is converted to Kcal_{CE} at a rate of 3.6 to 1.

Net energy was estimated by subtracting feedback of purchased goods and services from electrical output where both are in coal equivalents, or fossil fuel equivalents (FFEs). Net output, compared with Calories of tidal energy input, expresses the energy cost of converting 1

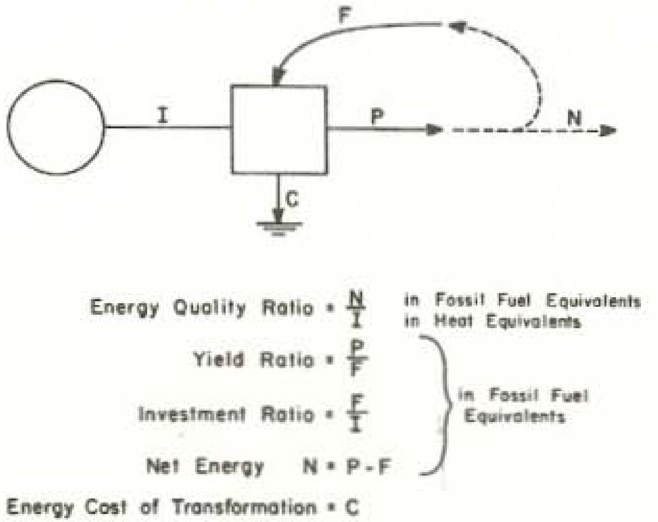


Fig. 2a. Energy diagram defining energy quality ratio, investment ratio, net energy, and yield ratio.

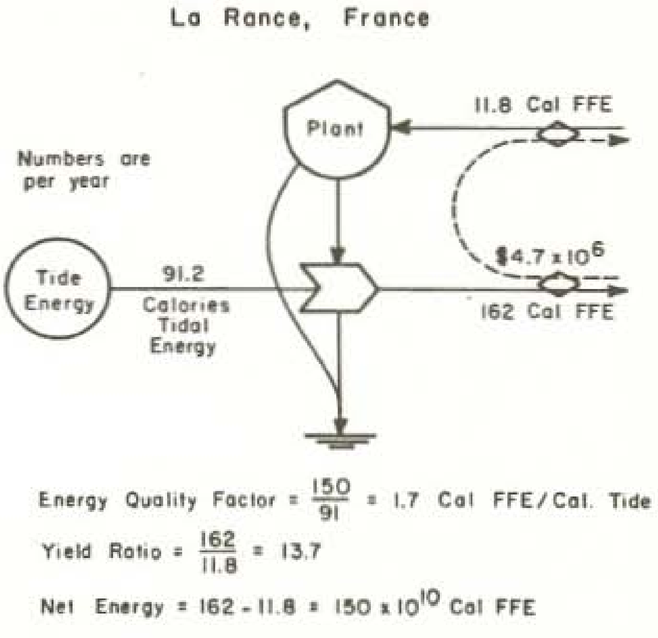


Fig. 2b. Energy flows in converting tidal energy at La Rance, France, to electric power with conversion of energy flows to fossil fuel equivalents (FFE) for calculation of net energy, investment ratio, and yield ratio. FFE is roughly interchangeable with coal equivalent (CE).

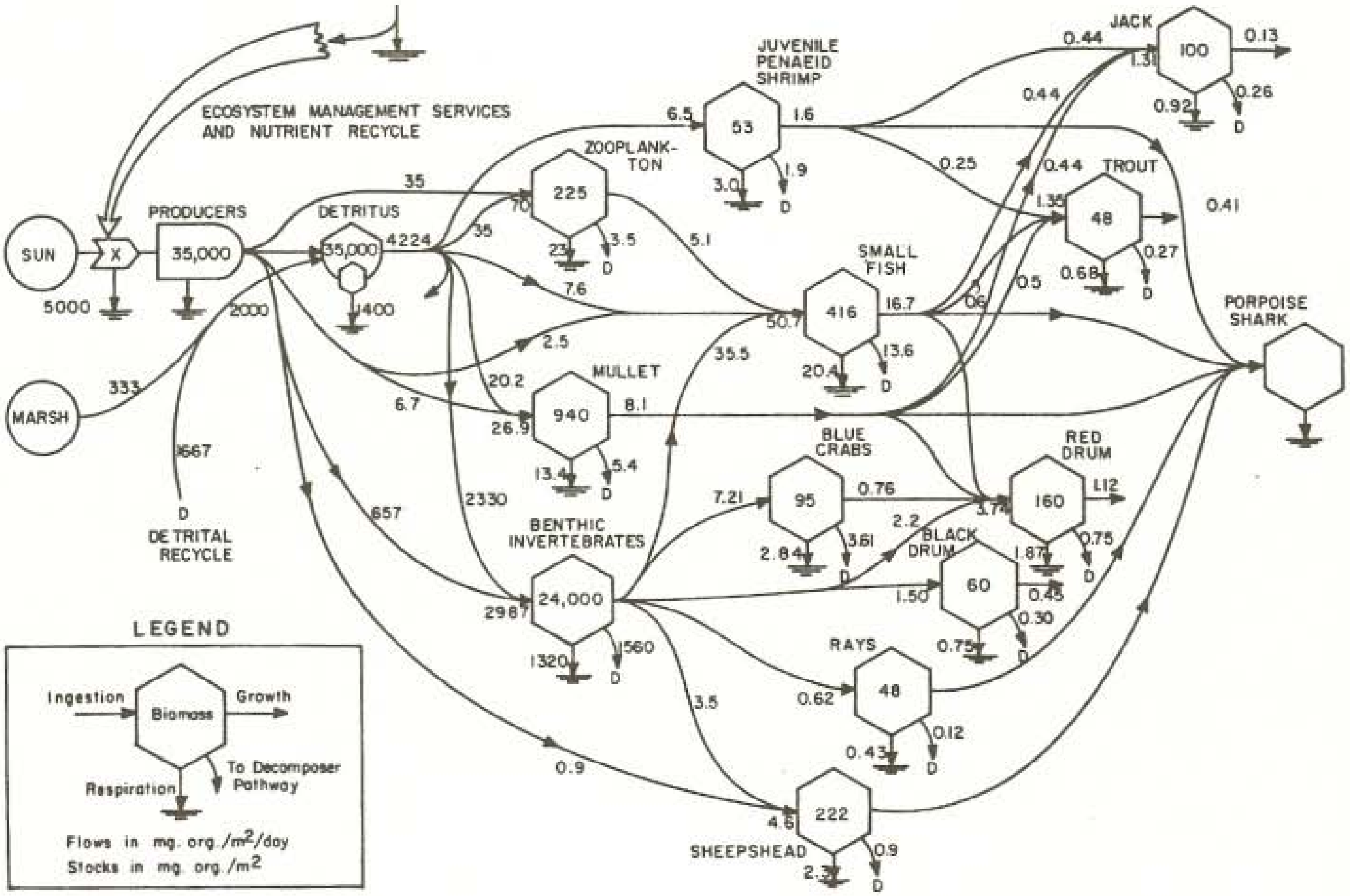


Fig. 3. Energy flows for the estuary at Crystal River, Florida, for estimating the energy quality of stages in marine food chains.

Calorie of tidal energy to 1 Calorie CE. The ratio of 1.7 Calories CE generated for each Calorie of tidal energy gained is the energy quality factor. Tidal energy of this height is higher quality than coal but not as high as hydroelectric power based on a continuous river head where the energy quality factor is 0.3.

Marine Food Chains. The webs and food chains of ecosystems are energy chains and may be evaluated for their energy conversion costs and energy quality. Given in Figure 3 are estimates of energy flow in food chains of the shallow estuary at Crystal River, Florida (Kemp, et al., 1975). The energy quality values represented by energy flows in the figure place algal biomass with wood, detritus and herbivores with coal, and carnivores with electricity. In Figure 4 is the energy chain for a blue-green algal mat ecosystem that generates an electrical output directly (Armstrong and Odum, 1963). Here the conversion of sunlight is similar to that calculated in Table 1.

Fig. 4. Energy flow and transformation in blue-green algal mat ecosystem from Armstrong and Odum (1963).

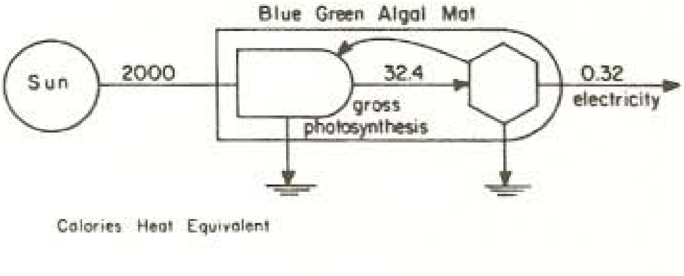


Table 1 Energy quality ratios used in this study

Energy Type	Coal Equivalents* (Kcal coal per Kcal)	Quality** Factor
Sunlight	5×10^{-4}	2000
Sugar of gross production still distributed over an acre	0.05	20
Wood still distributed over land	0.5	2
Winds, 10 mph	0.13	7.7
Tides, 20 ft	0.60	1.7
Waves	0.20	5.0
Water elevation potential	3	0.3
Water chemical potential	3	0.3
Electricity	3.6	0.28
Dollar flow, 1973	25,000	4×10^{-5}

*Fossil fuel mined and stored at place of use

**Reciprocal of coal equivalence factor

Young and Odum, 1974

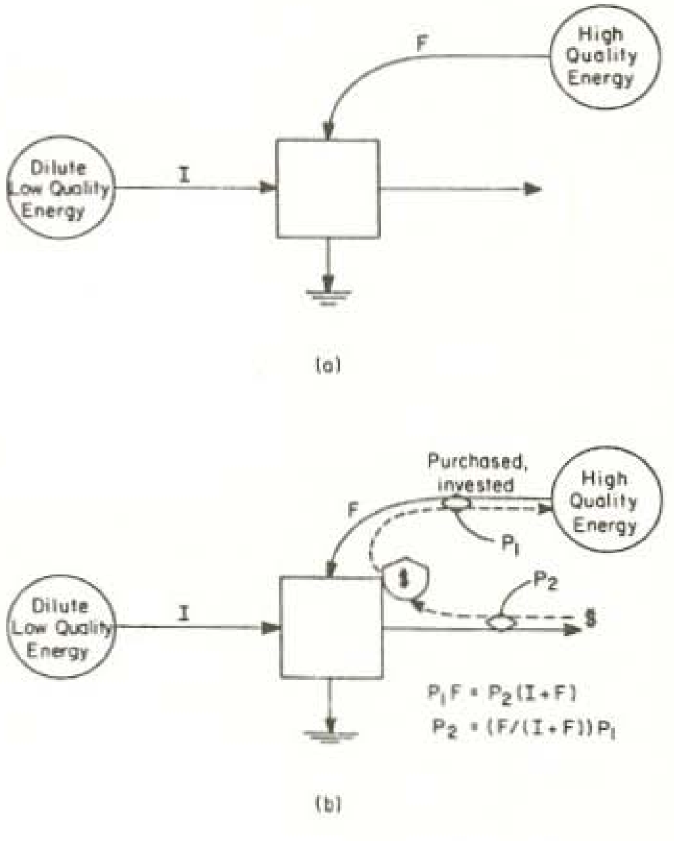
Energy quality evaluations of food chains can be used in judging the value of various organisms that are harvested or otherwise affected. Theoretically, organisms with higher energy costs are somewhere providing the system with greater energy services in return. Table 1 gives representative values of energy equivalents. In the left column, various energy types are expressed as coal equivalents (CE); that is, by the number of Calories CE per heat Calorie. The right-hand column of Table 1 shows the heat Calories needed to make 1 CE Calorie. This measure of energy replacement cost is called the energy quality factor. The energy quality factors are a measure of energy replacement cost and are postulated to be a measure of ability to contribute useful work to systems.

Principle of High Quality–Low Quality Interaction

According to the principle of maximum power (Odum and Pinkerton, 1955), systems that develop structures to interact high quality energy with low quality energy utilize the high quality to amplify the low quality flows so that more work is done by both. The point is made by sketches in Figure 5 for two flows.

There are important corollaries of this theory. If maximum power requires high and low quality energy interaction, either one can be limiting to the other. When there is only low quality energy it develops a chain of energy transformations that generates some high quality energy that can feed back as shown in the general energy chain of Figure 1a. Although energy quality factors for classes of energy flow are given in Table 1, the exact values may vary depending on the concentrations of energy that are interacting. The more limiting a flow, the higher the energy quality factor it has in any particular interaction such as the one shown in Figure 5. All the flows have the energy quality value of the common output since each is equally essential.

Fig. 5. The property of low quality energy attracting high quality energy for maximum work of both. (a) energy amplification in a system without money; (b) energy investment in a system where money is involved with the high quality energy.



Investment Ratio

The principle that high quality energy needs low quality energy to amplify it in order to generate maximum work potential takes a special form in the coupling of man's economic system to the free work of nature based on dilute solar energy. In Figure 5, high quality energy F is purchased at price P_1, and it interacts with free energy inflow I. Notice that money circulates as a countercurrent. Purchases and sales involve humans but do not pay for natural external inputs. Money income is obtained from the output sales of goods and services, and the price P_2 has to be adjusted so that income, in the long run, at least, equals expenditures. For growth, income needs to exceed money costs of the purchased inflows.

The system that has more free energy to match and interact with purchased energy generates more work and can sell its products at a lower price. In the price expression shown, the flows I and F should be expressed in units of the same energy quality. The larger I is the lower the price, P_2, and the more the system captures the market in competition with producers having smaller, natural free flows I. The investment ratio is defined as F/I, when both are in the same energy quality units.

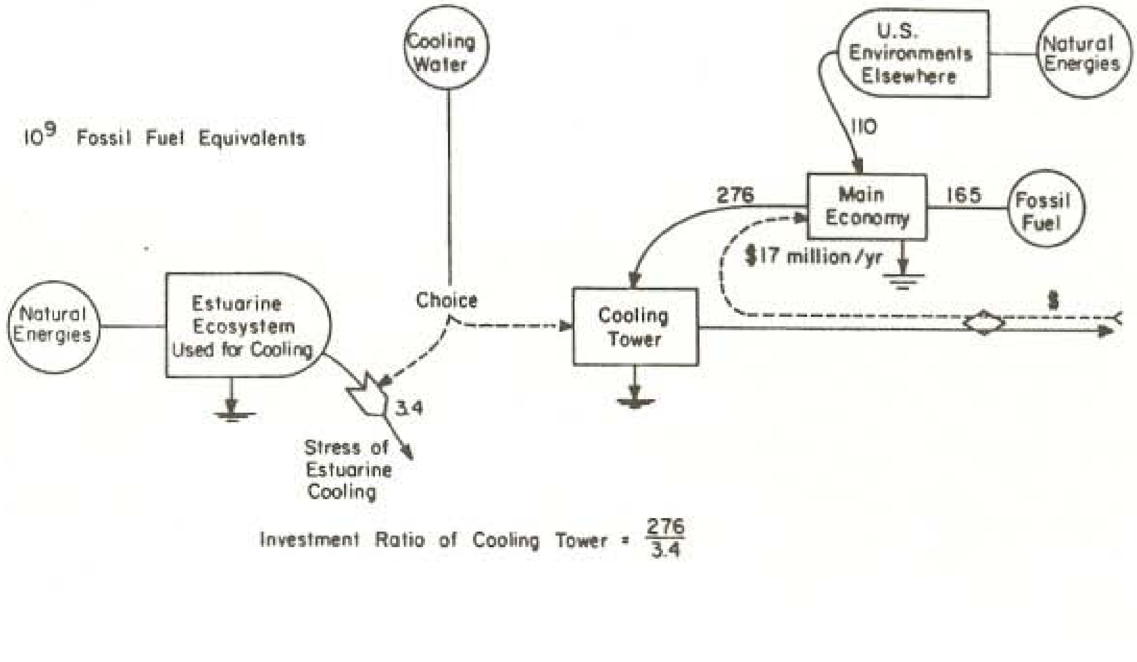
In the United States the ratio of high quality purchased energy to natural energy is roughly 2.5 to 1 (F/I). Investments of purchased energy at a higher ratio may be expected to be less competitive. The ratio is changing, however, and some high quality energy systems that are economic today will become less so in the future. The world-wide average is only 0.3 to 1. Low values such as these indicate underdevelopment, and may attract additional investment energy.

Energetic Viability of Environmental Projects

The investment ratio method distinguishes between projects that are economic and those that are not. Traditional monetary cost-benefit analysis makes a partial distinction but does not evaluate the matching of purchased with natural energy sources. Expenditures that do not maximize the match of energies to the system using the environment and purchased energy inputs well do not compete and will fail economically. Consequently, much well-meaning environmental technology may turn out to be energy-intensive and a poor expenditure of the conservation dollar. The investment ratio method was used to compare alternative design strategies in several studies, the main points of which are presented next.

Cooling of Thermal Discharges of Power Plant. The investment ratio principle was used to evaluate water cooling alternatives and impacts on the estuarine environment at Crystal River, Florida. After 6 years of regular operation, the productivity of some 160 acres of the estuary had been decreased by about 50 percent due to its

Fig. 6. Interaction of estuarine cooling with thermal effluent and the alternative of a cooling tower. Data from Crystal River, Fla. (Odum et al., 1975).



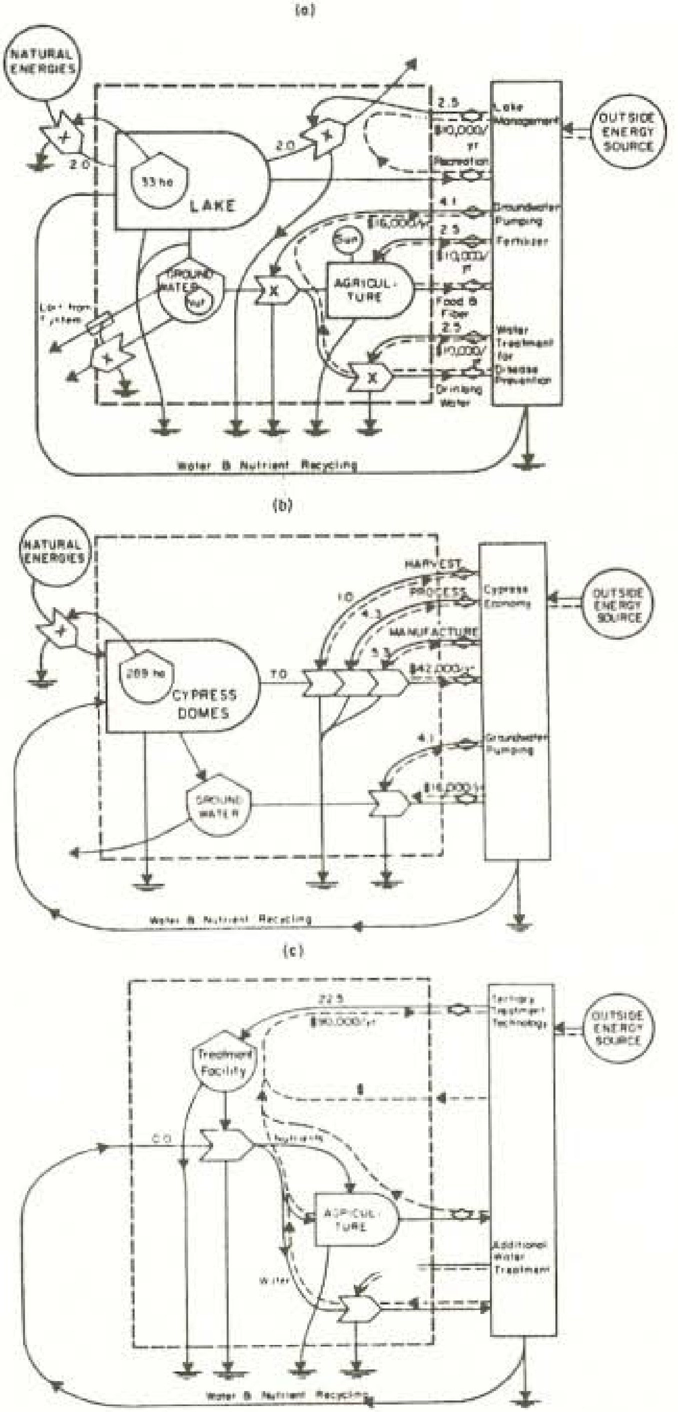


Fig. 7. Use of invested high quality energies for tertiary waste treatment in interaction with environment (Mitsch, 1975). (a) in eutrophic lake followed by groundwater injection, (b) in cypress swamp; (c) by technology only. Note that in (c) no investment ratio could be calculated because there was no matching with natural energies.

receiving discharge water from a once-through cooling system. The energy impact of this loss, in fossil fuel equivalents, was compared with the energy required for cooling towers, which would cost an estimated $17 million per year (Fig. 6). The energy needed to eliminate the power plant impact was vastly greater (100 to 1) than the energy loss through impaired productivity at the power plant site (Smith, 1976; McKellar, 1975).

In making this estimate, we assumed 25,000 Calories of energy for each dollar. Forty percent of the 25,000 Calories is taken to be the hidden, free contribution to the U. S. economy of solar-based natural inputs. At Crystal River, Florida, the load of the cooling tower on the environment elsewhere was greater than the local estuarine impact.

Waste Treatment and Natural Recycling. Figure 7 from Mitsch (1975) shows energy analyses of treated sewage waste processing. The investment ratio method was used to compare three alternatives: a) disposal in a lake followed by ground water injection (Fig. 7a), b) disposal in experimental cypress swamps (Fig. 7b), and c) tertiary treatment by technological means (Fig. 7c). Tertiary treatment, with almost no work done by the environment, proved too great an expenditure of fossil fuels, directly and indirectly, to be economic.

Coastal Fishery. The stepwise addition of energy investments is illustrated in Figure 8 by an analysis of oyster sales from Franklin County, Florida (Boynton, 1975). The figure shows energy added as oysters which are grown, caught, processed, upgraded in packaging and availability, and finally served as food. The investment ratio is 2.1 to 1, considering all flows, which is not far from 2.5 to 1, which is the national average. Much of the energy is added outside Franklin County. As energy becomes less available, high quality packaging will be less common, and fishery products will be used more often locally, with less preparation. Using the investment ratio one could *predict* that some aquaculture propositions that have very high ratios of purchased to natural energy will be uneconomic, before the bad match is found the hard way.

Housing Density in Coastal Areas. The investment ratio has also been used to evaluate housing developments in the coastal zone. High housing densities involve large quantities of purchased fossil fuel energy with less matching of the free environment in the hidden work of vegetation, wind, waters, soils, recreation potentials, scenic beauty, noise abatement, waste absorption, ground water supplies and the like. Calculations by Stellar (1975) and Boynton (1975) for housing developments in Florida showed that proposed plans were

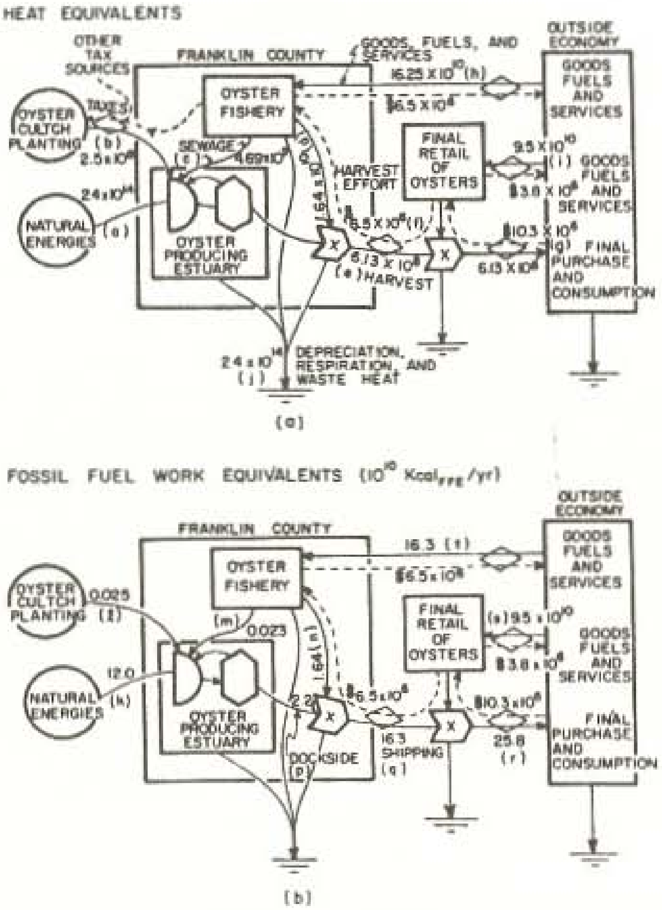


Fig. 8. Interaction of fishery products with fossil fuel based energies of high quality attracted, purchased, and invested by the free natural product (Boynton, 1975). (a) heat equivalent units, (b) fossil fuel equivalents with investment ratio.

satisfactory only if buildings were dispersed so that the overall investment ratio was kept reasonable. The full, proposed development of condominiums and the accompanying population density would have had very high investment ratios.

Feedback Reward Loop to Natural Systems

Odum (1967) has discussed the principle that any system of nature must, in order to remain competitive, feed back energy to its source system in amounts at least equal to that drained away. This concept is shown in the loop pathway in Figure 9. In exploiting wild fisheries, man has harvested species without making this feedback. There have been exceptions such as oyster leases, artificial reefs, and nursery flats. But we have operated generally on theories of optimum catch based on population considerations alone and have ignored the supporting system, as if the energy base was not subject to diversion.

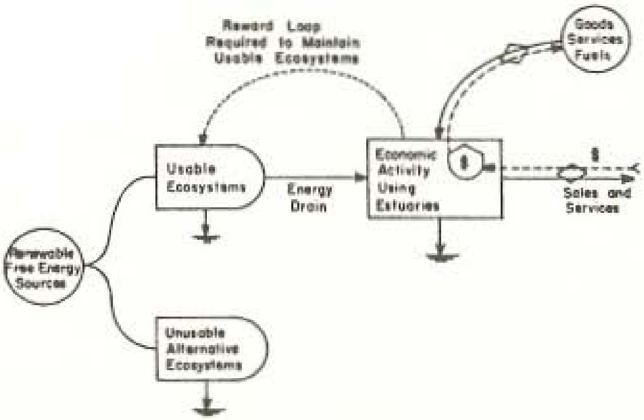


Fig. 9. Reward loop coupling of man's uses to estuarine stimulus.

It is difficult to find ways to stimulate feedback. In agriculture and forestry, feedbacks for wildlife have been developed. In estuaries, however, large size, public control of the water, invisibility of stocks, and difficulty of stocking have worked against this. Little wonder, then, that so many fisheries have been reduced, the energies going into other pathways.

Overall, the growth of coastal populations has resulted in the feedback to estuaries of the wastes of civilization. These wastes have energy value, but they cause energy stress as well. To whatever extent waste feedback to the sea is a reward loop for some species, we may expect those food chains to be sustained. We still have the challenge of finding better feedback rewards for the pathways of marine harvest.

Energy Signature for Biotope Measurement

A useful graph for energy analysis is a bar graph of the energy flows, as suggested in Figure 10. First the regular heat equivalent units can be used to show the flow in each source, including energy flows interacting from internal storages (Fig. 10b).

Next energy quality factors are divided into the heat equivalents to convert them to fossil fuel equivalents (Fig. 10c). By expressing these in units of the same quality, their relative energy cost is compared. The theory is that comparisons in units of equal quality show their relative value in generating work and controlling the system. In the example in Figure 4, sunlight seems pre-

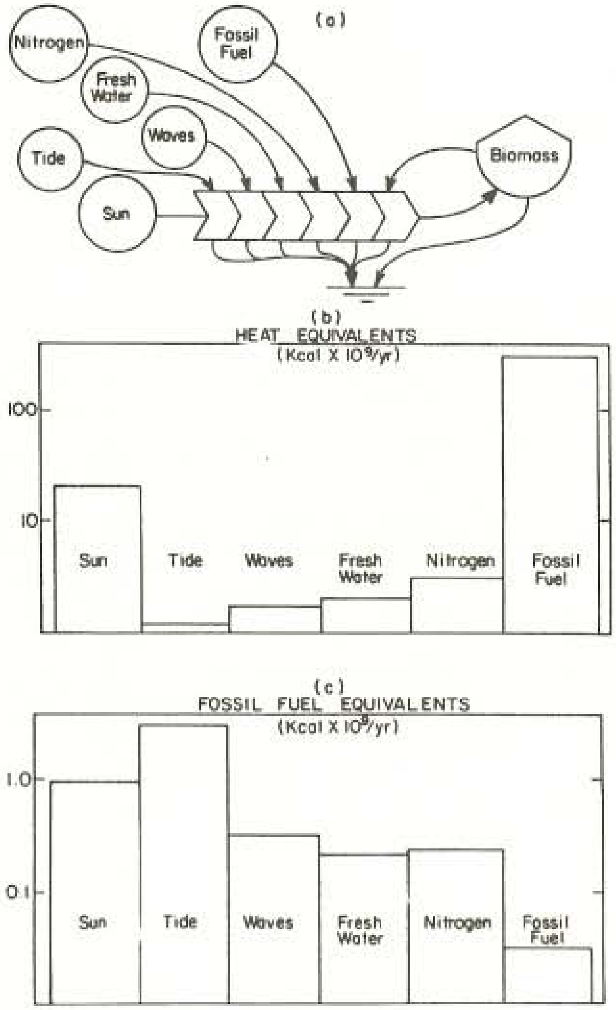


Fig. 10 (a) Energy signature, (b) heat equivalents, (c) fossil fuel equivalents.

dominant until it is put on equal quality basis, and then it is less important.

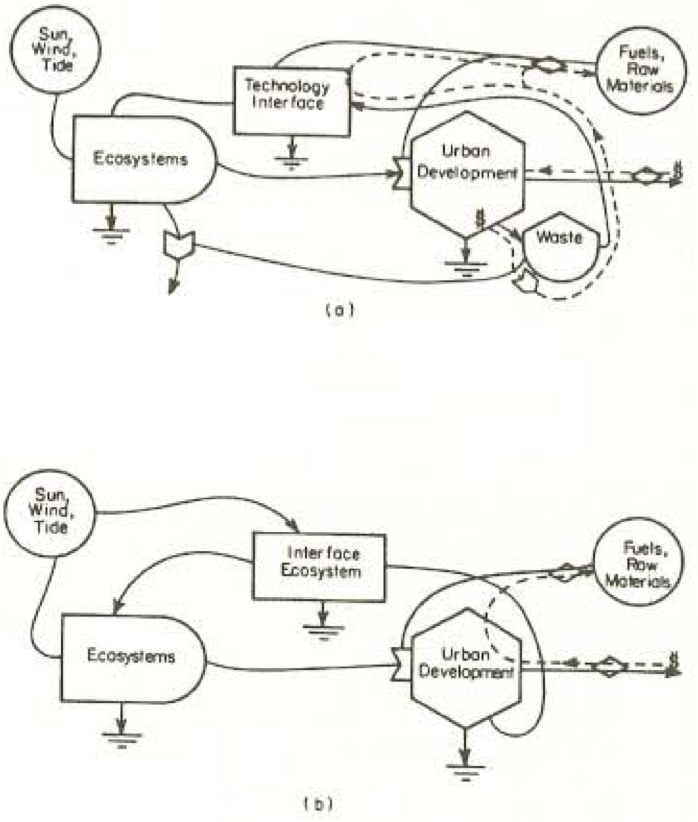
Developing energy signatures of environments and of characteristic systems should help with a very old general ecological objective (predicting ecosystems that result from known environmental factors). This group of environmental factors has sometimes been called the biotope.

Interface Ecosystems

Between human activities and the natural world of the estuary, new ecological systems often develop because of special interactions. The recycling of wastes puts stress upon many components of estuarine ecosystems, but other species adapt themselves to the new conditions by developing through trial and error the reward loops that generate new varieties of ecosystems. These we call *interface* ecosystems. They have grown up in environments affected by sewage, thermal effluents, pulp liquors, and other wastes.

As a principle in coastal management, we suggest the recognition and domestication of interface ecosystems as a way to reduce environmental impact and save money. An effort was made to identify and categorize interface ecosystems in a survey of U. S. estuaries made in 1968 (Odum, Copeland, and MacMahan, 1974). Since then, we and others have attempted to domesticate some of them so they could be used to good advantage. At the very least, nature's self-designs should be recognized as useful entities; they can also be adapted consciously and explicitly to serve the purposes of environmental management. Figure 11 is a generalized scheme of the interface function. Some specific examples are given next.

Fig. 11. Interface systems. (a) technological interface, (b) interface ecosystems.



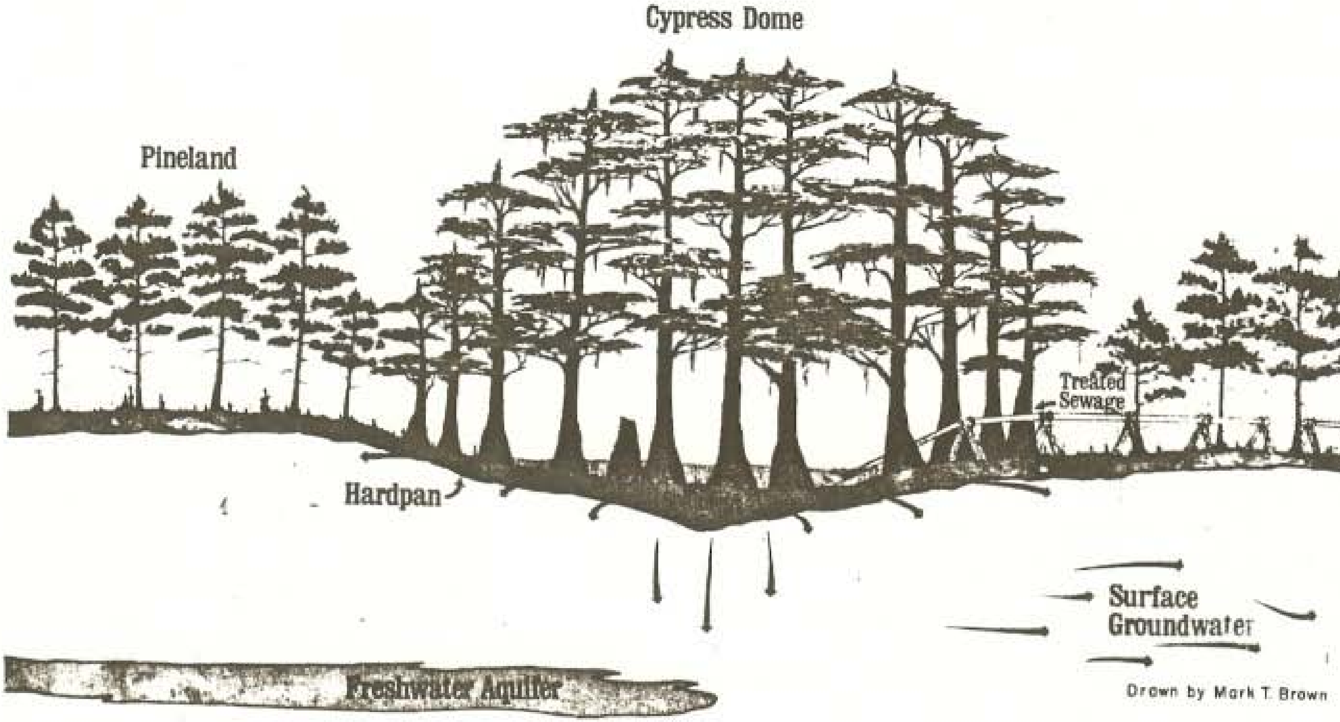


Fig. 12. Recycling treated sewage wastes into cypress dome in project at Gainesville, Florida (Rockefeller Foundation and National Science Foundation—RANN Division).

Treated Sewage in Marshes and Cypress Swamp Interface Systems

Evidence that salt marshes operate satisfactorily and with higher productivity under treated sewage conditions was obtained from a Sea Grant project at the Institute of Marine Sciences, University of North Carolina (Marshall, 1971). Sewage ponds in the marshes, somewhat simulating estuarine recesses, were more productive in their water phases, although lower in diversity by half due to low oxygen conditions at night. The large manuscript on this project is now ready for publication (H. T. Odum, E. J. Kuezler, A. B. Williams, J. Day, and W. Wood, 1976. Structure and functioning of estuarine ecosystems exposed to treated sewage wastes *unpublished* University of Florida).

Another project, supported by the Rockefeller Foundation and the RANN Division, National Science Foundation, has been testing recycling of treated sewage in cypress domes for the past two years (Odum and Ewel, 1974). Thousands of cypress domes in most counties of Florida act as natural water conservation systems. These self-contained areas of 1 to 50 acres can apparently accept 1 to 3 inches of waste water per week without difficulty, absorbing nutrients and microbes in their natural filterbeds and recharging ground waters slowly. Use of cypress domes may be preferable to less controllable release of wastes in salt marshes (Fig. 12).

Estuarine Cooling

An estuarine cooling interface at the inner bay, Crystal River, Florida, was studied by Smith (1976), Snedaker (1975), and others who found some special adaptations, such as higher productivity in winter and lower productivity in summer. There were some turbidities in these waters, but in the very shallow waters considerable bottom vegetation was maintained. The interface ecosystem that developed here was more productive than most marine ecosystems, although less productive than ecosystems of some nearby zones. Oyster reefs of the estuary, studied by Lehman (1974), were found viable and functioning in the heated discharge. Figure 13 from Lehman shows the model and Figure 14 the simulation used to consider the impact of temperature and other aspects. The simulations agree with field observations in showing productivity and decreased diversity.

The roles of intake and discharge canals from power

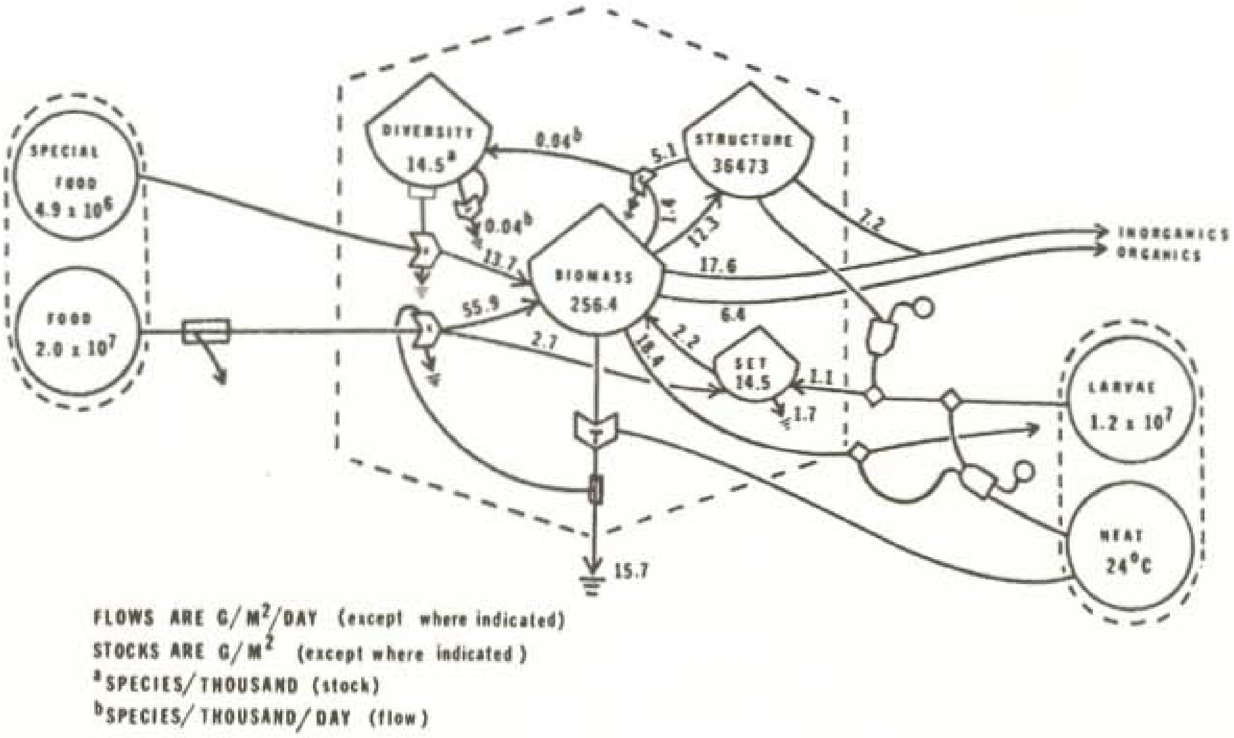
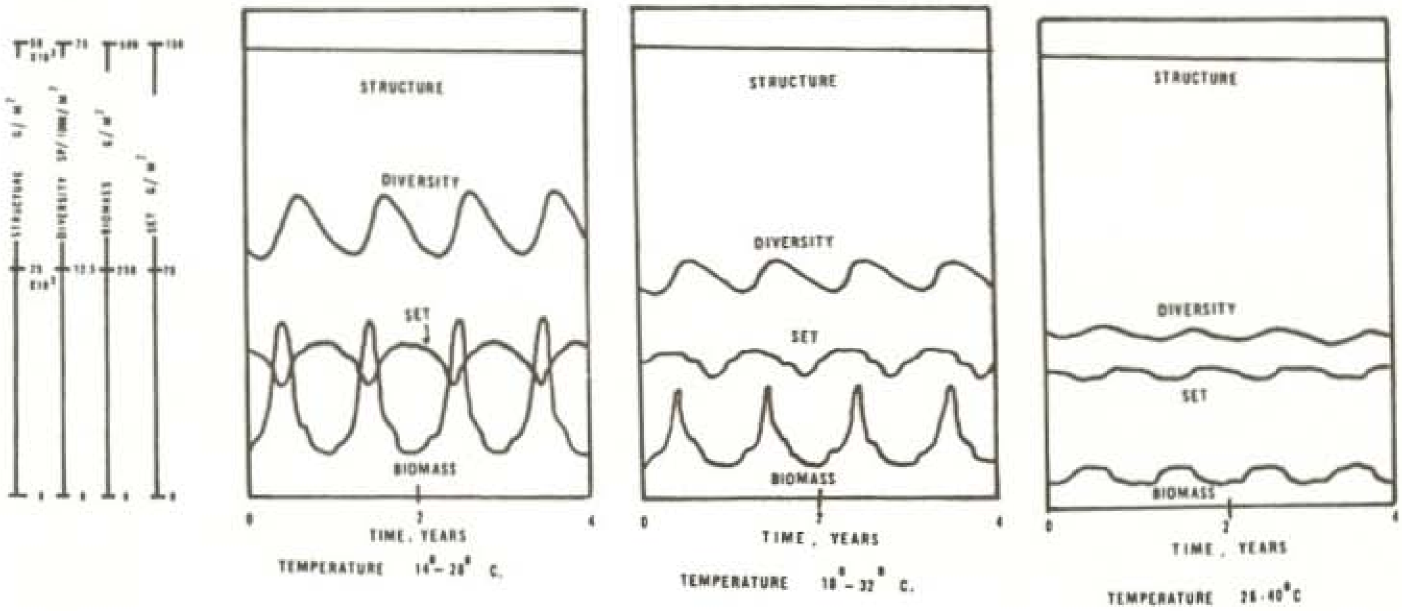


Fig. 13. Model of oyster reefs at Crystal River from Lehman (1974).

Fig. 14. Simulation of reef model in Fig. 13 for varying seasonal temperature ranges. Note declines in biomass and diversity at elevated temperatures.



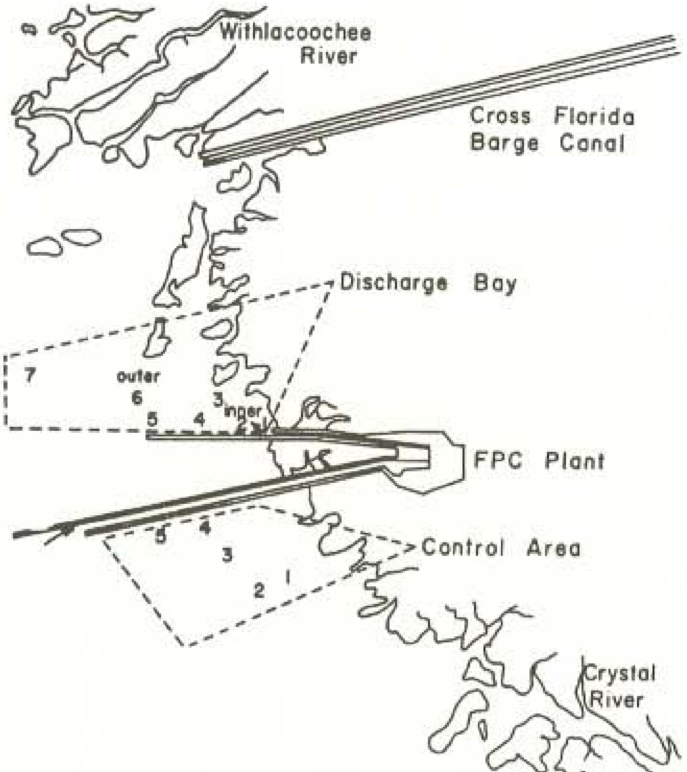
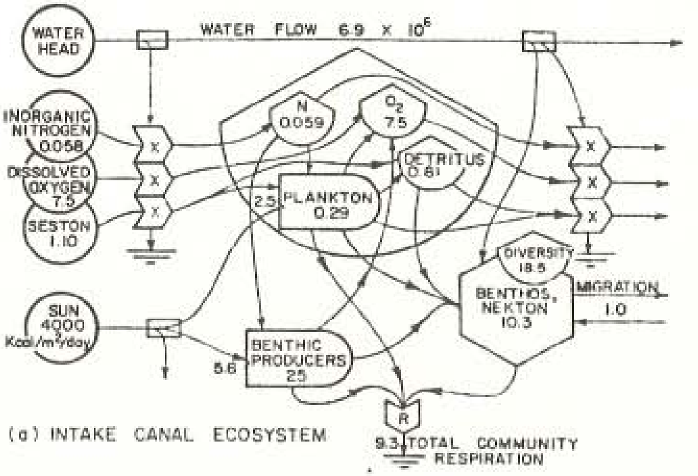
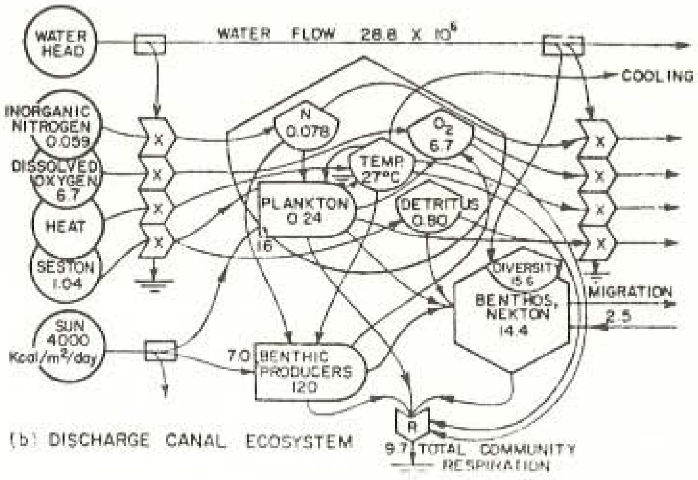


Fig. 15. Canals and power plants at Crystal River, Florida.



(a) INTAKE CANAL ECOSYSTEM



(b) DISCHARGE CANAL ECOSYSTEM

Fig. 16. Evaluated energy diagram of main components of canal ecosystems at Crystal River.

plants as interface ecosystems was studied by Kemp (In preparation). Their location between the estuary and the power plant is shown in Figure 15. In Figure 16, annual mean values for flows in grams of major elements (carbon, oxygen, nitrogen) per m^2 per day and storages in g/m^2 and spp./1000 individuals are provided for a) the intake and, b) the discharge canal ecosystems which interface power plant to estuary. It can be seen that the hotter, more turbid, swifter-flowing discharge canal had greater benthic biomass but was less diverse than the intake canal ecosystem. Annual mean gross community production of the two canal systems was about 41 percent greater than that of the bay systems they displaced, but was 39 percent less productive than the salt marsh ecosystems eliminated by canal construction (Kemp, in preparation).

Mangroves as Interface Ecosystems

Mangroves are good interfaces between man's settlements on the coast and the open waters. The mangroves act as a hurricane buffer, nursery, and nutrient buffer; they absorb and release energy with a stabilizing effect. Given in Figures 17-23 are simulations by Sell (In preparation) of mangrove models as they respond to nutrients, to hurricanes, and to defoliation. These studies included measurements of growth, nutrient uptake, and regrowth following herbicide application. Results of energy models and simulations are consistent with earlier ideas about mangroves and their coastal role.

Figure 17 is a simplified model of the mangrove ecosystem showing the interaction between mangrove biomass, mangrove detritus, and nutrients. Solar radiation is the major energy source, and part of it is converted to organic matter through photosynthesis. Energy subsidies are nutrients made available through rainfall, daily tidal exchange and fresh water runoff. Also, the tidal fluctuations act as an energy subsidy.

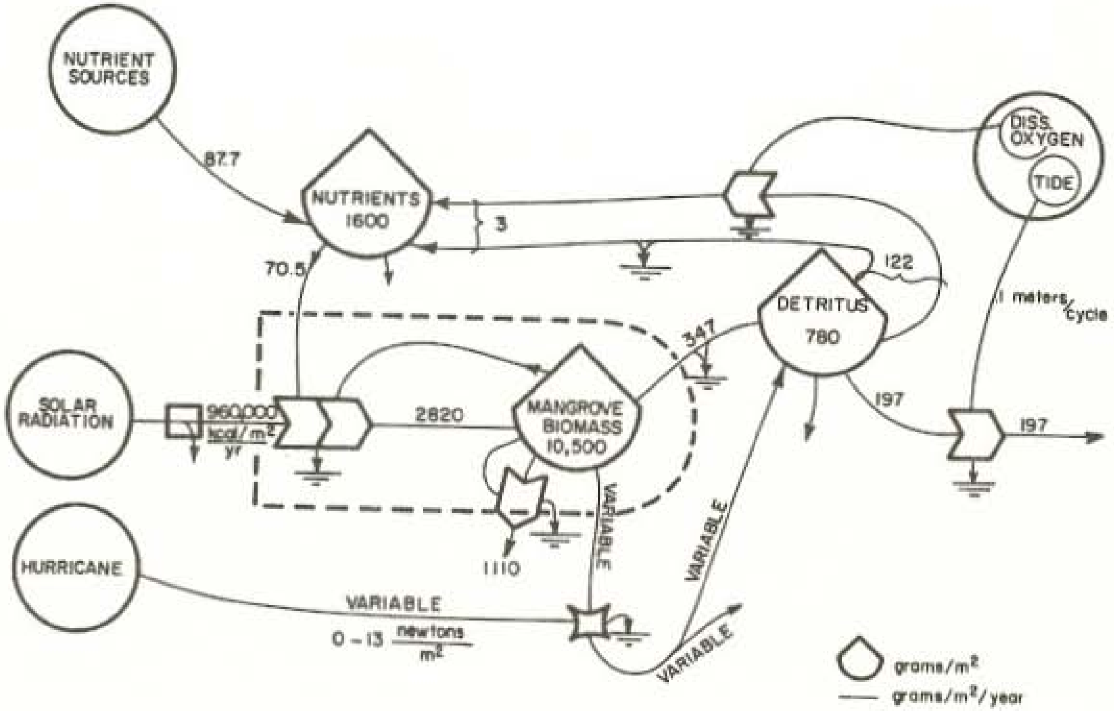


Fig. 17. Model of mangrove growth in Florida with hurricanes and the effects of nutrients. Values are given for the pathways and compartments and were from work done by Lugo and Snedaker (1973) and Carter et al. (1973).

Figure 18 shows the impact that might occur from altering the flow of nutrients into a mangrove community. Case I included the contribution from terrestrial runoff, tidal exchange, and rainfall; Case II eliminated tidal exchange; Case III eliminated terrestrial runoff; Case IV eliminated all but the nutrient flux from rainfall. In each situation, mangrove biomass increased to a maximum level, but the final level was lower as nutrient sources were removed. The worst situation was the removal of both tidal exchange and terrestrial runoff. This would suggest that the effects of dredging tidal creeks and impounding mangroves could be destructive to the mangroves. Bacon (1974) noted that in the Caroni Swamp of

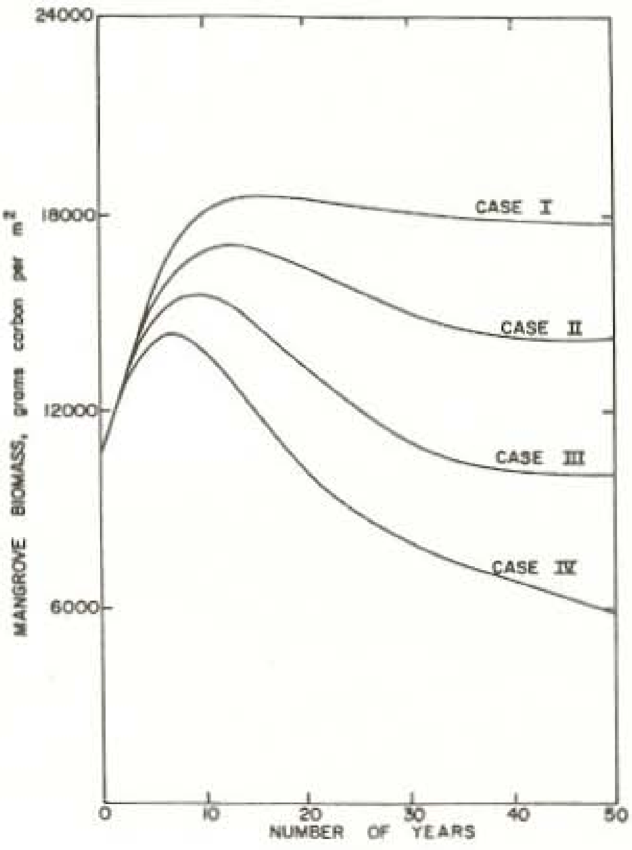


Fig. 18. Effect on mangrove biomass of altering the nutrient flows into the mangrove ecosystem: Case I—both terrestrial runoff and tidal exchange contribute nutrients to the mangroves. Case II—tidal nutrient contribution eliminated. Case III—terrestrial runoff nutrient contribution eliminated. Case IV—both tidal and terrestrial nutrient contributions eliminated.

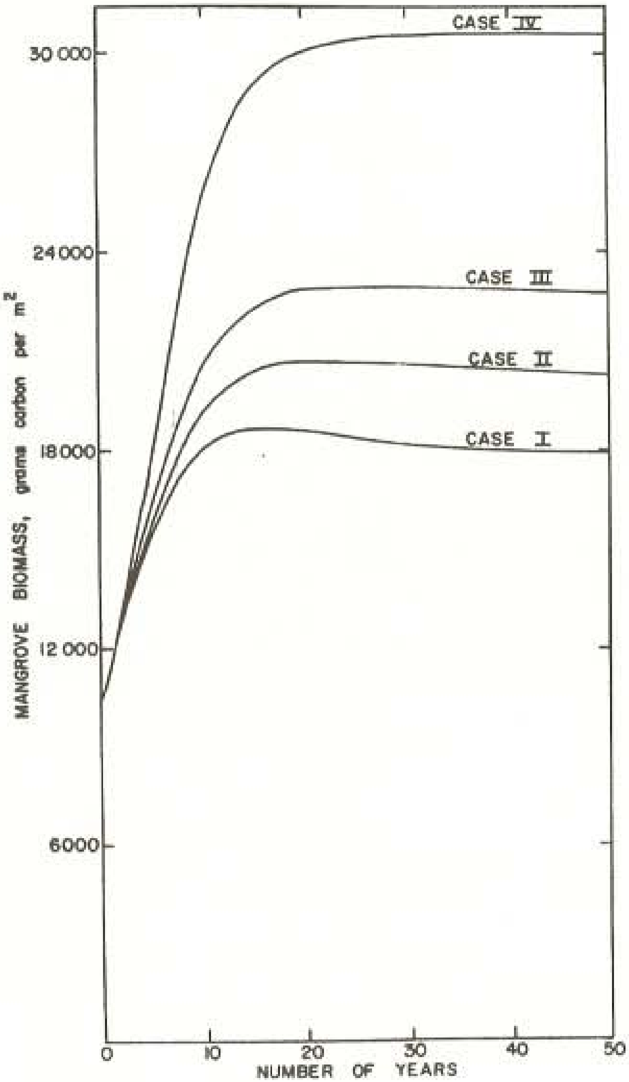


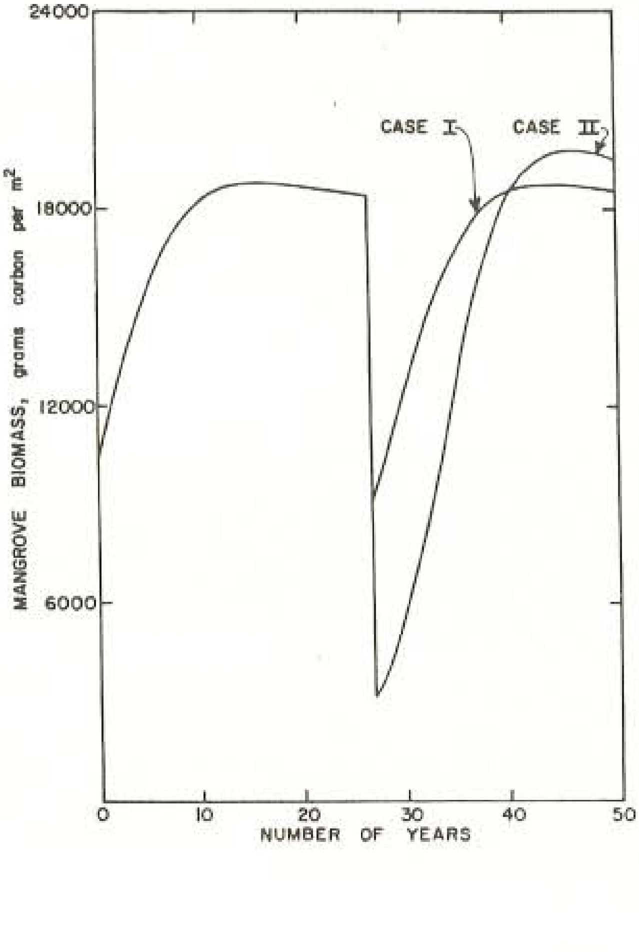
Fig. 19. Effect on mangrove biomass of increasing the nutrient flows from terrestrial runoff: Case I—normal nutrient flow. Case II—fifty percent greater than normal nutrient flow. Case III—twice normal nutrient flow. Case IV—three times normal nutrient flow.

Trinidad the isolation of mangrove forests from free water circulation resulted in the death of these forests. Mangrove areas cut off from fresh water inflow but not tidal movement continued to flourish.

Figure 19 shows four rates of terrestrial nutrient flux holding nutrient flux from rainfall and tidal exchange constant. As the nutrient input from land sources—municipalities, industry, and agriculture—is increased (Case I through Case IV), mangroves are shown to have higher biomass levels. Even though there is an increased uptake by the ecosystem, the level of nutrients in the estuary has also increased.

An infrequent high energy stress on the mangrove ecosystem is the hurricane. A major hurricane occurs along the mangrove coastlines of Florida about once every 20–25 years. Figure 20 shows the impact of a hurricane on the mangrove forest. In this figure only one hurricane was allowed to stress the mangroves during the 50 years the simulation was run. Case I was for a hurricane of moderate strength, with wind speeds of about 40 meters per second (90 miles per hour); while Case II was for a major hurricane, with wind speeds up to 90 meters per second (200 miles per hour). The moderate hurricane reduced mangrove biomass to 9000 grams carbon per m², and the recovery time to attain maximum biomass levels was about 16 years. The major hurricane reduced mangrove biomass to 3000 grams carbon per m², and the recovery time to attain maximum biomass levels was 20 years. The level after

Fig. 20. Impact of hurricanes on mangrove biomass. Case I—moderate hurricane. Case II—major hurricane.



the major hurricane was slightly greater than the maximum level without any hurricane occurring. According to this model, mangroves may attain their greatest biomass when a 25-year cycle of hurricanes is followed.

Adaptation to Disordering Stresses

A key aspect of an interface ecosystem is the substitution of faunas, floras, and general structure of ecosystem relationships so that energy flows that would have been a stress become users of stress energy instead. Marine ecosystems are already well adapted for stresses, such as excessive turbulence and exchange. By shifting to plankton ecosystems, they use the energy of stirring to keep small, low biomass populations stable (by keeping growth centers dispersed) thus saving the energy of developing roots, trunks, and massive biomass that is found on land. In two of the simulations done at Crystal River by Smith (1976) and McKellar (1975), the addition of flushing and mixing stabilized the evaluated models that were unstable before. These models are further evidence of the role of potentially disordering energies in a positive energy-saving role.

Another example of a disordering stress energy is that of widespread herbicide spraying in Vietnam, which resulted in destruction of a significant part of the mangrove forest as shown by the map in Figure 21. Figure 22 is a model of the mangrove ecosystem in South Vietnam, which includes the influence of herbicides, wood cutting, and also seed sources. Figure 23 shows the recovery of the devastated mangrove forests at the natural rate and at two rates of planting by man. Natural

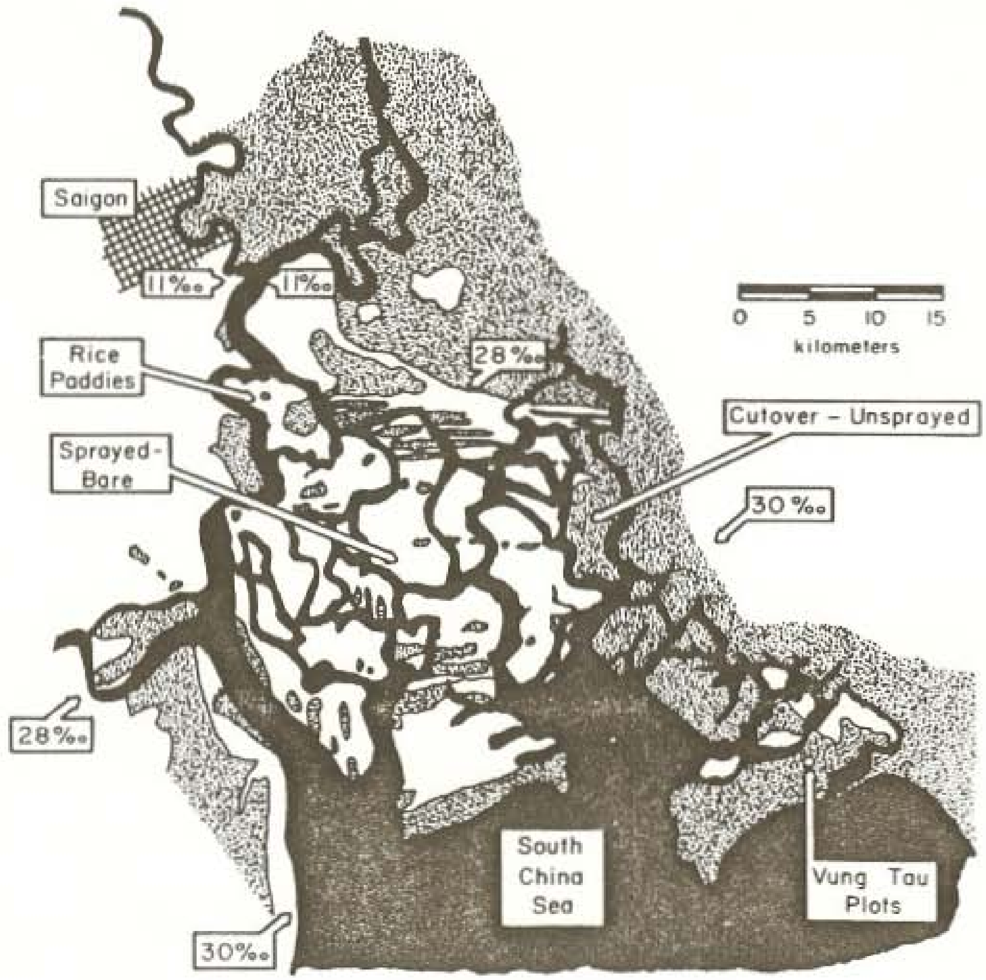


Fig. 21. Defoliated zone in mangrove swamp south of Saigon in Vietnam.

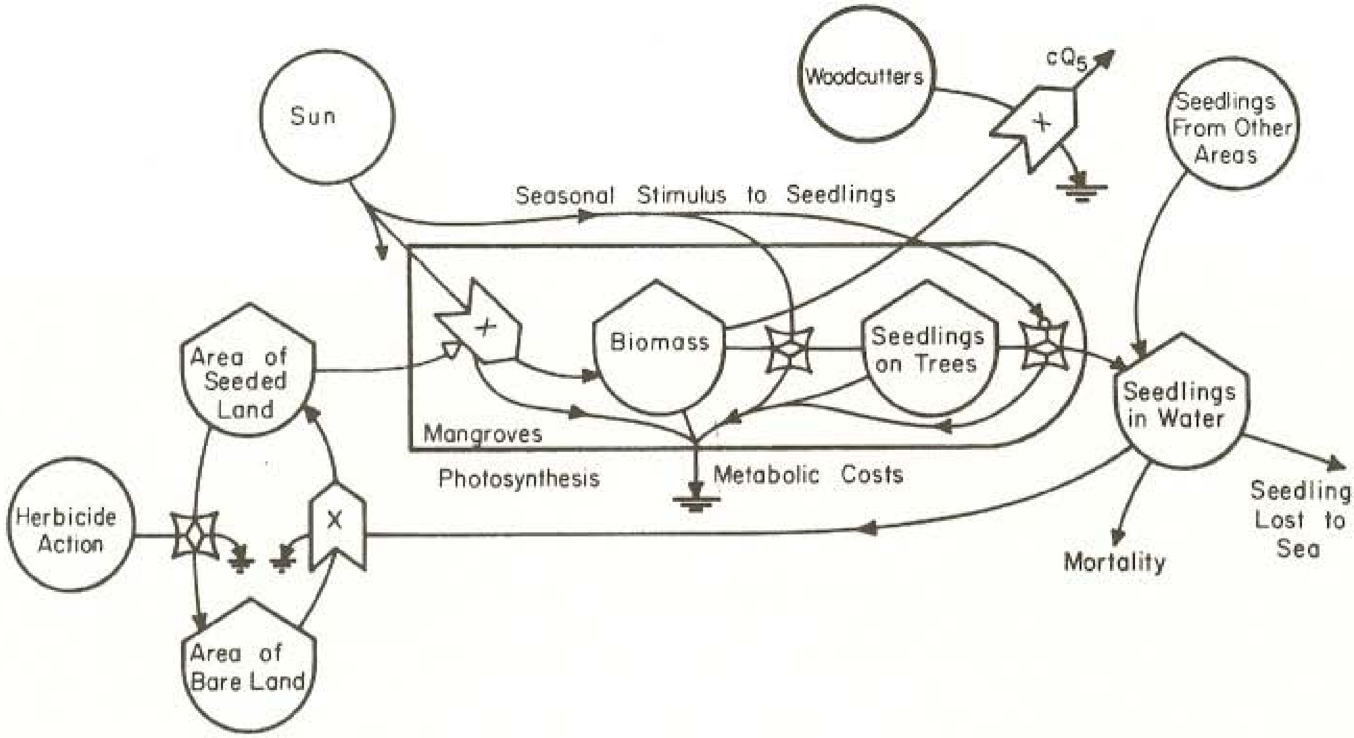


Fig. 22. Model of mangrove recovery in Vietnam from National Academy of Science Report, Sell (In preparation).

recovery may be a very slow process, but with some help from man, recovery time could be decreased considerably.

Ecological Engineering

Domestication of interface ecosystems is done by adjusting conditions between man and nature. Guiding self-design of interface ecosystems is one of the tools of ecological engineering in which one uses more energies of nature and less energies of technology. The repertoire of known interface ecosystems is growing, and it is now feasible to ask of proposed projects: "Have you arranged conditions so that wastes and impacts are kept in steady flow to the ecosystems to which they are adapted?"

Coastal Zone Models

Another tool in coastal planning is energy analysis on a regional scale. In a dozen recent projects (Table 2) researchers have constructed regional models of the coastal zone involving the economic system and various natural components of the environment: estuaries, swamps, and uplands. The critical feature of most models listed in Table 2 is the way outside driving functions are presented so that they show the impact of changing energy conditions in the world on prices and local energy availabilities and ultimately on the investment ratio. Figure 24 shows the simplified essence of driving functions applied to models of coastal Florida. Without exception, the increasing cost of getting energy leads to

Fig. 23. Graph of simulated recovery of the model in Fig. 22.

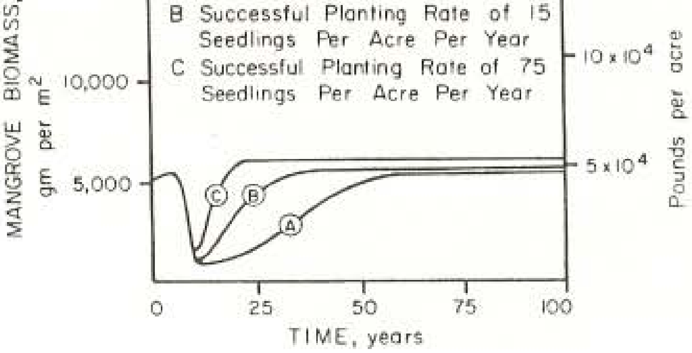


Table 2 Recent regional studies using energy analysis and models, 1973–1975

Name and Area	Special Questions	Agency Support	Authors of Report
Naples, Fla.	Swamp drainage or use as conservation zone within the city.	Collier County	Odum, et al. (1972)
Upper St. Johns River, Fla.	System of reservoirs and drainage or retention of part of marsh system	U.S. Environmental Protection Agency	Bayley and Odum (1973)
Lee County, Fla.	Areal growth patterns and energy	Sea Grant	Searl (1973)
Lee County, Fla.	Macromodels to aid coastal planning	Coastal Coordinating Council	Wetterquist, et al. (1974)
South Vietnam	Herbicides and their energy impact	National Resource Council	Odum, et al. (1974)
Dominican Republic	Balance of forestry, agriculture, and watershed use for power	Center for Latin American Studies, Timber Foundation	Antoni, et al. (1975)
Lee County, Fla.	Energy models and processes in growth	Dept. of Interior	Brown (1975)
Atchafalay River, La.	Alternative flood control measures, levees, channelization	Bureau of Sports Fisheries	Young and Odum (1974)
Appalachicola Bay and Franklin Co., Fla.	Marine fisheries in harmony with coastal housing development	Sea Grant	Boynton (1975), Hawkins (1973).
Crystal River, Fla.	Evaluation of environmental interactions with power plants	Fla. Power Corp.	Odum, et al. (1975)
Hendry County, Fla.	Agriculture and development	Dept. of Interior	DeBellevue (1975)
South Florida Region	Energy basis for carrying capacity and resource use decisions	Dept. of Interior	Odum and Brown (1975)
Lake Okeechobee	Energy relationships of Lake Okeechobee and the questions of eutrophication	Fla. Division of State Planning	Nordlie, et al (1975)
Green Swamp	Compatibility of water conservation area and development	Fla. Division of State Planning	Brown, et al (1975)

a cresting of growth and decline of those areas like Miami that already have high densities (Zucchetto, 1975).

An example of these evaluated and simulated models is given in Figure 25 for Apalachicola Bay (Boynton et al., 1975). One of the simulations is given in Figure 26. Other simulations showed sensitivity of the oyster industry to any interruptions such as closing of the bay due to high coliform levels.

World Trends

Although many areas are still planning for growth and increasing densities in the coastal zone, our various models suggest that we now need to plan for less favorable investment ratios. Decline in net energies available from outside will lead to further inflation. Many economic tenets, such as economies of scale, should now reverse themselves. We may expect decreasing technology, decreasing motorized exploitation of the sea, decreasing luxury packaging and handling of food products, decreasing centralization, and decrease of coastal wastes.

Judging by annual fishery statistics, the world fishery harvest has already crested due to a combination of overfishing, habitat destruction, and declining energies for further fishing. There may finally be some decrease

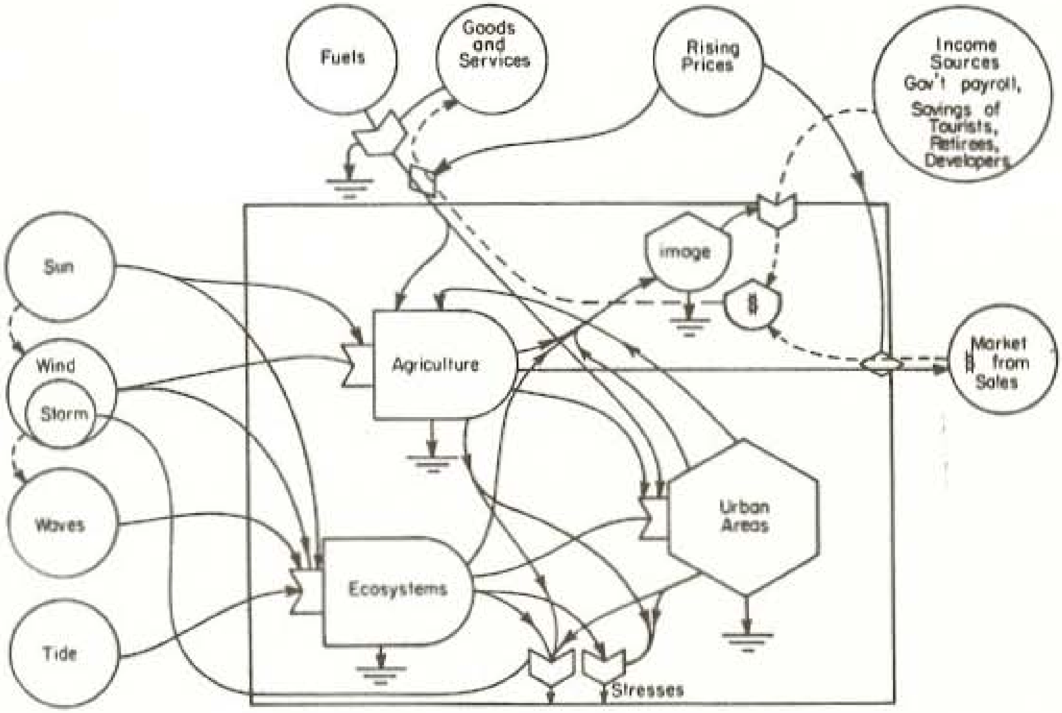


Fig. 24. Main features of coastal planning models in Table 2.

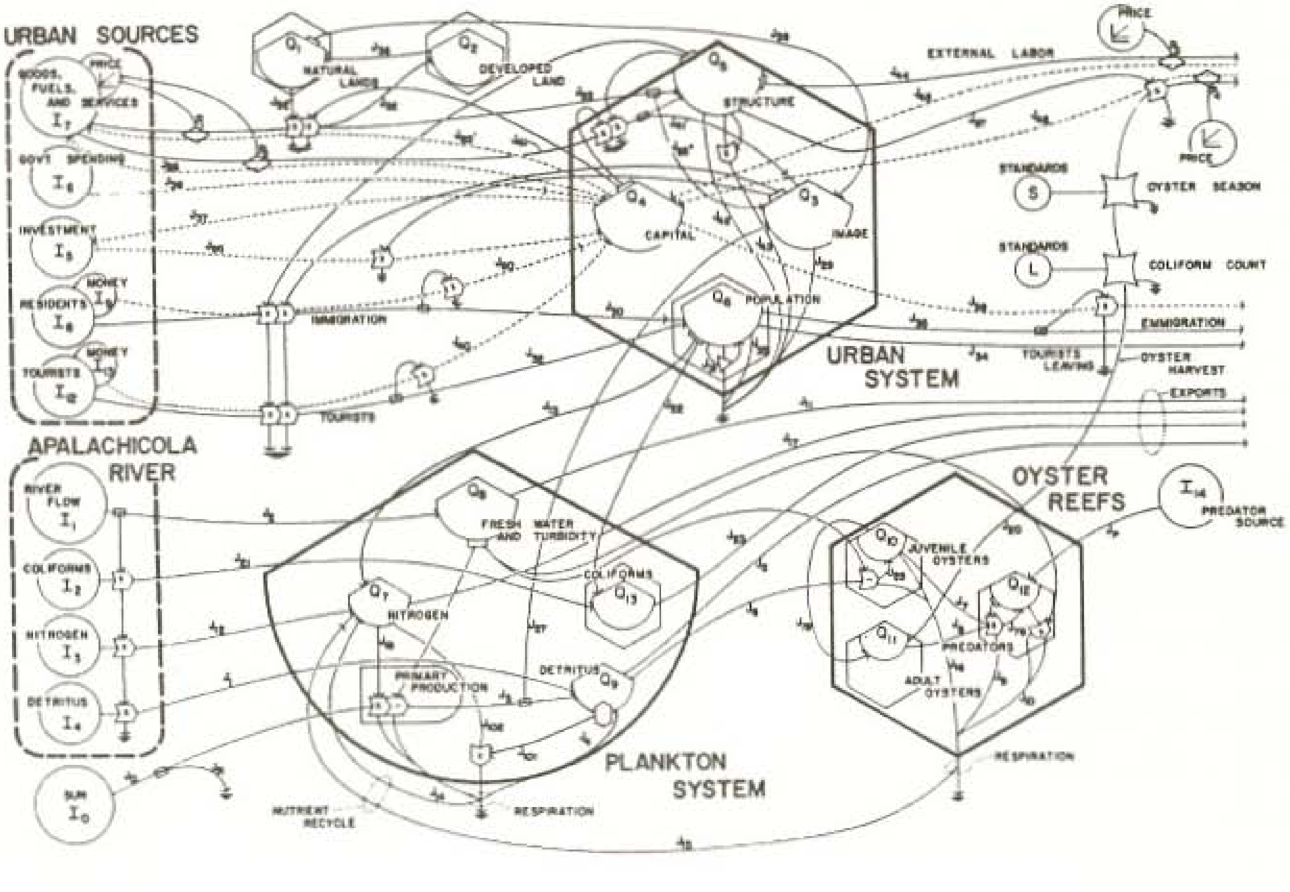


Fig. 25. Energy model of Franklin County and Apalachicola Bay, Florida. For details of I, J, and Q numbers, refer to the original table (Boynton, et al., 1975).

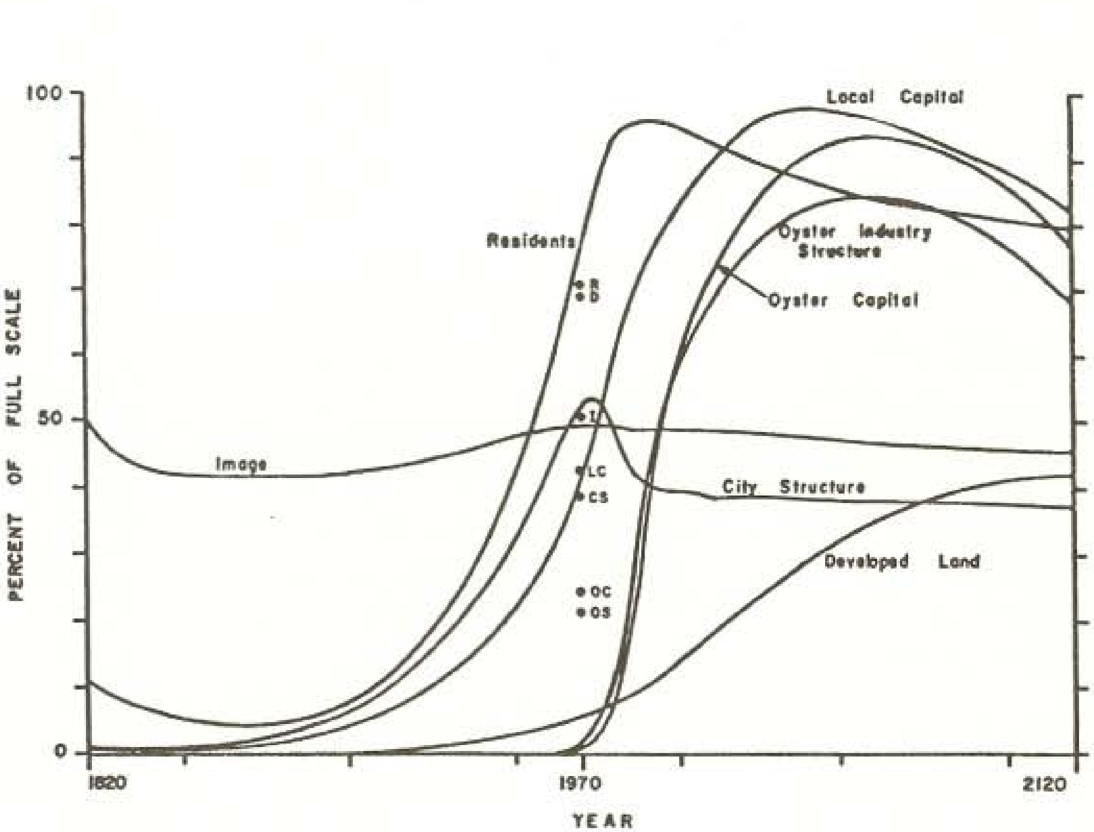


Fig. 26. Simulation of history of the county using the model in Fig. 25 (Boynton, et al., 1975).

in pressure on the fisheries. There will not be energies to support the huge load of operations and structures that manage the tidal waters. We may see a trend back to use of natural management, adapting man to the shifting shores and bottoms rather than using massive engineering projects and scarce energies against the natural work of waves and tide. The greatest new environmental problem may be the expansion of agricultural lands as we are forced to shift to more labor, more land area, and less technology in food production. Does science have designs for man and nature in a period of lower energy, and eventually in a steady state with renewable resources?

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