ROLE OF WETLAND ECOSYSTEMS IN THE LANDSCAPE OF FLORIDA

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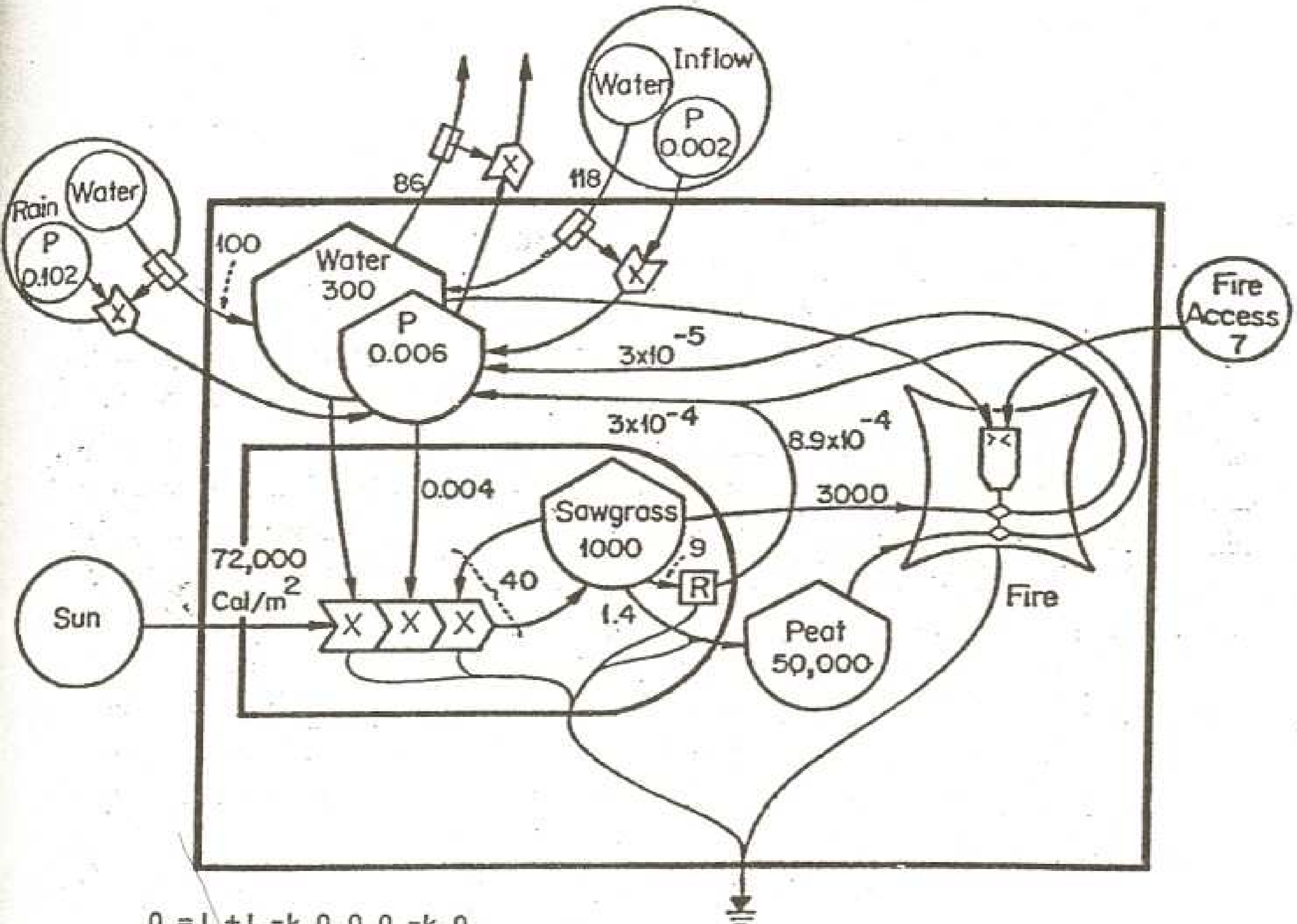
INTRODUCTION

In most parts of the earth new landscape ecosystems are emerging that include elements of older ecosystems and the interfacing new patterns of humanity. Wetlands had special roles in the landscapes of the past in which human societies were relatively sparse. Now, however, new kinds of symbiotic relationships are emerging between high density, high energy human economies and the supporting landscape. Recent studies of the role of wetlands in the landscape are reviewed here, and at the same time principles of self organization and design at the landscape dimension are suggested.

Understanding the landscape systems involves perceptions, calculations, and simulations of simplified versions which we call models. Representing models in a way that can be readily read, compared with others, and related to principles requires diagrammatic languages that show parts and wholes. In this paper energy circuit language is used to help review and compare models on wetlands and landscapes and to clarify some principles. Qualitative aspects of the language were given by Odum (1967,1971) and Odum and Odum (1976,1981). Quantitative aspects were given by Odum (1971,1981). An example of the use of symbols, corresponding differential equations, and simulation is given in Fig. 1 redrawn from Bayley and Odum (1976). The model has both continuous and logic functions which lead to pulsing. In this model increased eutrophication causes more rapid build-up of biomass and more frequent pulse by fire. However, pulsing frequencies are a function of the hierarchy of size distributions, one of the principles of organizations to be considered further here.

TYPICAL WETLAND MODEL

In Fig. 2 is given a typical wetland model, one with main outside driving functions like sunlight, water, wind, and genetic exchange. The sources of external influence are arranged by convention from low quality, beginning with sunlight on the left to high quality ones to the right. Similarly, low quality components such as leaves are on the left and higher quality components such as logs and carnivores are on the right. This convention makes the diagram represent hierarchy, eliminates unnecessary crossing of lines, and makes positions standard from one diagram to the next, improving comparability.



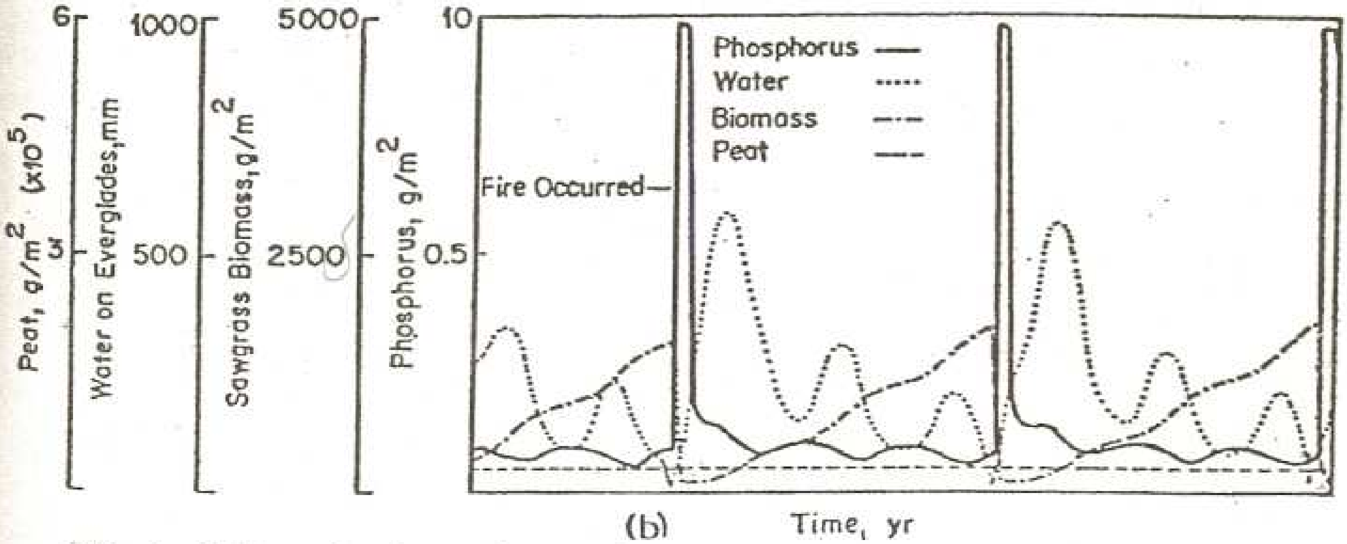
(a)

$$Q_1=J_1+J_2-k_3Q_1Q_2Q_3-k_1Q_1$$

$$Q_3=k_3N_3Q_1Q_2Q_3-k_7Q_3-k_6Q_3+k_{13}N_4$$

$$Q_2=k_2J_1+k_{13}J_2\overbrace{+k_9Q_4+k_{12}Q_3}^{\text{when fire is on}}+k_4Q_3-k_{10}N_3Q_1Q_2Q_3-k_{14}Q_2$$

$$Q_4=k_3Q_3\overbrace{-k_9Q_4}^{\text{when fire is on}}$$



(b)

Fig. 1. System of water and grass in Everglades. Period of oscillation of fire oscillators dependent on level of energy resources. (a) Energy diagram

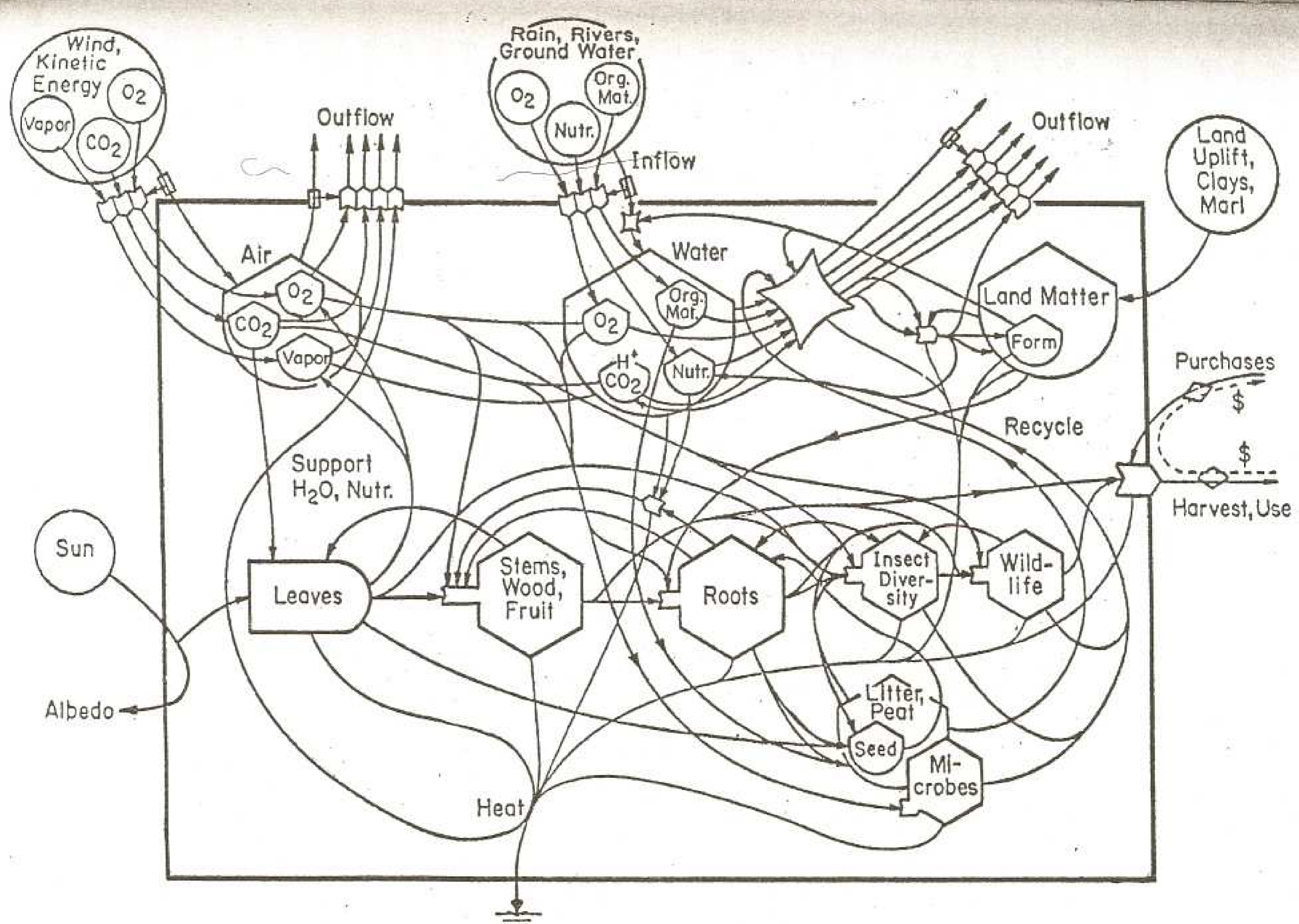


Fig. 2. Main features of a floodplain swamp (Wharton, Odum, Ewel, et al., 1976).

Notice that main processes diagrammed include the water storages and basin structure which is built by the system; photosynthesis, transpiration, and mineral cycles; food chains; processing of sediment, organic peats; and pathways of use by humans.

EMBODIED ENERGY AND ENERGY TRANSFORMATION RATIO

The hierarchical position of energy flows and storages can be quantified according to the embodied solar energy of the flow or storage. Embodied energy is that energy of one type (i.e., global solar energy) which is required to generate the item being considered. The Calories of global solar energy required per Calorie of the type considered is the Energy Transformation Ratio. Estimates are obtained by taking ratios observed in the biosphere where it may be assumed that competitive actions have helped maximize that efficiency consistent with maximum utilization of energy for contingencies of survival. In Table 1 are given some energy transformation ratios which are useful for considering wetlands.

The embodied energy concept was offered as a measure of value utilizing the idea that successful surviving systems would maintain items that required more energy only if they had a proportionate effect (Odum, 1975; Odum and Odum, 1976). The embodied energy concepts provide a way to convert information on wetland models and hierarchies into predictions of value.

ECONOMIC VALUE

When work of nature, such as that of a wetland, generates useful products such as wood, clean water, soils, etc., these products may be the basis of some part of the human economy, ultimately causing circulation of money to represent value. As shown in the model diagram in Fig.3, the money paid for the product at the point of entry into the human economy is much less than the circulation of money that the product ultimately causes. Thus, first prices are not measures of dollar value to the economy as a whole. The embodied energy concept of value is the ultimate and long range value, not the value to individuals locally, which is more a function of scarcity and marginal effect. As indicated in Fig.3, the embodied energy of a wetland product can be converted to an estimate of dollar value contribution to the economy by proportion. The dollar value is that fraction of the Gross National Product that the embodied energy of the product is of the total solar equivalent energy supporting the economy. Since the actual energy supporting the economy includes large flows of fossil fuel, these are expressed in global solar equivalents so that all energies supporting the economy are

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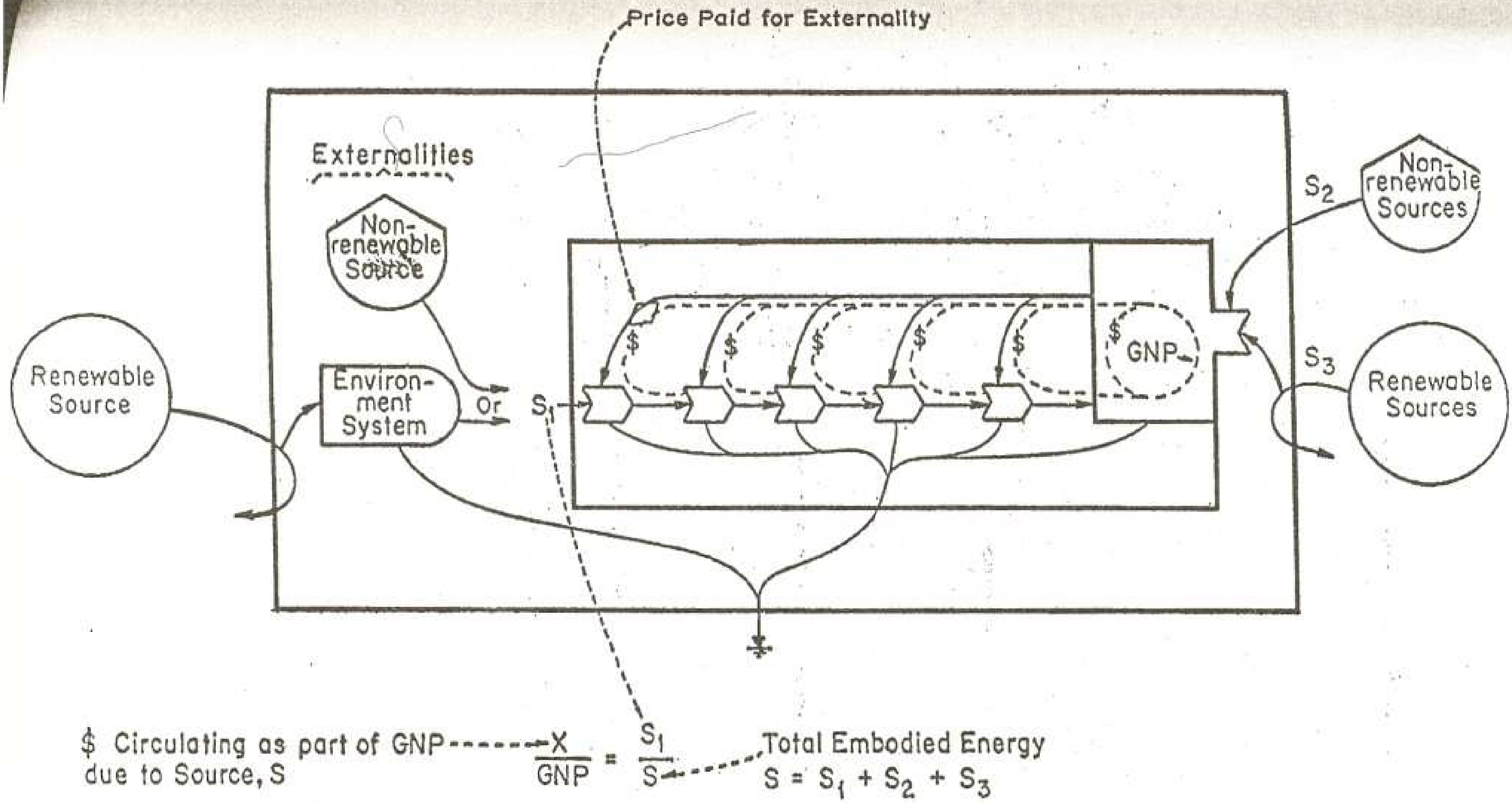

Fig. 3. Relation of externalities to dollar circulation in the economy. The ultimate contribution of the environmental sources are much greater than the first price paid at the point of entry of the resource input. The calculation of value in dollars per year is made by estimating the proportion the externality is of the total flow of embodied energy.

Table 1. Energy transformation ratios useful for evaluating wetlands in Florida.

Item	Basis	Global solar Calories per Calorie
Sunlight	1	1
Physical energy of rainwater	2	4×10^3
Chemical purity of rainwater	3	6.9×10^3
Runoff draining into swamps	4	6.9×10^4
Cypress wood and peat	5	7.2×10^4
Wood storks	6	5.8×10^8
Phosphate concentrated by swamp water solution	7	2.3×10^9
Basin dissolved by ecosystem work	8	3.3×10^{11}

Footnotes to Table 1

1. One Calorie per Calorie - by definition.
2. Ratio of global solar energy to physical energy in rain on land.

   Physical energy in rain reaching ground

   $(8.75 \times 10^4 \text{cm elevation})(1.05 \times 10^{20} \text{g/yr rain over land})(980 \text{ cm/sec}^2)$

   $\times (2.38 \times 10^{-11} \text{Cal/erg})$

   $= 2.14 \times 10^{17} \text{Cal/yr}$

$$\text{Energy transformation ratio} = \frac{8.56 \times 10^{20} \text{global solar Cal/yr}}{2.14 \times 10^{17} \text{Cal/yr}}$$

$$= 4 \times 10^3 \text{solar Cal/Cal}$$

3. Ratio of global sunlight to Gibbs free energy of rain overland.

$$\Delta F = nRT\ (C_2/C_1)$$

$$= (\tfrac{1}{18})(2 \times 10^{-3} \text{Cal/g})(300^\circ\text{K})(2.3)[\log\ (999{,}990/965{,}000)]$$

$$= 1.18 \times 10^{-3} \text{Cal/g water}$$

global ratio of sunlight to rain over land

$$= \frac{(8.55 \times 10^{20} \text{global solar Cal/yr})}{(1.05 \times 10^{20} \text{m}^3\text{/yr rain})(1.18 \times 10^{-3} \text{Cal/g})}$$

$$= 6.9 \times 10^3 \text{solar Cal/Cal}$$

4. Ten percent of rains on a Florida area reaching wetland. Energy-transformation ratio of rain times ten. Water budget 2 m direct and 1 m from area surrounding that is ten times the wetland.

5. Three meters of water processed per year, net organic matter deposition in peat and wood, 1000 $g/m^2/yr$

$$\frac{(10^6 g/m^3)(3\ m^3/m^2/yr)(1.18 \times 10^{-3} Cal/g)}{(4.5\ Cal/g)(10^3 g/m^2/yr)} = 7.2 \times 10^4 \text{ global Cal/Cal}$$

6. See Fig. 13.

7. Phosphate concentrated by factor of ten

$$\text{Gibbs free energy} = \frac{RT}{m} \ln \frac{C_2}{C_1} = \frac{RT}{35} \ln 10$$

$$= \frac{(2 \times 10^{-3} Cal/mole)(300)(2.3)(1)}{35\ g/mole}$$

$$= 0.0394\ Cal/g$$

Phosphorus per cubic meter dissolved and concentrated is

$(2 \times 10^6 g)(0.5\%\ P) = 10^4 g$ phosphorus

Actual energy stored

$(.0394\ Cal/g)(10^4 g\ P) = 394\ Cal$

$$\text{Energy transformation ratio} = \frac{(3636 \text{ years})(2.44 \times 10^8 Cal/m^2/yr)}{394\ Cal}$$

$$= 2.25 \times 10^9 \text{ global solar Cal/Cal}$$

8. From Table 3. 3636 years are required for one meter basin; energy in basin is that of displaced weight

$= (\text{density})(\text{mass displaced per } m^2)(\text{height}/2)(g)$

$(2\ g/cm^3)(100\ cm^3/cm^2)(100\ cm/2)(980\ cm/sec^2)(2.38 \times 10^{-11} Cal/erg)$

$\times (10^4 cm^2/m^2)$

$= 2.33\ Cal/m^2$ stored in basin

Calories of water used: (see footnotes 3, 4, and 5)

$= (1.18 \times 10^{-3} \text{Cal water/g})(6.9 \times 10^4 \text{ solar Cal/Cal water inflow})$

$\times (3\ m^3/m^2)(10^6 g/m^3)$

$= 2.44 \times 10^8$ global solar $Cal/m^2/yr$

Energy Transformation Ratio =

$$\frac{(3636 \text{ yrs})(2.44 \times 10^8 \text{ global solar Cal/Cal})}{2.33\ Cal/m^2 \text{ stored}} = 3.81 \times 10^{11} \text{ global solar Cal/Cal}$$

in Calories of one type. When this was done, the ratio of global solar equivalent Calories to GNP dollars was 6.8 x 10^7 Global Solar Calories per dollar. This ratio is also useful to evaluate the energy embodied in the feedback of complex goods and human services which have been formed by convergence of the web of the economy.

There has been considerable controversy over these methods of estimating dollar value of externalities. See Gilliland (1978). A manual has been prepared to assist environmental evaluations (Odum et al., 1981).

GLOBAL SOLAR ENERGY VERSUS DIRECT SOLAR ENERGY

It has long been customary in ecology to calculate the efficiency of photosynthetic conversion of sunlight to organic production taking the Calorie value of the organic matter divided by the direct solar energy received. Wetlands are among the most productive. Usually this productivity is explained by the excess of various factors required in production such as nutrients and water.

There is another way to consider photosynthetic process as the convergence of factors generated by global solar energy acting on the earth as a whole, especially over the oceans to generate winds, rains, nutrient cycles and part of the geologic work. By this view the primary production of the wetlands should be compared with its share of the global solar energy not just its direct solar energy. Wetlands receive more than the land's typical share of waters and nutrients. They are receiving "liquid sunlight." The waters received directly and indirectly have a high embodied energy content of global solar energy, much more than they receive as direct sunlight. Higher productivity is because they receive more embodied energy. As shown in Fig.4, a land area received more than one input from the global meteorological processes including the wind, rain, rivers, sediments, etc. Since these are byproducts of each other derived from the same global solar energy, it would be double counting to simply add the embodied energy of each. However, taking the largest one and estimating its embodied energy using transformation ratios obtained globally provides the estimate of global solar energy converging on that ecosystem to become embodied in its production processes. For wetlands, the largest one is the water received. The intensity of the embodied global solar energy per hectare per unit time is a predictor of productive phenomena.

Production is the combination of commodities of different quality to generate a product of intermediate quality, higher than the main energy source, but lower than the feedback control actions received from the system. Production concepts apply to geological, meteorological, and economic production as well

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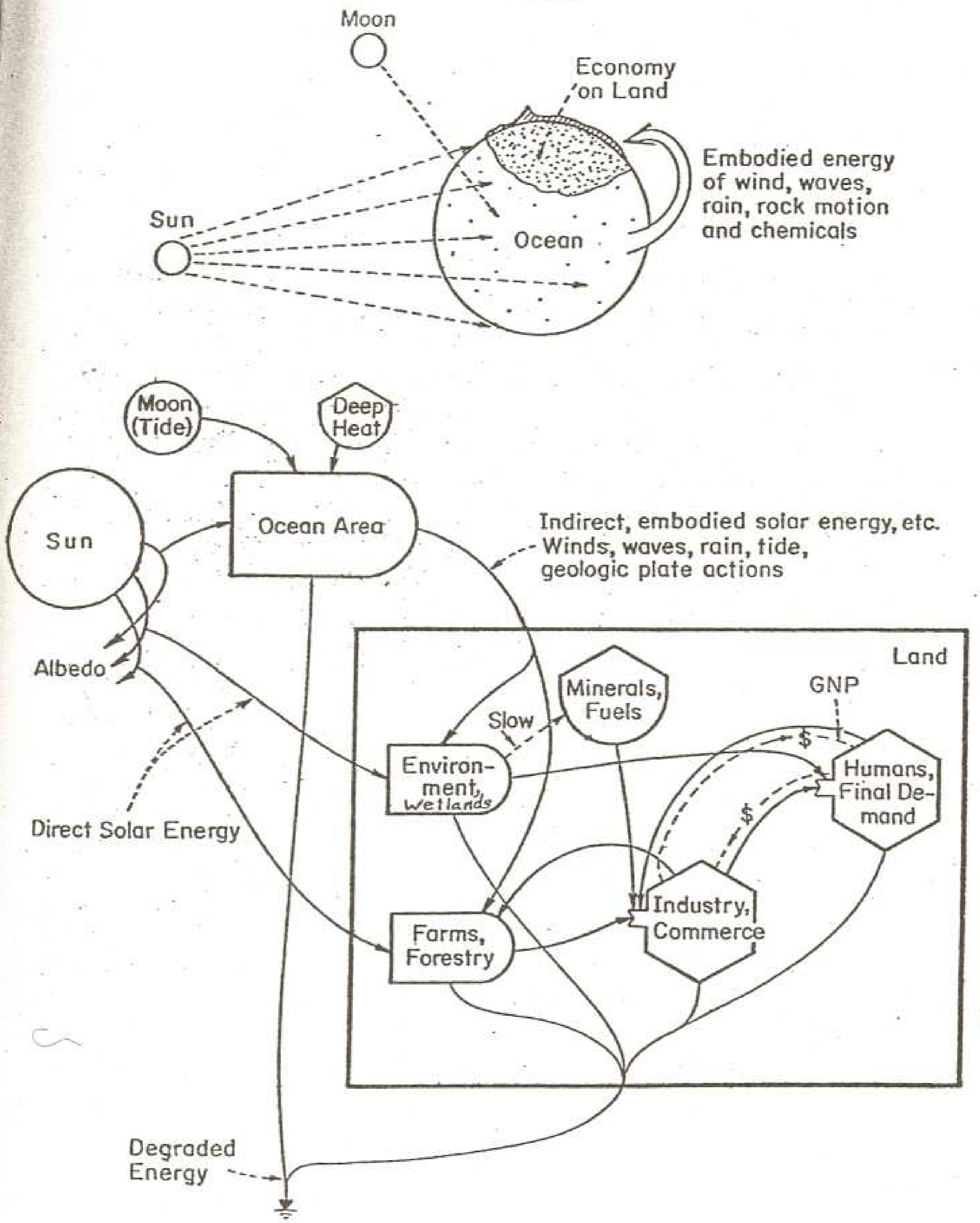

Fig. 4. Diagram of global solar energy driving the web of the biosphere with biological, meteorological, oceanographic, and biological work ultimately converging on wetlands on land. (a) Sketch; (b) energy diagram [illegible] indirect sunlight from ocean products and direct sunlight on

as to biological production. Because more production is generated by interaction of different quality energies, there is a general tendency for various quality factors to interact rather than to be used separately. Thus, wetland production tends to involve most of the energy sources impinging on the system. The way the system develops components' feedbacks and interactions so as to interact the various source flows is readily observed in energy diagrams of the way wetlands work. See typical wetland in Fig.2. The dominance of one kind of energy flow when measured in units of the same global equivalent solar Calories is readily perceived by graphing embodied energies of the different sources of an ecosystem that form a characteristic energy signature. The large embodied energy of water which predominates the energy signature of most wetlands causes the dominance of water adapted components, living and non-living in wetland ecosystems. The embodied energy provides a quantitative scale for classification. See, for example, data for wetlands of Florida in Table 2.

WEB OF MULTIPLE USE

When the economy of humans is connected to a wetland ecosystem the properties of the ecosystem web extend to the human-environment interface. An example is given by Burr (1977) in Fig.5 for use of swamps in Collier County, Florida. High quality inputs from the main economy on the right feed back to the left to interact with products from the ecosystem web, illustrating the principle of interaction between high quality and lower quality energy. The model helps to see what is directly and indirectly a byproduct, and the way the useful products are carrying the embodiement of the energy of the whole ecosystem following productive interactions and feedbacks.

For a consumer such as human user to draw on the products of a system without putting that productive system to poor competitive advantage may require a feedback from the user to the supporting chain further to the left to help maintain its production. In other words, good multiple use may require return "reward loops" for stable design. The runoff from developed areas into marshes and swamps is one kind of feedback reward loop that may be developing interactions of the type needed even though these have often developed without prior plan.

ECONOMIC LOADING AND DETERMINING WHAT IS ECONOMIC

The production of the wetland generates products which attract the human users and with them investments of goods and services, fuels, electricity, etc., much of which has an outside source of energy being delivered through the feedbacks from the human economy. It is the environmental production which makes

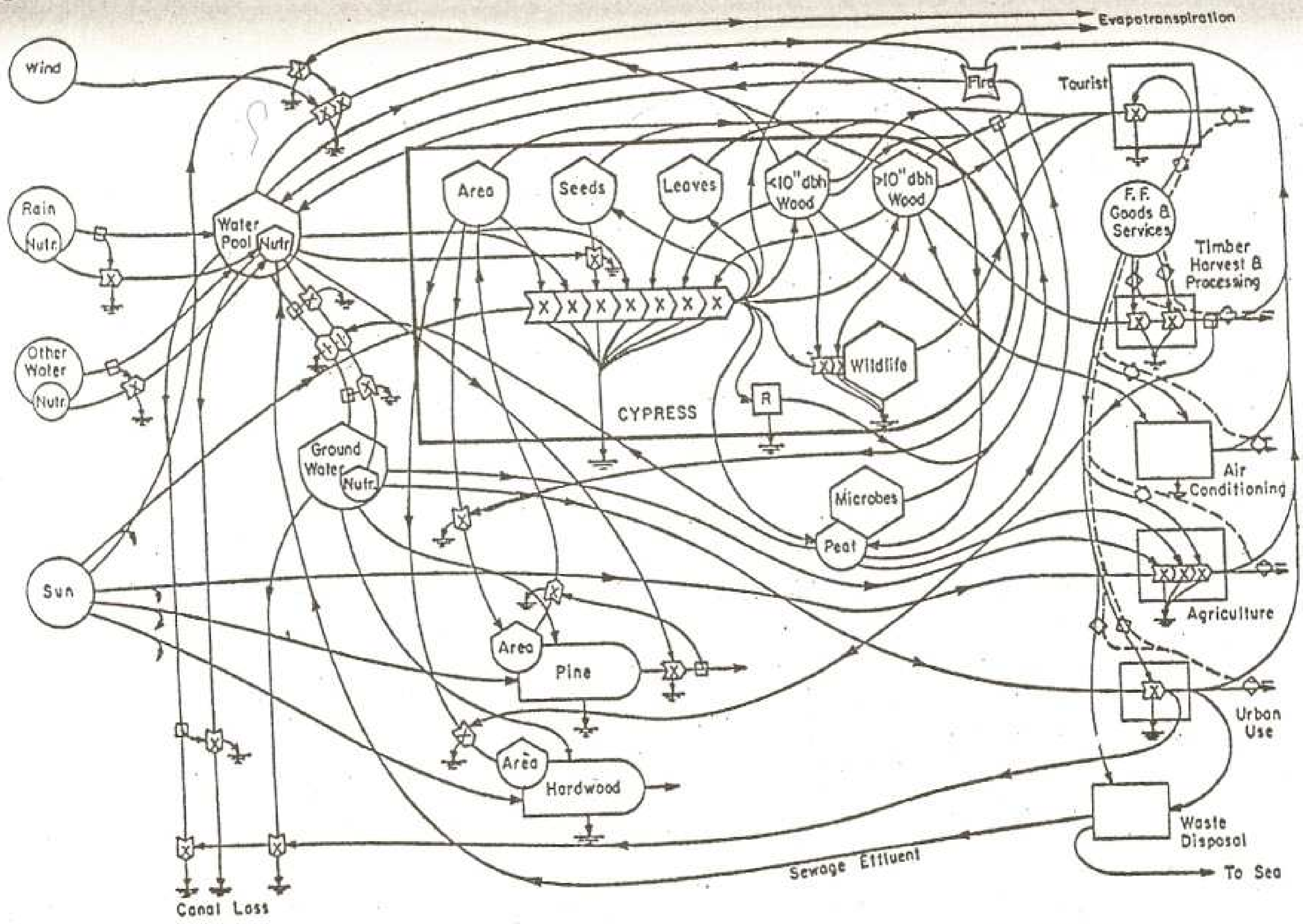

Fig. 5. Interactions of human use with cypress used to evaluate economic interactions in Collier County, Florida, by Burr (1977). The diagram serves as an impact summary between development and a region dominated by cypress.

possible the attraction of additional energy from outside. The ratio of that attracted to that produced has been called an energy investment ratio (Odum, Brown, and Costanza, 1975). This ratio is a measure of the loading of the environment by the use. If the average ratio in the United States is about three embodied solar Calories invested for each one embodied solar Calorie contributed from environmental production, then usages with higher than this ratio may be regarded as overloading of the environmental systems.

The same ratio can be used to estimate if the usage of the wetland is economic. If more than the average investment of outside energies bought with money are required for a usage in relation to the embodied energy value contributed from nature, then that activity will not tend to be as economic as the average. It will draw less from the environment for what is invested than the competing investments. Costs are relatively higher and thus the products will tend to be less economic.

Figure 6 aggregates the wetland and its attracted, interacting investments from the next larger system, that of the human economy.

CRITERION OF MAXIMUM POWER

The interaction of wetlands and human utilization (Figs.5 and 6), by drawing from two sources of energy tends to maximize power. According to the theory of maximum power selection, systems prevailing in self organizational processes are those which develop more energy resources. The combined economy of man and nature interacting in a symbiotic way maximizes power over that which would be generated by either acting separately. More sources are used and more amplifier actions are facilitated.

WETLAND PRESERVATION AND INVESTMENT RATIO

Whereas there are many attitudes in conservation towards isolating wilderness and gene pool areas from economic interactions, the maximum power theory suggests it may be difficult to preserve environmental areas without letting them be used in some interactive way with the economy. To study the question of energy and national parks, a model and energy analysis was made for the Everglades National Park of southernmost Florida (DeBellevue, Odum, Browder, and Gardner, 1979). The model is given in Fig.7, showing the main ecosystems of the Everglades Park interacting with the park management and tourists visiting the park. Most of the park is wetlands including the freshwater sloughs, "River of grass", dwarf cypress and mangrove swamps. Each of the main pathways of production were evaluated for its embodied energy and the tourist expenditures were

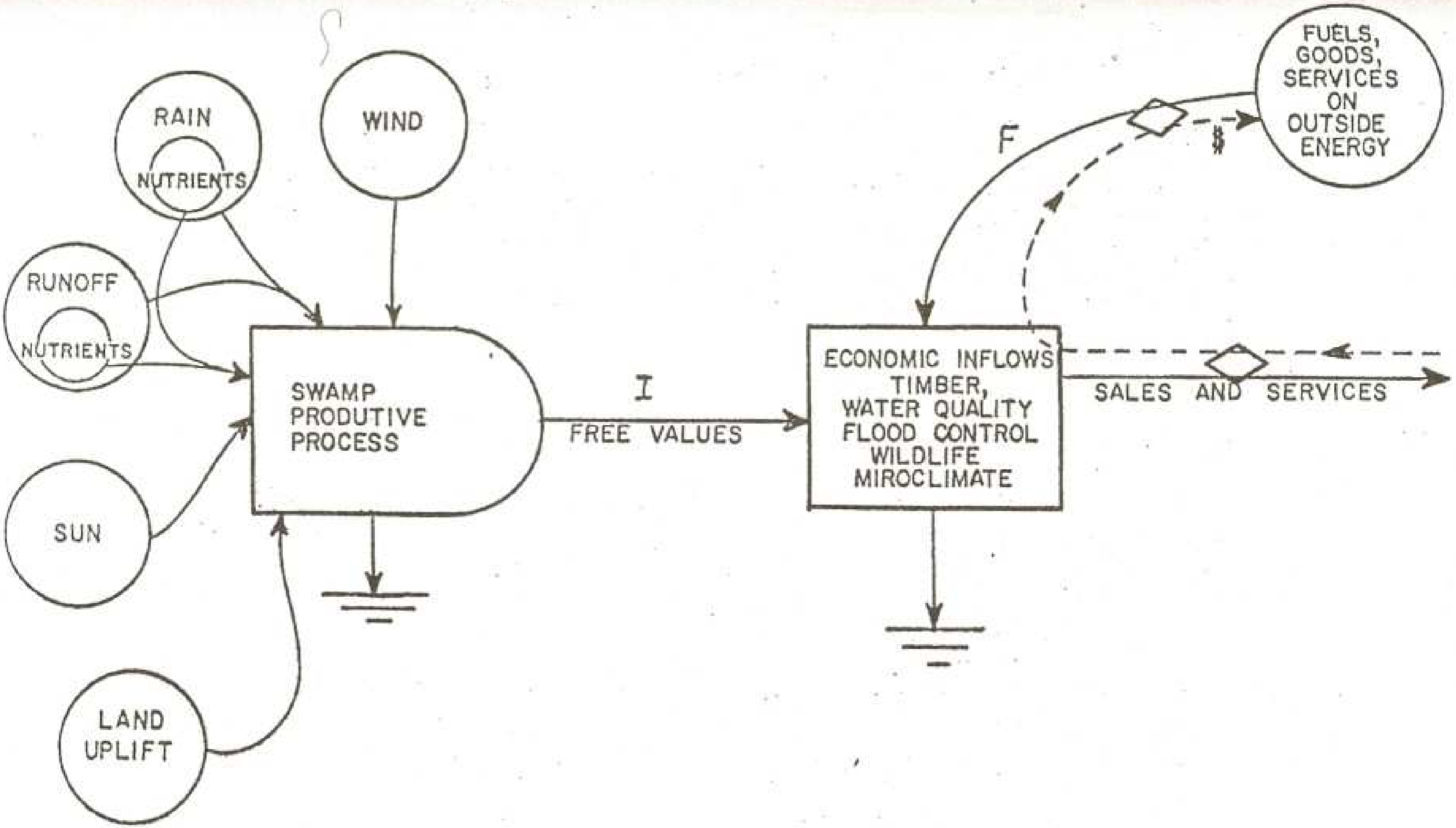

Fig. 6. Aggregated diagram of the interaction between the wetland environmental production and the feedback of high quality interactions from the main economy. The Investment Ratio is the ratio of F/I where both are expressed in Calories of the same quality of energy.

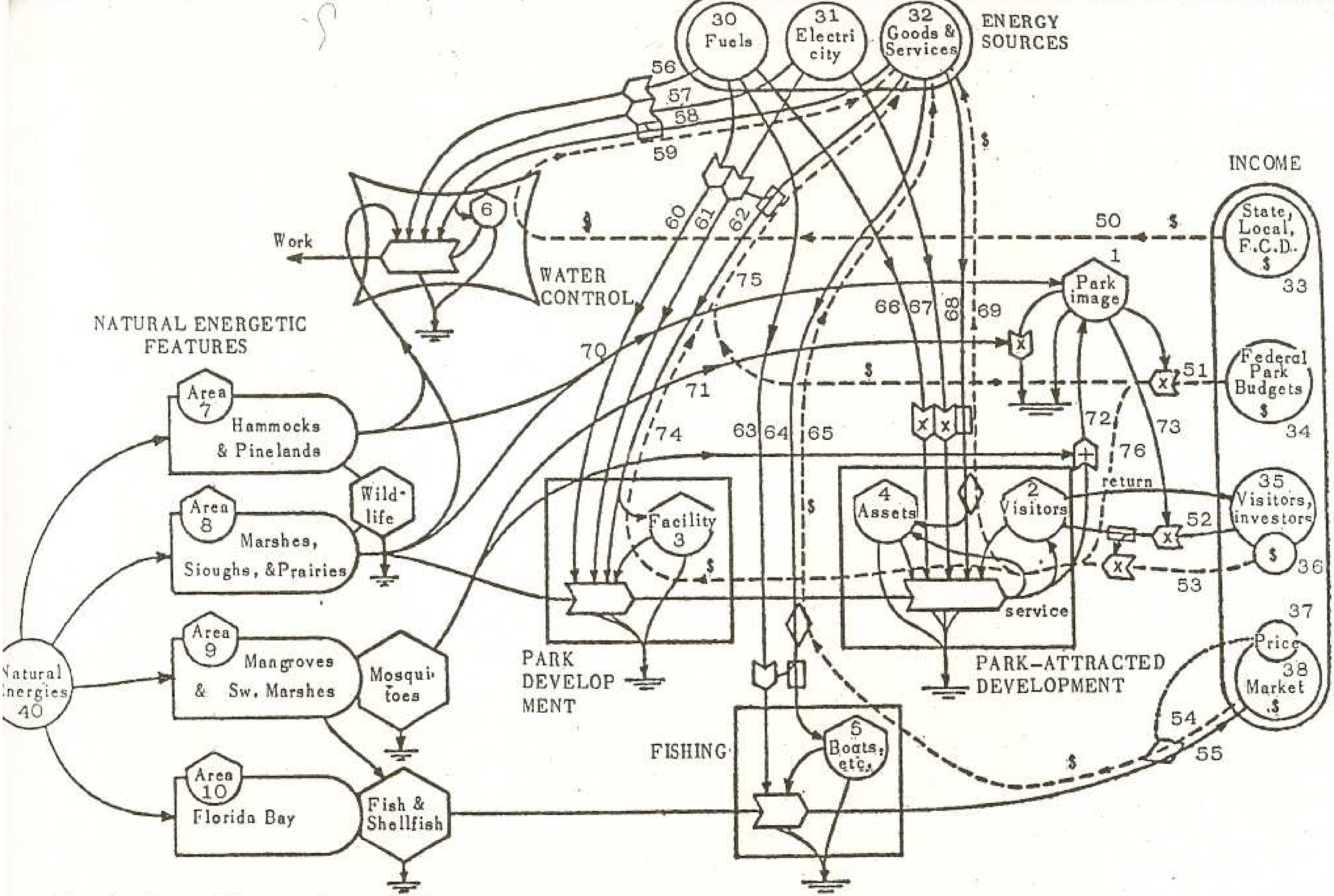

Fig. 7 Energy diagram of Everglades National Park in south Florida with the interactions with management and tourist economy (DeBellevue, Odum, Browder, and Gardner, 1979).

Table 2. Embodied energy of swamps in Fig. 17.

Item	Water processed per year m^3/m^2	Embodied energy available per year global solar Cal per $m^2/yr \times 10^6$	Water used by evapotranspiration m^3/m^2	Embodied energy used global solar Cal per $m^2/yr \times 10^6$
Direct sunlight	-	1.5	-	1.3
Bog, bay with rainwater only	2	16.3	0.7	5.8
Dwarf cypress - small inflow of runoff	4	32.6	1.1	9.1
Strand (flowing swamp)	40	326	1.4	11.6
Flood plain	100	814	2.2	18

converted to embodied energy and the tourist expenditures were converted to embodied energy using dollar energy ratios. The resulting investment ratio for the park was less than one, at a time when south Florida had an investment rati generally that was higher than the national average. Apparently the park is underutilized compared to other areas. It is not as popular as a national park as many others because of the heavy incidence of biting mosquitoes. In 1981 public discussion developed in newspapers over the question of whether too much area was set aside in parks. If public policy tends to follow energy principles theory offered here - then the ratio of parks to economic areas that tends to develop should be that which maximizes regional power, one with a competitive investment ratio.

TYPICAL REGIONAL SYSTEM CONTAINING WETLANDS

Fifteen percent of Florida's landscape was wetlands. Some were flat perched plateaus receiving only rainwaters and others were lower land strands and floodplains, or tidal marshes and mangrove swamps. The region 1 system of landscape containing swamps includes the flows and storages of water, and mosaic of several kinds of ecosystems of upland and lowland, and the economic system of humans which includes urban areas, agriculture, forest plantations, highways, and electric networks. Typical energy diagrams of regional systems of Florida are given in Figs. 8-9. As in Fig. 7, there are the natural lower quality production areas on the left, those interacting more with human economy as in agriculture and forestry next, and the urban concentrations shown on the right with their heavy inflows and outflows of goods and services, fuels, and electricity. Thus, the energy diagram shows the hierarchy of nature and humanity following the quality convention increasing from left to right. Figure 8 is a model used to evaluate alternatives in a water management district. (Bayley, Odum, and Kemp, 1976). Note flow of water from uplands to wetland areas. Figure 9 is the peninsula of Florida with the whole state economy and its relation to the natural areas including wetlands. Evaluations written on the model are coal equivalent Calories per year.

HIGH QUALITY OF WETLANDS

Already evaluated in Table 1, wetlands process and store more embodied energy than many other ecosystems because they are part of the converging process that goes with the hydrologic flows. Water drains from its broad rainfall pattern into swamps, marshes, and floodplains, doing work on the terrain that further organizes the water system to more readily converge. Rainfall has a high embodied energy of the global solar energy brought to land and this converges

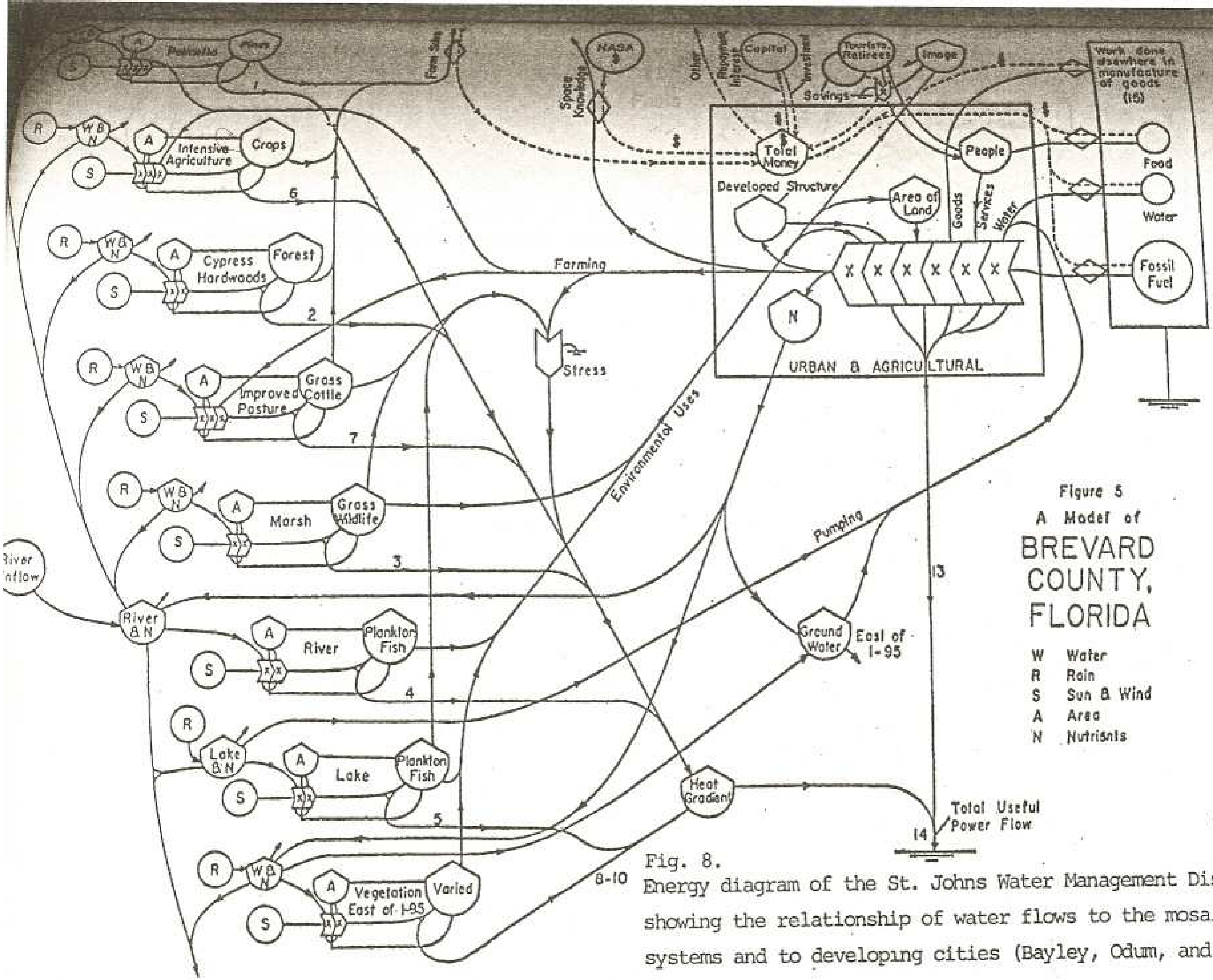

Fig. 8.
Energy diagram of the St. Johns Water Management District of Florida showing the relationship of water flows to the mosaic of landscape ecc systems and to developing cities (Bayley, Odum, and Kemp, 1976).

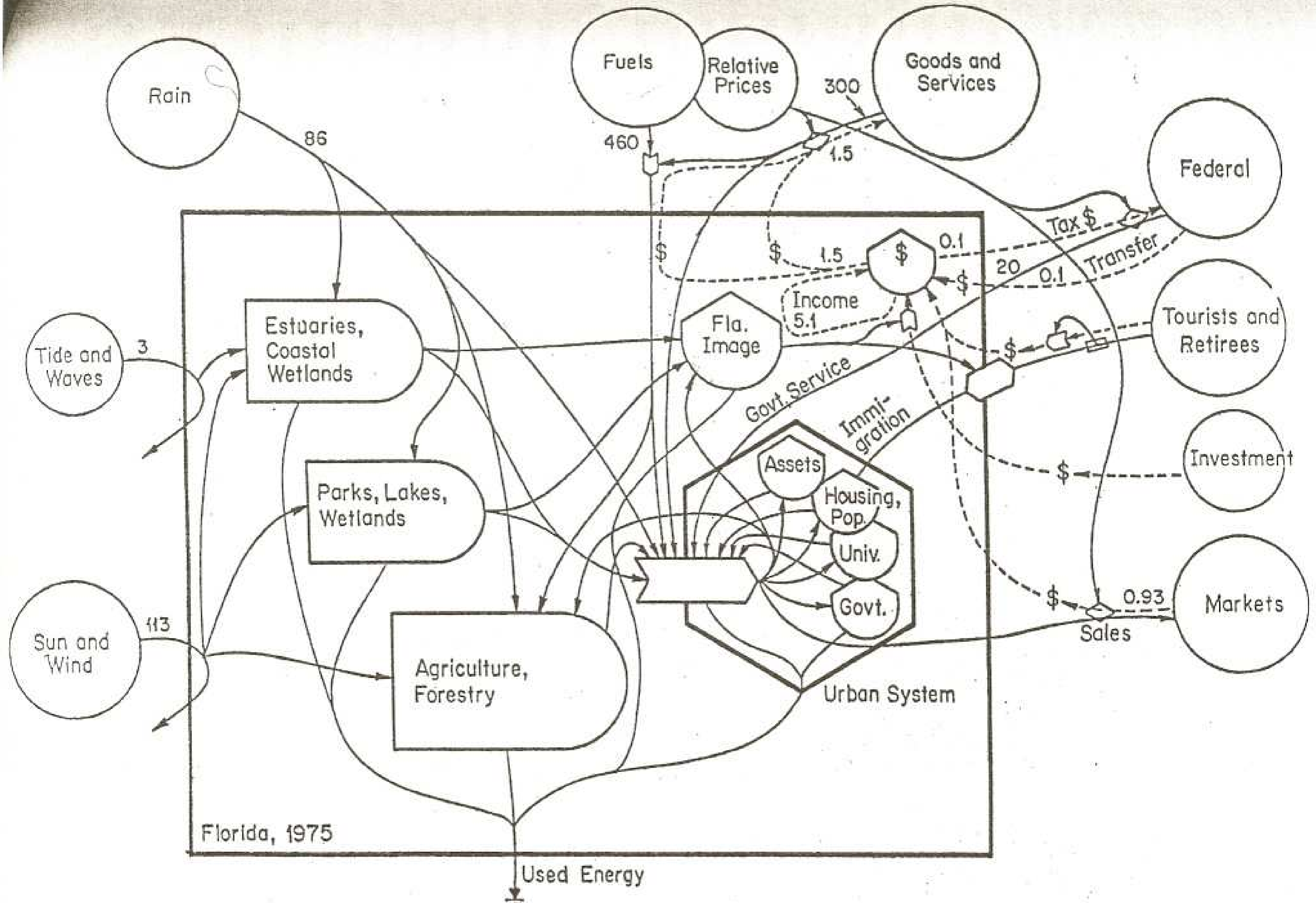

Fig. 9. Model of Florida in 1975. Flows are 10^{12} Calories coal equivalents per year. Dollar flows (dashed) are 10^{10} dollars per year.

further so that the wet areas represent a high position in the water transformation "food chain". The high embodied energy of the wet area gives them greater area value but not necessarily increased biological produce.

GEOLOGICAL WORK AND LANDFORM OF WETLANDS

Much of the work of wetlands may be in geological production of stream banks, bars, meanders, tributary networks, distributary channels, natural levees. These need to be part of wetlands models.

In Fig. 10 is a wetlands model in which the geological work of developing a basin by acid solution of limestones is shown as part of the convergence of high quality work. The basin structure in turn feeds back service to augment the swamp by supplying better water storage, convergent drainage, and storage space for peat, nutrients, etc. The geological process is like a top consumer consuming the energy converging developing even higher quality storage, and contributing by reward loop to the survival of the system. This system is found over much of Florida where percolation of perched swamps dissolves limestone. About 100 parts per million of organic matter percolates downward at about an inch a week and sometime before it emerges from deeper aquifers as spring waters the organic matter is converted to acid which dissolves marls to generate hard water and some slumping and diagenesis beneath the swamp. About 3636 years generates a meter of basin. See Table 3.

Gilliland (1975, 1976) simulated this process of solution, which also generates concentrations of phosphate, uranium and high fluoride, finding commercial phosphate deposits develop in 25 to 60 million years of solution, a time interval that corresponds with the observed geologic time. In other words, the action of sunlight in supporting a landscape with uplands and wetlands over limestone generates high quality geological deposits over long periods of time. The energy transformation ratio of the phosphate deposits is given in Table 3, modified from Odum (1978) and Odum and Odum (1980). The model in Fig. 10 is an example of the way geologic work may be incorporated in ecosystem models; ecosystem models without these kinds of processes are incomplete. Kangas (1981) developed models and calculations of embodied energy for many ecosystems with landforms such as reefs and beaches.

GENERAL THEORY OF HIERARCHY AND PULSING

So far in this paper it has been possible to represent components and sources of ecosystems in webs organized by quality from abundant low quality flows on the left to high quality, low actual energy, but concentrated and embodied

Table 3. Estimates of time and energy in solution of limestone to form swamp basin as modelled in Fig. 10.

Data, assumptions, and conversion factors used:
130 cm water/yr percolating down (Heimburg, 1976);
100 mg/l organic matter ultimately converted to CO_2 acid;
$10^4 cm^2/m^2$; 50 g carbon/100 g organic matter; atomic weight of carbon, 12;
1 mg/l - 1 g/m^3; 1 mole of CO_2 generates one mole of active hydrogen ions plus one of biocarbonate, which dissolved one mole of $CaCO_3$ to biocarbonate solution; gram molecular weight of calcium carbonate is 100; density of marl is about 20 g/cm^3.

Moles of acid generated per square meter per year:

$$\frac{(130\ \text{cm/yr})\,(10^4\text{cm}^2/\text{m}^2)\,(50\ \text{g C/m}^3)}{(10^6\text{cm}^3/\text{m}^3)\,(12\ \text{g C/mole})} = 5.5\ \text{moles/m}^2/\text{yr}$$

Volume of marl dissolved per m^2 per 1000 years:

$$\frac{(5.5\ \text{moles H}^+/\text{m}^2/\text{yr})\,(10^3\ \text{years})\,(100\ \text{g/mole})}{(2.0\ \text{g/cm}^3)\,(10^6\text{cm}^3/\text{m}^3)} = 0.275\ \text{m}^2/\text{m}^3$$
$$= 0.275\ \text{m}$$

This is the average depth leached per 1000 years.

Time required for basins one meter deep = 1.0/.275 = 3636 years.

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values on the right. Fig. 11 helps generalize about the way hierarchy leads to spatial patterns of successive concentration and size. Units to the left are small, each converging to larger units to the right.

Larger items have longer inherent periods as many have shown. More important, the actions of units feeding back on the system to the left pulse with long periods (low frequency) as their size and convergence area (territory) increases. The many small pulses moving from left to right are absorbed in the larger storages to the right in filter actions, whereas the large pulses feeding back on the lower quality units causes them to pulse with the same period of the feedback. For more on these theories see: (Odum, 1979; Odum, 1981). Alexander showed that there are large consumers with long periods that pulse the systems that are smaller in a way usually regarded as a catastrophe because the frequency is lower than the normal lifetime of units and therefore tends to be outside the normal experience of each unit. Alexander (1978) applied this concept of catastrophe as high quality frenzied consumption to earthquakes, hurricanes, and extraordinary floods. The patterns of humanity in recent decades have bacome larger and larger and with longer and longer periods. Forrester (1976), for example, describes Kondratieff economic cycle. Some of the larger scale patterns of human society, economy, and culture have longer periods and larger spatial extent than many geologic phenomena.

Shown in Fig. 11 are the distributions of frequency according to position in the energy quality chain. In other words, period of pulsing action is postulated as proportional to embodied energy so that one may be generated from the other. The further an ecosystem is to the right in the hierarchy scale, the longer are its periods of pulsing. The more an outside source represents concentration of global solar energy, the longer its period, the greater effect it may have, and larger territory of control. Because wetlands receive high quality energies such as floods, they are further to the right than many ecosystems and more subject to long period pulsing.

MODELING WITH HIERARCHICAL FREQUENCY

The concepts discussed imply that ecosystems are determined for the most important aspects of change by long period pulses from the top end of the quality spectrum and especially by long period pulses from the next larger realm - from the right in the energy diagrams. Most ecological modelling has worked from the size of interest toward mechanisms of the parts and thus dealt with small scale variations that are mostly evened out in the hierarchical converging filter. The implication of this theory is that one should always put in an

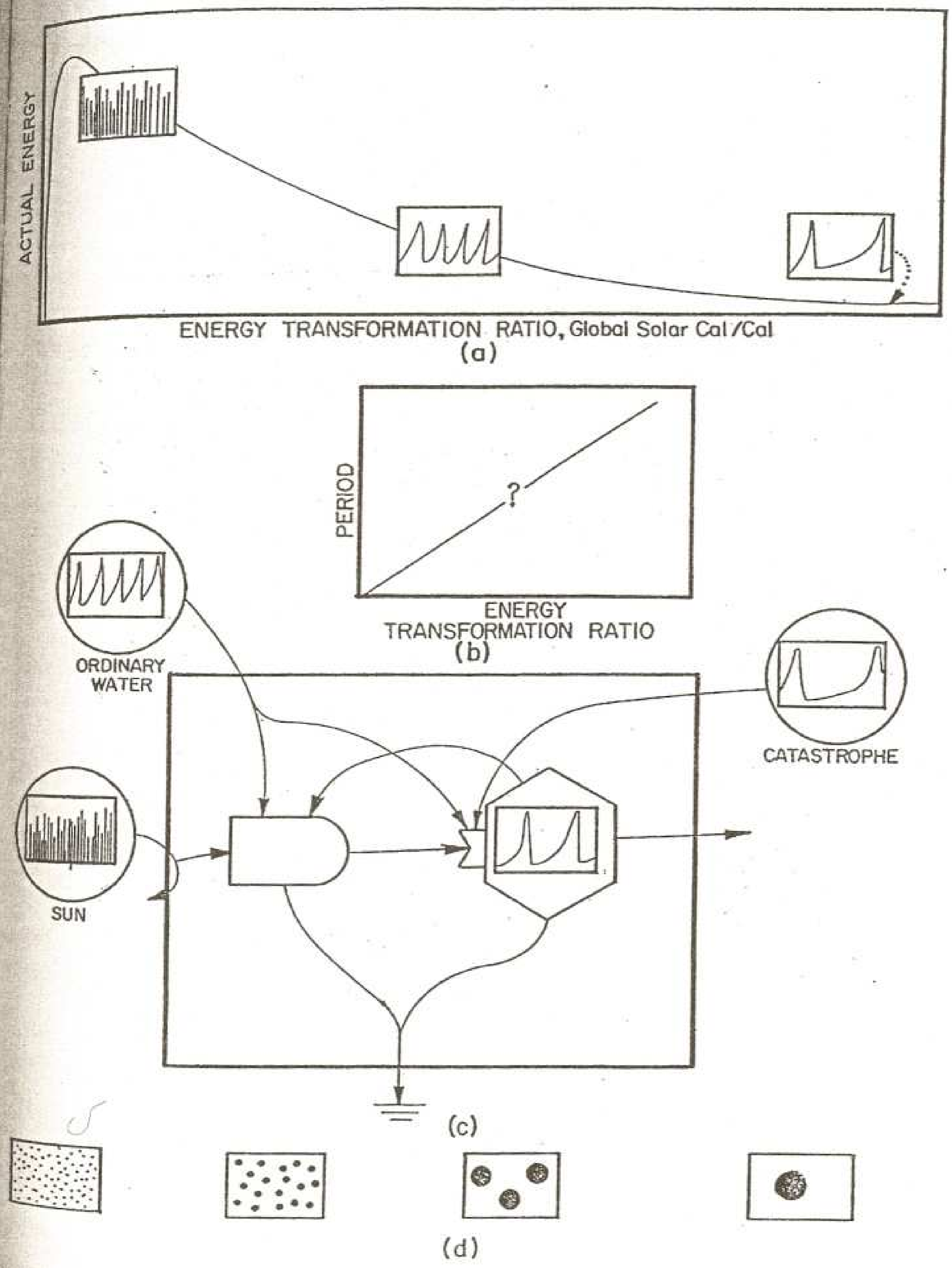


Fig.11. Concept of energy hierarchy and the relationship to pulsing.

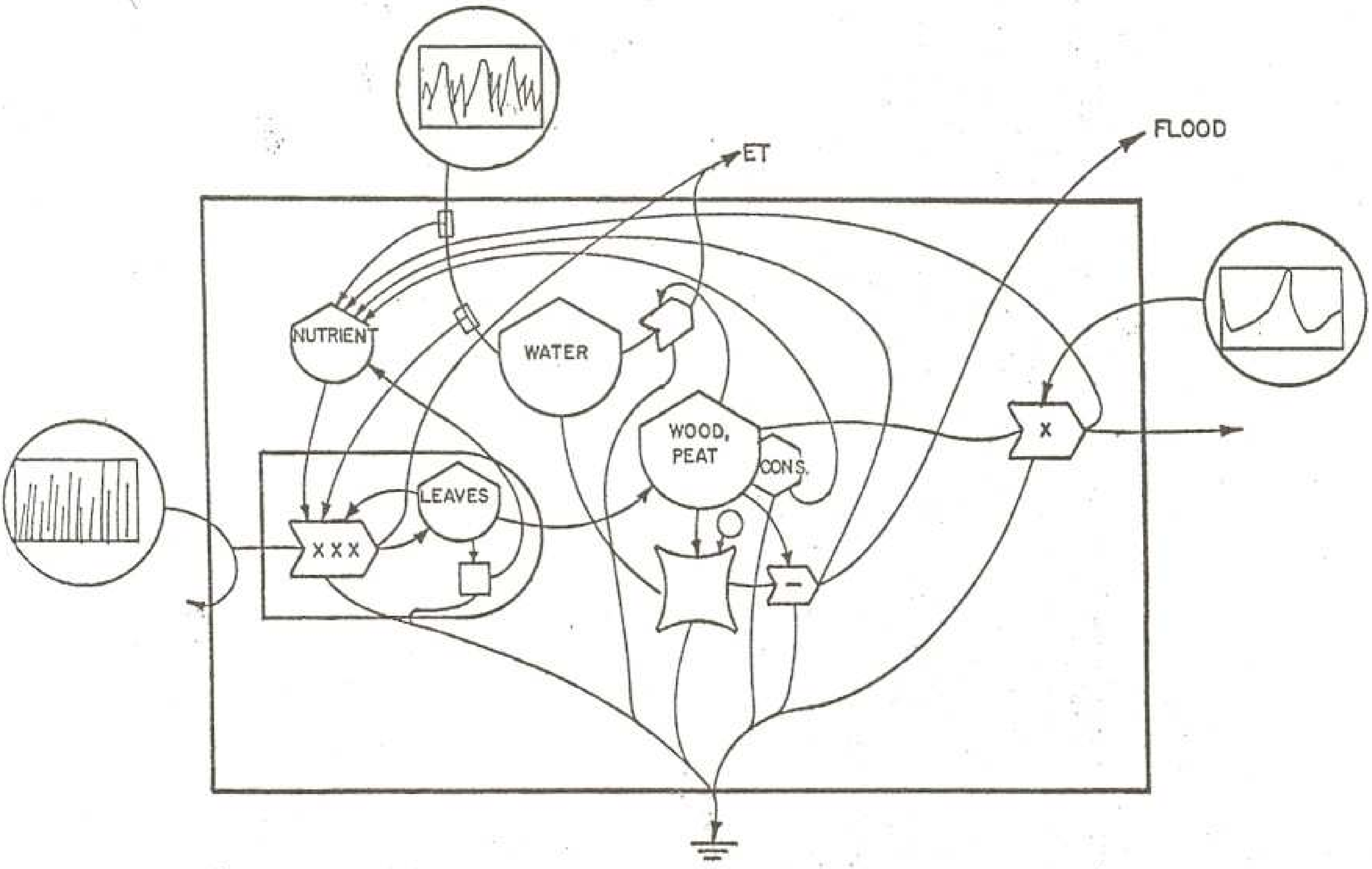


Fig.12. Model of wetland with essence of longer period interactions.

outside driving consumer pulse function from the high quality end of the system with longer period than that of anything in the system, that is, if one wishes to have predictive value for longer periods of time.

Figure 12 summarizes the frequency patterns of ecosystems to be modelled. The variations on the left are so small they can be handled as noise. The ones on the right need to be coupled so that the hierarchical pattern of Fig. 11 is maintained.

ADAPTATION TO FREQUENCIES

A wetland receives many frequencies in various water regimes that are called hydroperiod plus other kinds of frequencies as in waste releases from human economic cycles, cutting cycles of forest consumption, cycles in sediment of forest management, cycles on uplands, etc. It may be reasoned that organisms and other units within a wetland ecosystem have adaptations for the longer periods, perhaps with an association of rapid successional repair, a single-aged reproductive pattern, or other means for maintaining high energy utilization (maximum power) under conditions of longer periods than in many ecosystems.

MANIFESTATIONS OF HIERARCHY AND ADAPTATION IN WETLANDS

The Horton stream classification numbers streams as first order, second order, third order, etc., depending on the number of converging branches. The convergence of the network of rivulets into small streams and eventually into large streams decreases in total energy and volume as does a food chain, but the terminal streams have high energy concentration, high embodied energy, and large abilities to affect the system. The convergence of embodied energy mediated by water is one of the main organizational methods of the biosphere.

Another example of the convergence of embodied energy facilitated by convergence of water was studied by Browder (1976). The nesting of wood storks is timed to the drying up of water-holes in south Florida. The waters contracting concentrate small fishes which the storks can readily use for the increased food demands of nestlings. As shown in Fig. 13, the embodied energy in wood storks is higher than in many other birds because of the extra action of the hydrologic cycle in its concentrating phase. Presumably the storks have important effects on the ecosystem through their ability to migrate from one area to another as different areas develop excesses in their food supplies.

MODELLING CATASTROPHIC INTERACTION

Examples of modelling of catastrophic interactions are given in Figs. 14

Cal per Day per Cal Nestling:

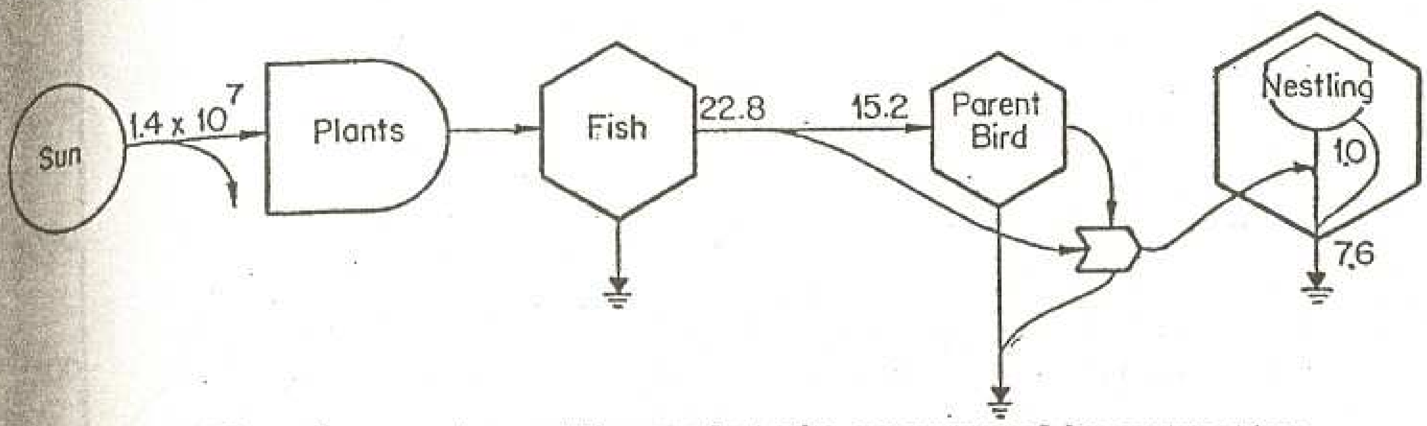
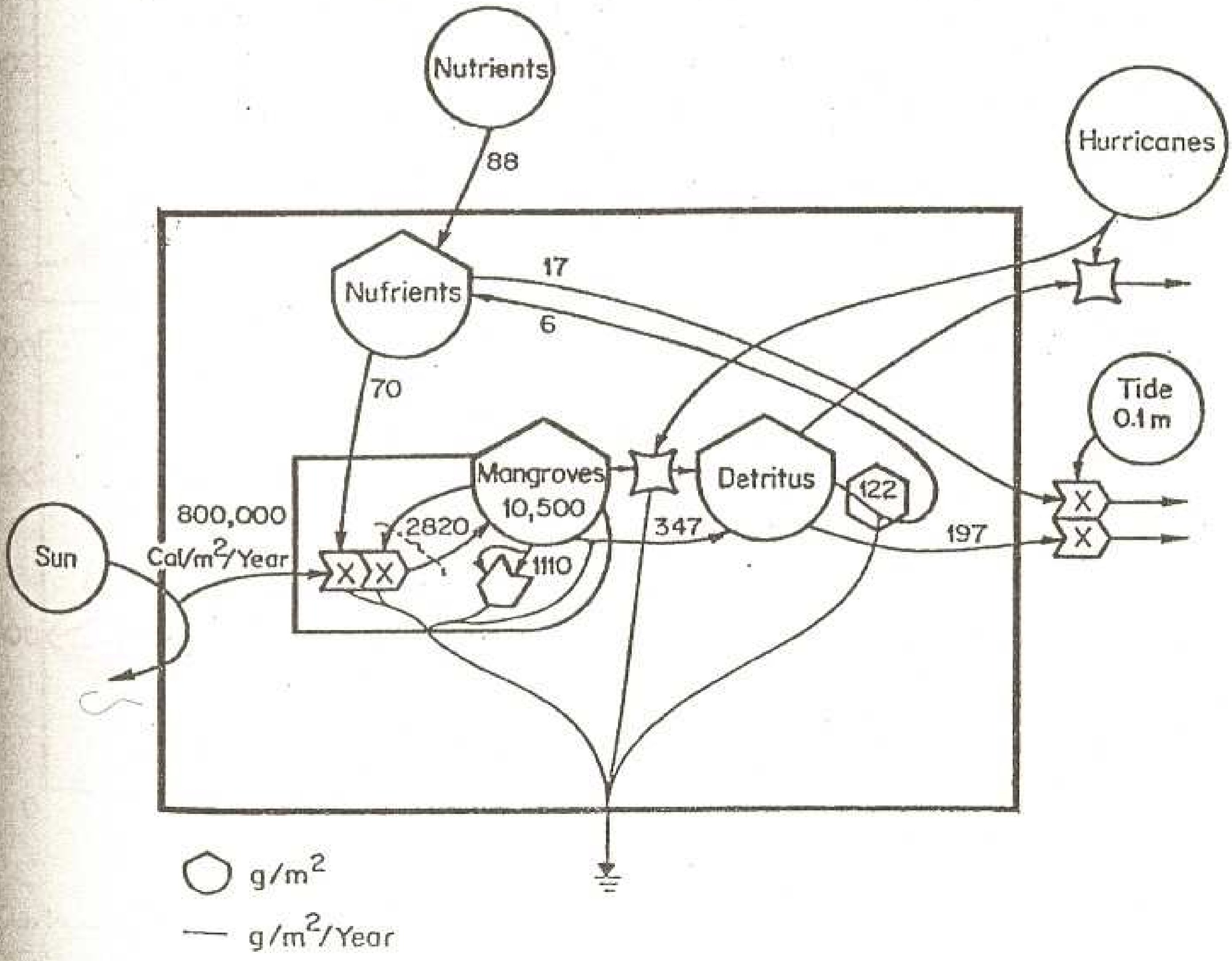


Fig.13. Flow of energy to nestling wood storks concentrated by contracting waters in dry season. Numbers are actual Calories. Energy transformation ratio between direct sunlight and the birds is 1.7×10^7 direct solar Cal/Cal. If global sunlight is contributing through indirect contributions to rain, etc., multiply by 3.4 to obtain 5.78×10^8 global solar Cal/Cal (Browder, 1976; 1978).



(a)

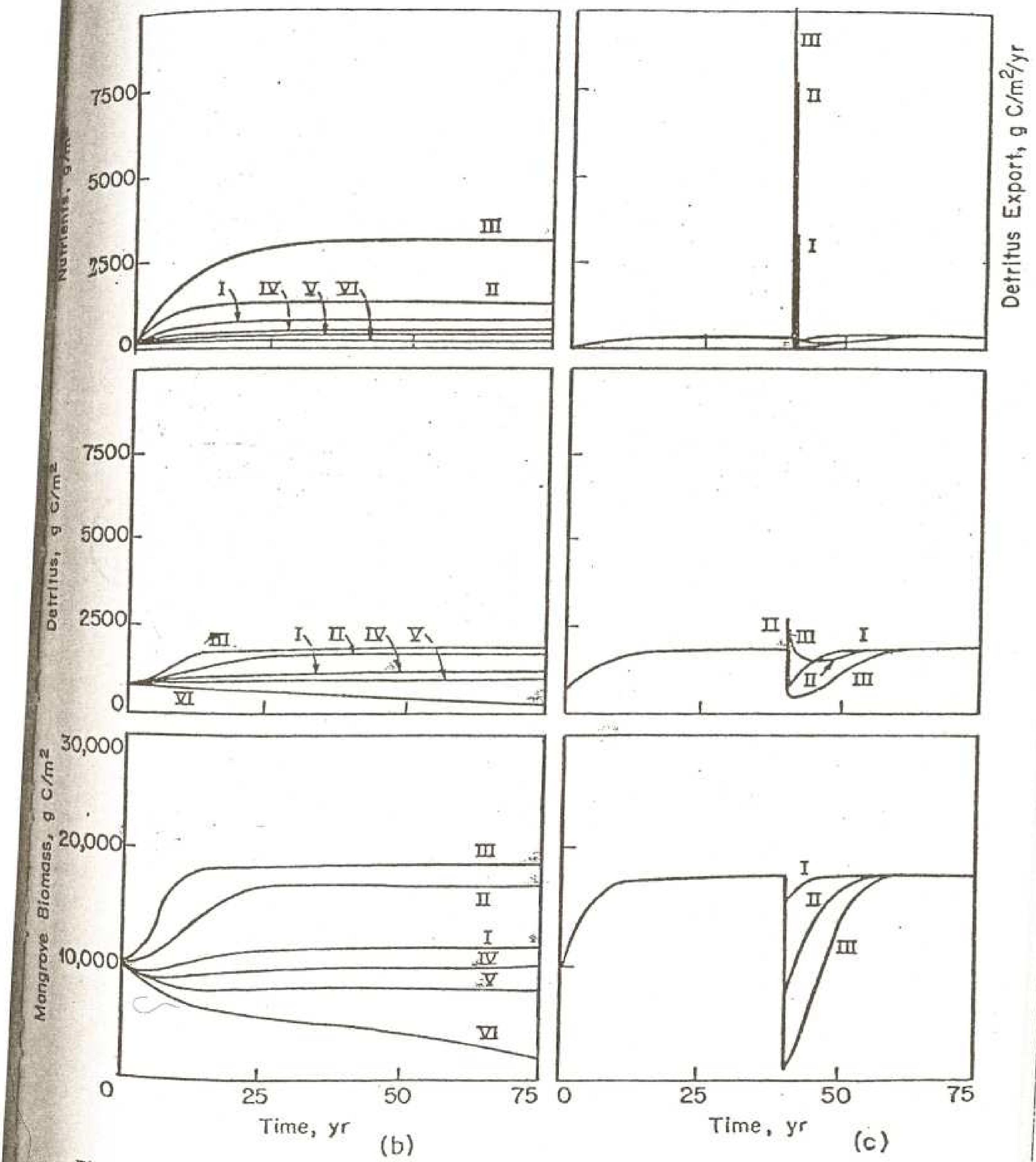
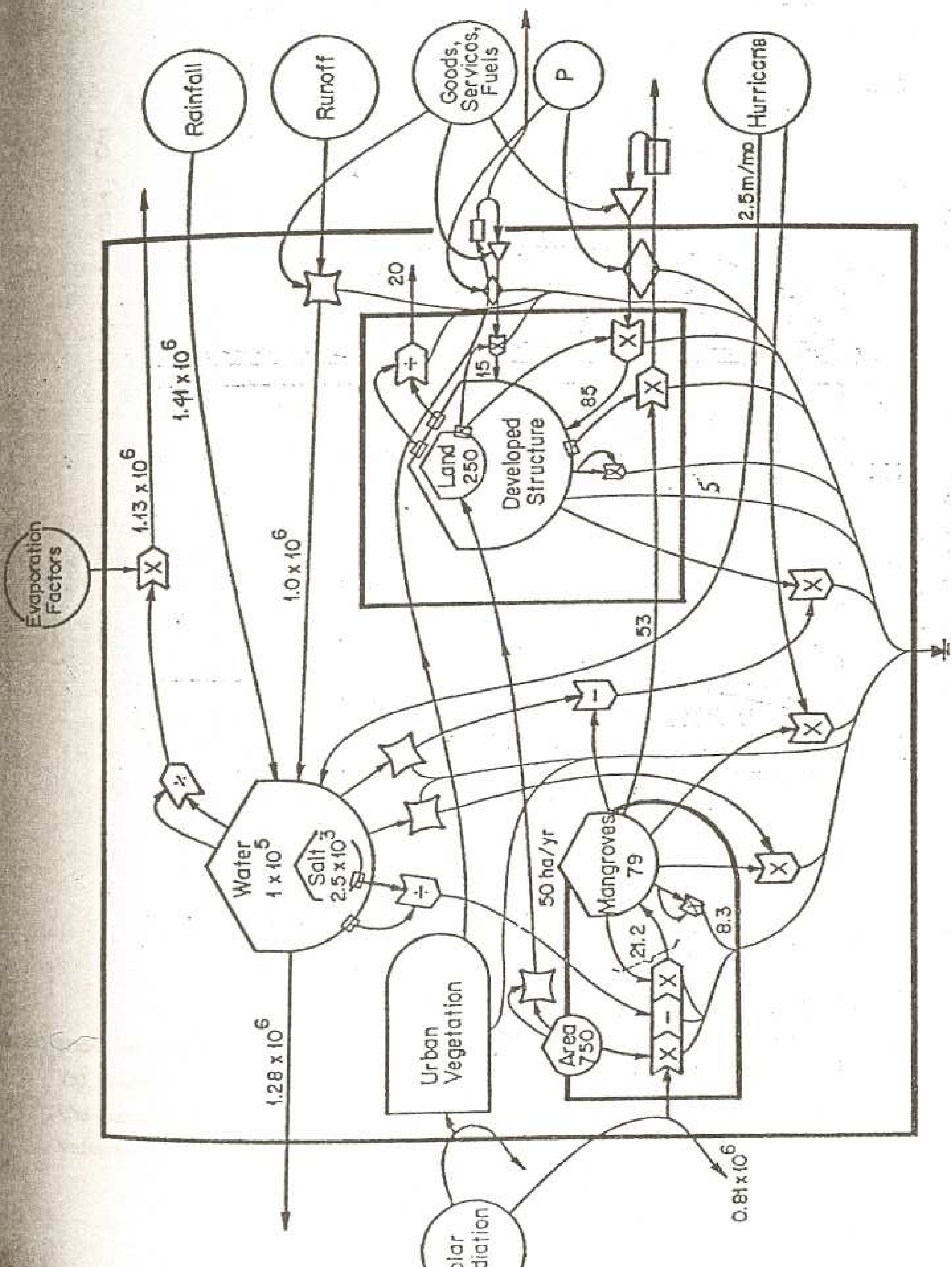


Fig.14. Simulation of tide and hurricane effect on nutrients of mangrove swamp in Florida (Sell, 1977). (a) Energy diagram; (b) simulation of effect of nutrient inflow. I. 87.7 g/m^2/yr; II. doubled; III. four times; [illegible] only rainfall: (c) simulation of the effect of


Evaporation Factors
1.13 x 10^6
Rainfall
1.41 x 10^6
Runoff
1.0 x 10^6
Goods, Servicos, Fuels
P
Hurricans
2.5 m/mo
20
15
85
Land 250
Developed Structure
5
53
Water 1 x 10^5
Salt 2.5 x 10^3
Mangroves 79
50 ha/yr
21.2
8.3
Area 750
Urban Vegetation
1.28 x 10^6
0.81 x 10^6
Solar Radiation

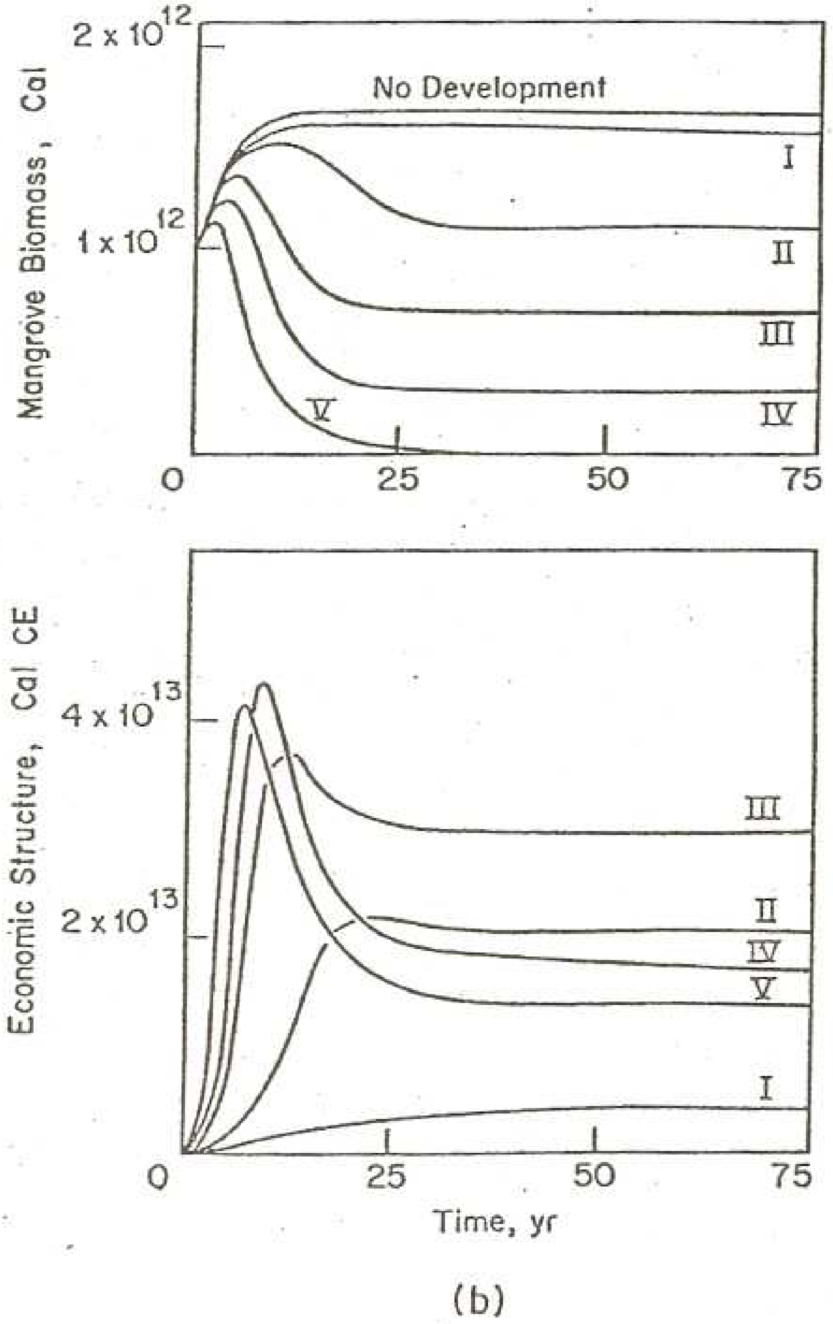


Fig. 15. Model of housing and mangrove with the effect of hurricane (Sell, 1977). (a) Energy diagram; (b) simulation: I to V are decreasing values of P, the purchased inputs attracted by the interaction of mangroves and development.

and 15. Lugo, Sell, and Snedaker (1978) showed adaptation of the mangrove wetlands to a hurricane frequency of about 16 years with the model in Fig. 14. In Fig. 15, Sell (1977) modelled larger combined systems of housing developments and coastal mangrove wetlands and then exposed the model to the long period pulse of hurricanes. Here the housing economy has larger storages and longer periods than the capital storages of the wetlands ecosystems if one does not count the peat and channels that develop over a very long period and more rarely disturbed by most hurricanes. As shown in Fig. 15b, the lower the external price of purchased goods and services, P, the greater the development, initially, but there is an optimum degree of development that maximizes economic value.

THERMAL EFFLUENTS AND SALT MARSHES

Power plants on the west coast of Florida at Crystal River have provided thermal effluents to the salt marshes over a period of 10 years. The power plants have been off and on because of mechanical problems so that the increased heat amounting to 3 to 7°C has been on and off with periods of less than a year. Studies by Young (1974) and Hornbeck (1979) showed maintenance of biological gross production, but a higher turnover, smaller sized individuals, and an adaptation to a short period regime. Animals are those with energies for adapting to a varying temperature regime such as oysters. It might be postulated that a longer regime of pulsing would generate more total production. Figure 16 is a model of the response of the marsh grass to the temperature change which was simulated. Because it is calibrated with observed storages, it has some of the properties needed to have real frequency response.

NUTRIENTS AND CYPRESS SWAMPS

The cypress swamps of Florida may be arranged in a series according to the waters they receive and with them the nutrients available. In Fig. 17 swamps are arranged in order of increasing water drainage from the rainwater dwarf cypress areas at the top to the floodplain at the bottom. With this series there is also an increase in productivity, period of pulsing because of larger storages of wood and peat, and larger pulses in the waters received. Apparently this series differs because of phosphorus and other nutrients. These have very high energy transformation ratios as was calculated for phosphate in Table 1.

COUPLING OF HUMAN WASTE WATERS

Treated sewage waters were added to cypress swamps in Florida as part of

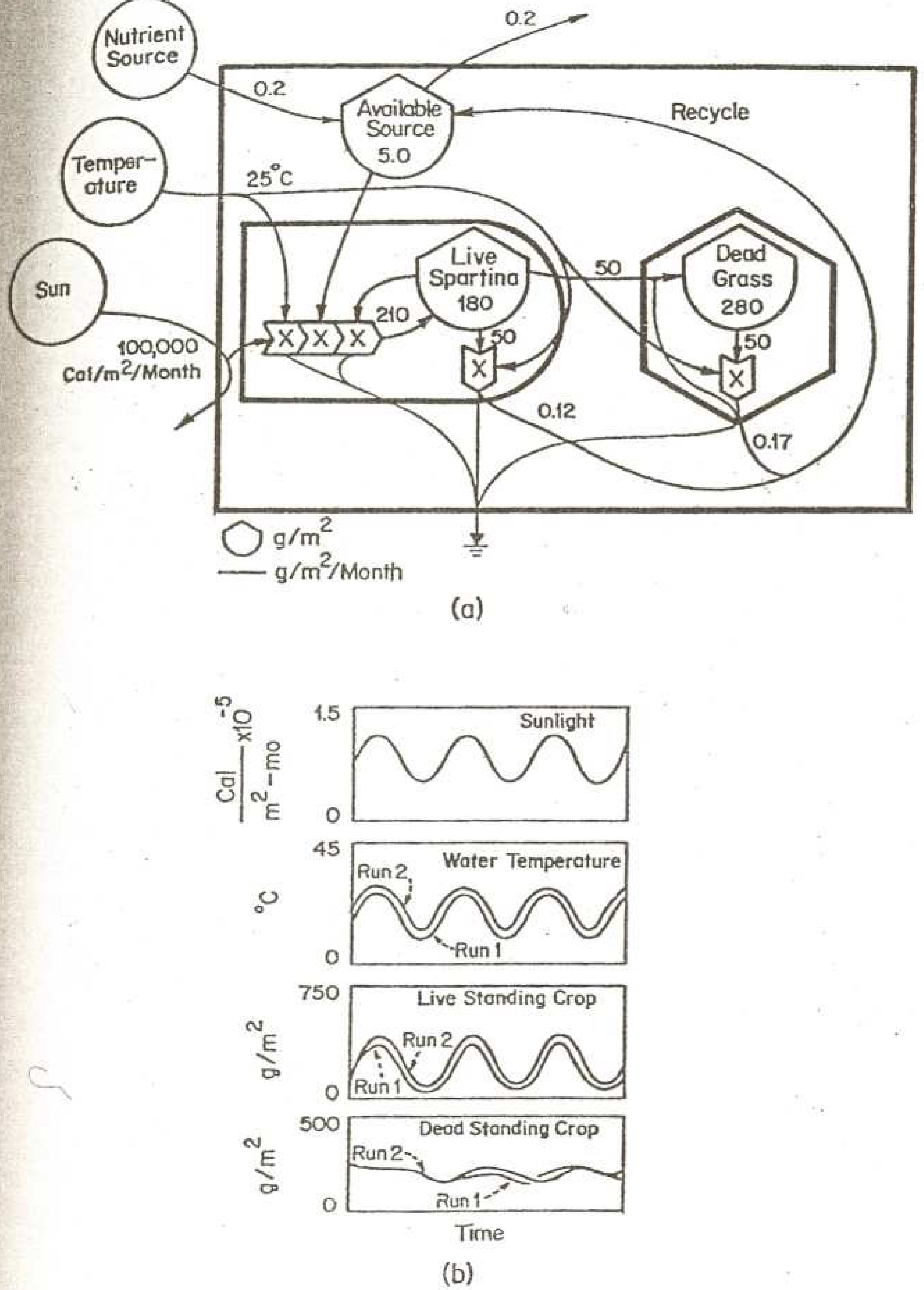


Fig. 16. Simple simulation model of salt marsh and effect of thermal effluent (Young, 1975). (a) Energy diagram; (b) simulations: Run 2, 4°C higher than Run 1.

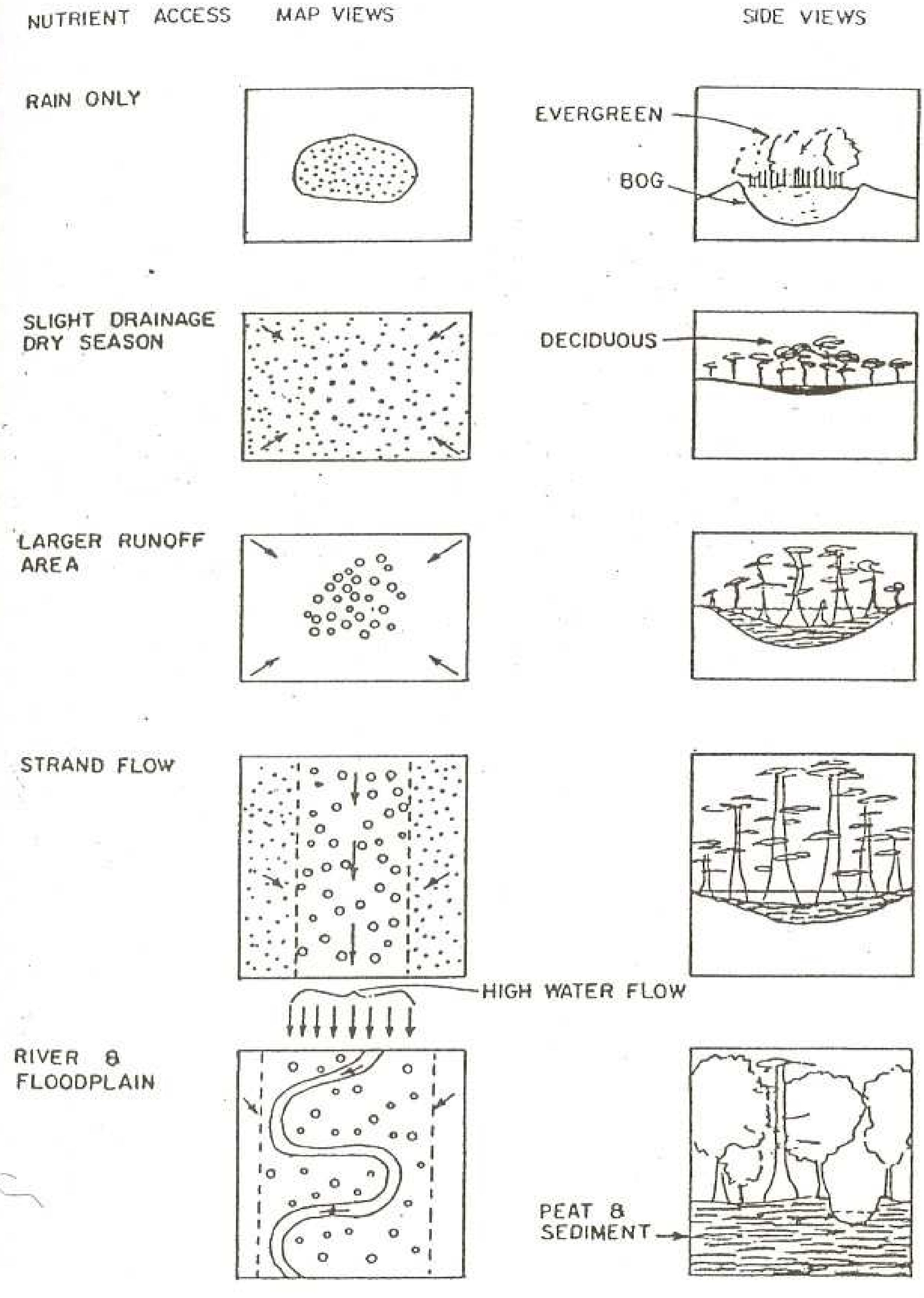


Fig. 17. Cypress swamps of Florida arranged in order of increasing nutrient and water availability from top to bottom (Odum, 1978).

long term rural practices and in experimental studies conducted by us (Odum and Ewel, 1975; Ewel and Odum, 1981). This pattern uses wetlands as an interfaced ecosystem for improving economy of nature and humanity through symbiotic relations.

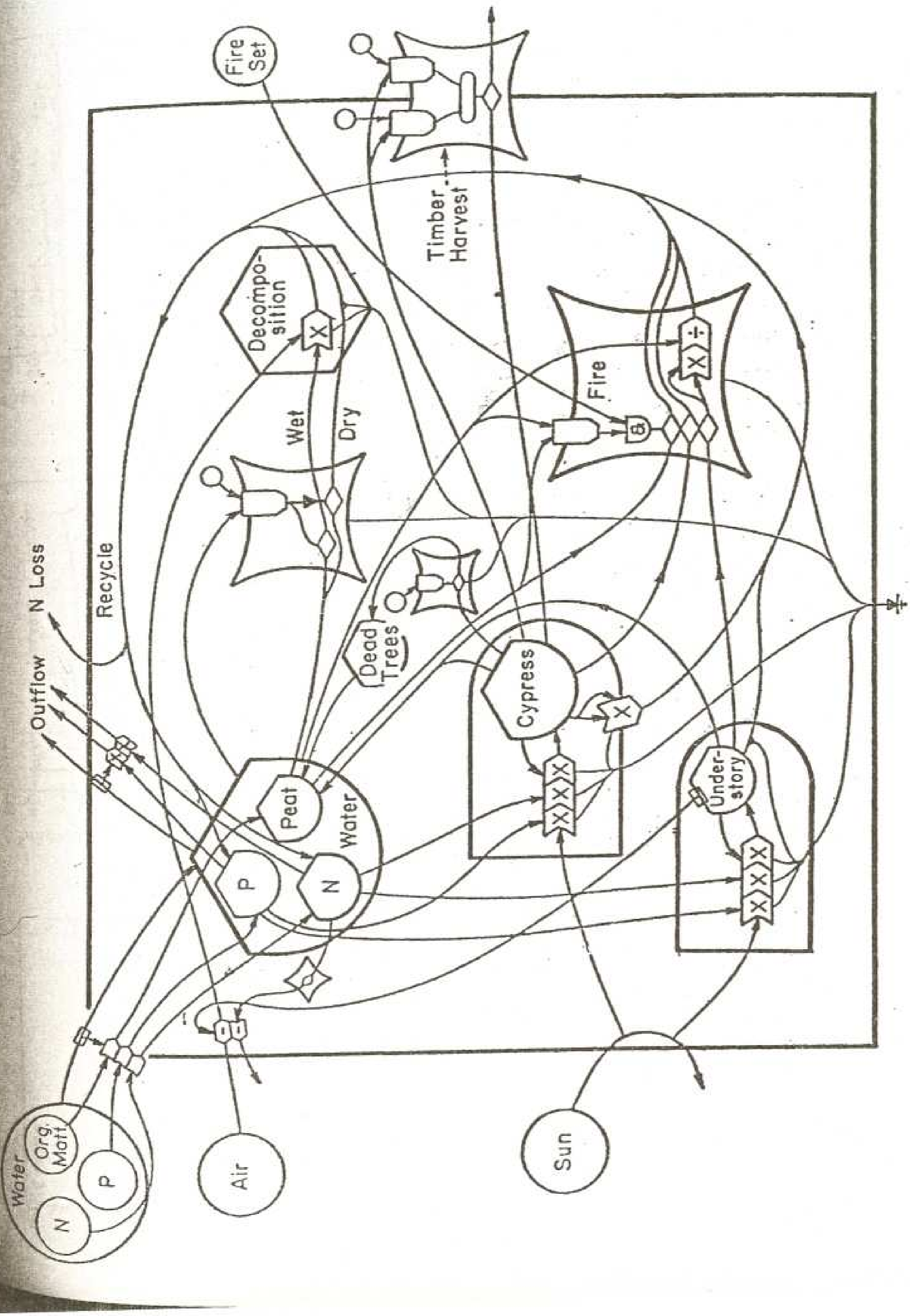
Cypress swmaps in Flroida were mainly cut in the past 100 years. In other words, the economic utilization by humanity is a long period pulse which has dominated the swamps. Whether this period is like their pre-human period or not is not known, but the means of regeneration require conditions that do not occur every year. The even age stands now found may be the normal ones. In connecting sewage waters to the swamps, questions are raised as to what pulsing frequency to use. In recent experiments the sewage waters were removed from a burned cypress dome after it had received the high nutrient waters for 4 years. In the following 4 years the cattails and duckweed diminished and eutrophic conditions diminished. A new set of seedling regeneration did develop in the third and fourth years.

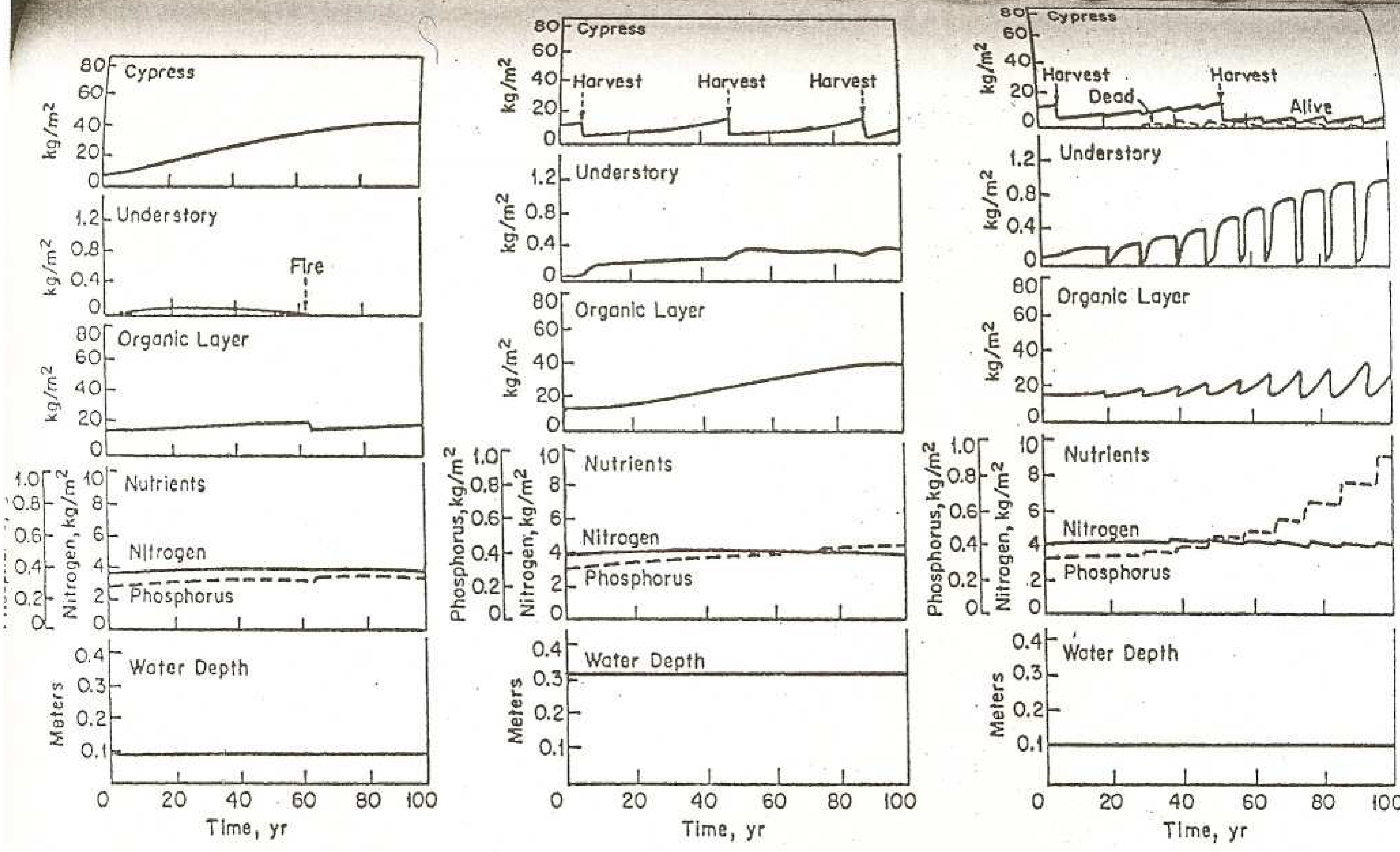
Klose and Deb (1978) simulated swamp waters receiving paper wastes and showed the oxygen range was that of many natural swamps.

Mitsch (1975) developed a model for the nutrient receiving cypress swamps which included fire that had been observed in two experimental domes and a cutting cycle. The model and some simulation results are given in Fig. 18. The model was able to support a cutting cycle without losing its pattern, but not if it was also pulsed with fire. The fire patterns may have been the original natural pulse for which a cutting cycle is now being substituted. The swamps receiving the convergence of the larger pine uplands has a higher quality and longer period than the pines. The matching of ecosystem frequencies to external frequencies is an important opportunity for research and for management. The timing of waste release may be important to maintaining a regime of ecosystems which is predictable, and continuing.

MODELS OF HARVEST CYCLE

Mitsch (1975) developed a model for the nutrient receiving cypress swamps which included fire that had been observed in two experimental domes and a cutting cycle. The model and some simulation results are given in Fig. 18. The model was able to support a cutting cycle without losing its pattern but not if it was also pulsed with fire. The fire patterns may have been the original natural pulse for which a cutting cycle is noe being substituted. The swamps receiving the convergence of the larger pine uplands has a higher quality and longer period than the pines. The matching of ecosystem frequencies to external


Water
N
P
Org. Matt
Air
Sun
Outflow
N Loss
Recycle
P
N
Peat
Water
Cypress
Under-story
Dead Trees
Wet
Dry
Decompo-sition
Fire
Timber Harvest
Fire Set



(b) (c) (d)

Fig. 18. Cypress swamp simulation from Mitsch (1975). (a) Energy diagram; (b) simulation of fire without cutting; (c) repeated harvest without fire; (d) combination of harvest and fire.

frequencies is an important opportunity for research and for management. The timing of waste release may be important to maintaining a regime of ecosystems which is predictable, and continuing.

WATER SAVINGS BY WETLANDS

In the studies and models of wetlands in Florida evidences have accumulated that many of the swamps retain more water from evapotranspiration than the same area of open water. See data on cypress domes by Klaus Heimburg (1976) and data on freshwater marshes (Dolan, 1978) where dieback of dead grasses in winter dry season shields waters from sun and wind. Brown (1978), using data on cypress domes simulated a model of the hydrologic budget of the green swamp region, an area of cypress domes scattered over a landscape of pines and agricultural uses. Clearing and draining the cypress swamps in this example was shown to lose half of the available water due to increased runoff and transpiration losses.

In conserving water and in recycling wastes, the swamps are apparently already well adapted to serve as filters and conservation areas. The period of use and loading of the swamps for the various multiple uses will be that of the pulses in the human economies local and international. How the ecosystems will adapt to these long periods remains to be adequately modelled and understood.

The details of water processing by mangrove vegetation in relation to microclimate was modelled and evaluated by Burns with results given in Fig. 19.

SUMMARY

Wetlands of Florida, including freshwater marshes, salt marshes, cypress swamps, bays, and floodplain forests are high quality ecosystems receiving a convergence of embodied energy with converging water flows. The human settlement pattern is now developing interfaces and use connections to these wetlands, preserving many as their values become better known in saving water, absorbing nutrient wastes, developing valuable products, etc. The emerging hierarchy of landuses shows in the local and regional patterns of humanity and nature. Embodied energy and renewed period appear to be correlated so that modelling of wetlands requires driving functions representing the larger scale with long period pulses of utilization and recycle. Models are useful in regional studies for large scale simulations, for estimating values, estimating economic potentials, for organizing impact statements, for planning spatial distributions of humanity and nature, and understanding the mechanisms within wetland ecosystems that adapt them to the larger scale pulses characteristic of water regimes. Models of smaller aspects of wetlands have short term predictability since they

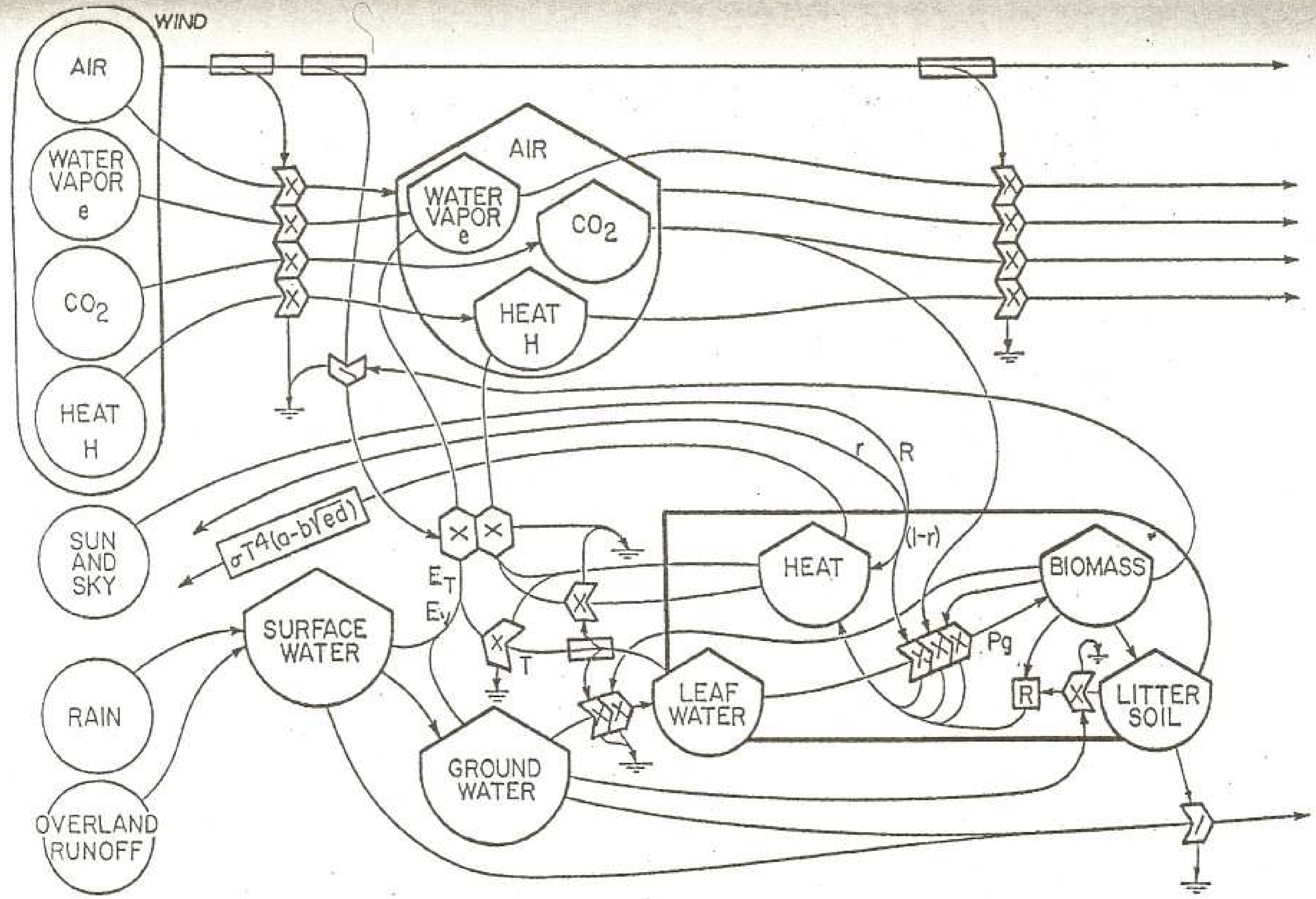


Fig. 19. Water model for section of Fakahatchee Strand (Burns, 1978).

are driven and entrained by larger systems of which wetlands are part.

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