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ENERGY BASIS FOR HIERARCHIES IN URBAN AND REGIONAL SYSTEMS[1]

Mark T. Brown[2]

Abstract.—Understanding the hierarchical patterns of energy flow in landscapes is a major objective in the sciences of environment and human settlement. Data on regional and national patterns of landscape organization are used to test theories of energy flow control of hierarchies. Simulation models are developed to quantitatively relate ideas of mechanism and energetics to hierarchical structure, spatial pattern, and spectral distribution observed in systems of humanity and nature.

INTRODUCTION

Complex systems such as ecosystems, industrial processes, and networks of cities in the landscape appear to be organized in webs of energy flow with multiple levels of components (fig. 1a). These may be visualized in simplified form with diagrams as in figure 1b. The patterns have spatial manifestations, with many small units converging energy to a few larger ones.

Theories developed to account for these hierarchical patterns may be based, in part, on the theory that systems compete for power and survive by developing a structure of energy flows that maximizes useful power. The maximum power principle was enunciated by Lotka (1922) and additional corollaries were proposed by Odum (1967, 1971, 1975) and Odum and Odum (1976). The type and form of web adapting to different combinations of energy from the environment produces different spectral distributions and spatial patterns, which may be predictable from simple models.

Theoretical Concepts

An Energy Basis for Hierarchies

Given in figures 1a and 1b are simplified energy circuit models (Odum 1971) that depict energy flow and storage in hierarchically organized systems. These diagrams show energy flow and control action feedbacks in five-compartment (level) hierarchies and are the basic configuration for the organization of data in this investigation of an energy theory of hierarchically organized systems.

The following concepts and theories about the relationship of energy, its spatial distribution, and resulting hierarchies are postulates and are the basis for examining data on systems of Florida and the nation.

Energy Constraints

Systems operate under the constraints of the First and Second Laws of Thermodynamics and Lotka's Maximum Power Principle (Lotka 1922) and corrollaries as proposed by Odum (1975) and Odum and Odum (1976); and are organized in a manner to remain competative and stable, increasing inflowing energy when excess energy is available.

Energy Quality and Embodied Energy

Odum (1976, 1977, 1978a, 1978b) and Odum and Odum (1976) suggest that there is a quality to energy, which is a measure of its ability to do work. Quality of energy is related to the degree to which it is concentrated; with dilute energies like sunlight, winds, waves, and other natural energies having lower quality than the more concentrated energies of fossil fuels.

Energy Quality and Frequency of Energy Sources

Recently, Odum (1981) and, in earlier studies of the cycles of order and disorder, Alexander (1978) have suggested that the quality of an energy is related to its frequency in the time domain.

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Others (see Simon 1973) have suggested that frequency and place in hierarchy are related to the extent that high frequency is associated with low place in hierarchical order and low frequency with high hierarchical place.

Energy Quality and Power Density

One measure of the intensity of energy utilization in the landscape is power density (Odum, Brown, and Costanza 1976), or the rate of energy flow per unit area (Cal/acre·year). In this manner, the energy intensity of one area can be compared on a relative scale with others. In urban systems, power density is considered to be the rate of embodied energy consumption per unit area and in natural ecological systems of the landscape, power density is the rate at which energy is fixed, as measured by gross primary production.

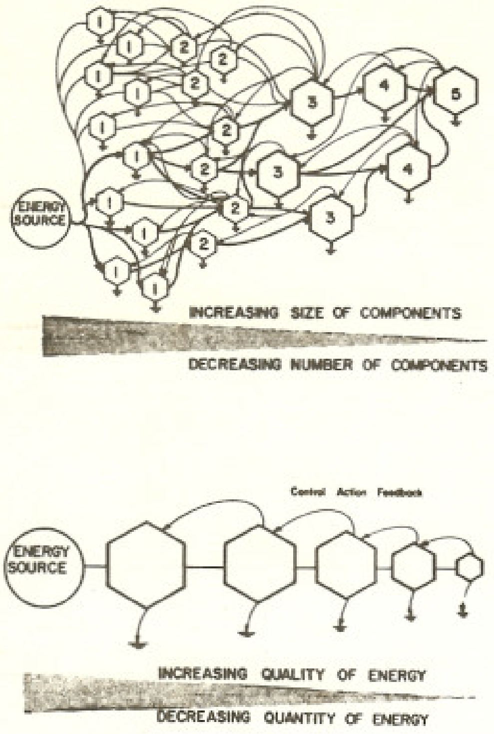

Figure 1. The web of energy flow and compartments of complex systems. Shown above is a hypothetical energy web, and below a simplified form organized as a hierarchy.

Previous Studies of Hierarchies

Many theories for hierarchical organization of systems and the resulting distributions of components, dating from antiquity, are prevalent in the literature. As the amount of published scientific literature has grown exponentially in the last 80 years, so has the number of scientists using the concept of hierarchy in the analysis of physical, biological, and social systems. Most notable in recent years are Woodger (1929, 1937), Whyte (1949, 1969), von Bertalanffy (1933, 1968), Simon (1962, 1973), Wilson (1969), Bunge (1969), Weiss (1971), and Laszlo (1972, 1973). Hierarchy in social systems is investigated by numerous authors (i.e., Aldrich 1979; Blau 1972, 1974; Burgess and Park 1924; Emery and Trist 1973; Glassman 1973; Landau 1969; Monane 1967; Thompson 1967; Weber 1946, 1947).

The hierarchy associated with the landscape of cities in regions was first enunciated in 1933 by Christaller (1966) and further developed by Losch (1954). Many authors have applied central place theory to regions and developed the theory further (see Dokmeci 1973; Henderson 1972; Purver 1975). Others have been critical, finding at least four specific weaknesses (see Beckman 1955; Henderson 1972; Tinbergen 1968; Van Boventer 1969). A number of authors have used gravity models and equations of diffusion for allocating regional influence of centers and calculating the spread of innovation (see Beckman 1956, 1958, 1970; Berry 1972; Hagerstrand 1966; Isard and Peck 1954; Mansfield 1963).

Zipf (1941) and later Steward (1947) have suggested there is a mathematical relationship between rank of cities and population size. MacArthur (1957) has suggested rank-abundance curves for the study of the structure of animal communities, and Odum, Cantlon, and Kornicker (1960) have postulated a hierarchical organization of ecological communities using a cumulative logarithmic species-diversity index.

Few previous studies of hierarchy have dealt with the energy control of landscape organization, but many with economic aspects and some with the physical constraints of hierarchical organization.

Plan of Study

In this study the hierarchical organization of the landscape and resulting energy spectrum of energy storage and flow were investigated at three levels: the regional level of ecosystems and urban land uses, the organization of cities in the landscape, and the organization of land uses within cities. In addition, relationship of intensity of development to the spatial area of influence was investigated at different levels of organization in the nation, the state, and within districts of the state. The specific plan for the analysis of regions, districts, and subdistricts is as follows.

First, energy spectra for many different types and sizes of systems were constructed to understand general trends of energy flow and storage in observed hierarchies.

Second, maps were made of ecosystems and land uses at two levels of study; the regions of Florida and cities within these regions.

Third, generalized models of each urban land use type were evaluated and spectra and energy storage and energy flow were calculated.

Fourth, specific analysis of the external energy requirements of areas of different sizes and an energetic evaluation of cities of different sizes were conducted.

And fifth, a series of theoretical models of hierarchical organization were simulated on analog and digital computers to explore different energy flow and storage characteristics under different organizations and pathway configurations. And then data from an aquatic ecosystem of Florida were used to test theories of hierarchical distribution and energy control.

METHODS

General Methods and Definitions

A graphic language is used throughout this paper to describe energy flow and interaction in complex systems. The language is a graphic means of depicting systems as Nth order differential equations, since each symbol represents a mathematical relationship of either energy flow, interaction, or storage relative to time. For a complete description of the language and its development see Odum (1960, 1967, 1971, 1973, 1976a).

Evaluation of Observed Hierarchies

The trends of hierarchical organization and energy spectra were graphed semilogarithmically for systems of differing scales and complexity. Data were gathered from various sources in literature and from various local, state, and federal agencies in published reports and in some cases unpublished data.

Land Use Maps of Region and Cities

Three regional areas of differing character and size were analyzed for total energy budgets, land use, and resulting hierarchic organization: the Kissimmee Everglades Basin in south Florida, a subtropical region of relatively intense urban development; the St. Johns River Basin, a region on the coast of central Florida dominated by a major river and agricultural lands with moderate urban development; and Lee County, Florida, an area in southwest Florida that is a coastal county with extensive tourism and an agriculture based inland. The county has experienced recent very rapid growth (fig. 2).

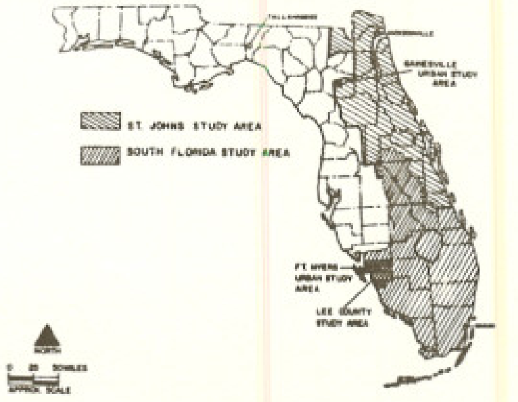

Figure 2. Map of Florida showing three regional study areas and two urban study areas.

Two urban areas were analyzed in detail for total energy budgets and power densities, energy budgets and power densities of land uses within the urban areas, and resulting hierarchic organization of the urban landscape: Ft. Myers, Florida, an urban area on the southwestern coast of Florida whose main economic inputs are from tourism, and is a government center; and Gainesville, Florida, an urban area in central Florida that is a governmental center and center of university education (fig. 2).

The average direct power density for each of the land use classifications was calculated by first selecting a representative sample of structures in each of the land use types (approximately 10% sample size), and then obtaining yearly energy consumption data from local utility records for each of the selected structures.

Indirect power density was calculated for the land use categories in the Ft. Myers study area only. A detailed model of energy flow between the main sectors of the local economy for 1973 was evaluated (Brown 1980) to obtain the energy embodied in goods and services that were consumed in the residential, commercial, industrial, and construction sectors of the economy. Evaluation of the flows of dollars among sectors of the economy was used and converted to embodied energies using a conversion factor of 21,000 Cal CE/$.

The structure associated with each land use was determined from property tax records of both cities where total area of structure for each of the sample structures was used. Volume of structure was calculated by multiplying area by average height of buildings.

Land Use Maps

Land use maps were constructed from false color infrared and black and white infrared photographs taken in 1973 and 1974. The land use map for the south Florida region was prepared during previous studies (Odum and Brown 1976). Areas of each land use were determined by cutting different land uses from the map and weighing them on an analytical balance. A conversion factor of grams/acre was used to convert from weight to area.

Urban Land Use Power Densities

Power density is a measure of energy flow per unit of time per unit of area. In this study, power density if expressed in units of Cal CE/acre ·year. Power density is expressed as the addition of energy consumption of fuels and electricity per unit area (referred to as direct power density), and consumption of the energy embodied in goods and services per unit area (referred to as indirect power density). Total power density results from the addition of both of these types of input energies.

Classification of Cities by Average Power Density

An average city power density was determined for all cities within each region by using averages derived in detailed studies of the two urban areas, Gainesville and Ft. Myers, Florida. The area of each city is not necessarily the actual area within legal city limits, rather it is the area that when viewed from aerial photographs is within the major concentration of urban land uses. In some cases this area may be smaller than actual city limits and in other cases, where suburban sprawl is evident, the area may be considerably larger.

Development Density and Imports/Exports

One measure of production and consumption in regional systems is gross domestic product (GDP) as determined from the total flow of dollars within a regional economy. While domestic product is not always available for regions, it may be determined from employment data and averages for productivity per employee in each economic sector.

GDP for counties in Florida, states, and nations were determined from employment data, and "development density" was calculated by dividing GDP by land area of each county.

Export multipliers for each county and state were determined in the following manner: employment data for eight broad economic sectors (agriculture, manufacturing, wholesale and retail trade, government, services, transportation and public utilities, banking and finance, and construction) were obtained and compared to the same data from the U.S. economy. Positive departures from the U.S. percent employment were considered to indicate that portion of each economic sector that was export employment (for a detailed discussion of location quotients and methods see Hielbrun [1974]).

Exports were determined by multiplying number of export employees in each economic sector by the productivity per employee for that sector. It was assumed that local differences in employee productivity were negligible.

GDP and exports for 21 selected countries were obtained from United Nations (1978). Calculations of export multipliers and GDP were not necessary since published data are available directly.

Simulation Models of Hierarchical Organization and Energy Spectra

A series of theoretical models were simulated on both digital and analog computers to test hypothesis and evaluate structure and characteristic properties of systems organized in hierarchical fashion. As the models grew in complexity and insight gained, a final model, which was a synthesis of previous models, was simulated using data from Fontaine (1978) for an aquatic food chain.

Simulation Techniques

Models were drawn using the energy circuit language, and computer programs were written directly from the graphic model. The facilities of the Northeast Regional Data Center on the campus of the University of Florida were used for digitial computer simulation, and DYNAMO simulation language (Pugh 1970) was used. Some models were simulated on an EAI Miniac analog computer. The simulation models had one thing common to all—each is a chain of five autocatalytic components connected in series. Differences in the successive models are in the kinetics of the connections between components; with the first models having simple linear flows between components, and later models being more complex.

RESULTS

Similarities of Differing Systems and Scales

Empirical evidence of hierarchical trends in large-scale, complex systems of the landscape are presented as energy spectra in graph form, where the number of units in each level of the hierarchy is graphed on the vertical axis, and the power per unit (or power density per unit) is graphed on the horizontal axis. The energy spectra presented here are a few examples of the many systems investigated.

Figure 3 is an energy spectrum of cities in Florida. Zipf (1941), using population and rank of cities, described a frequency distribution that existed for cities in the United States and other countries. He empirically reasoned that all rank-size distributions of cities should be a straight line when plotted as a log-log graph. Countries not exhibiting a straight log-log distribution were suffering from some form of disunity, and would tend toward unity (as described by his straight line log-log plot) if the forces causing disunity were removed. In a growing region like Florida, the forces of population growth may well account for the departure from a straight line distribution shown in figure 3a. The departure from the ideal distribution that occurs with the smallest cities may be a function of data, since many small cities are not incorporated and therefore not included in the statistical census of cities.

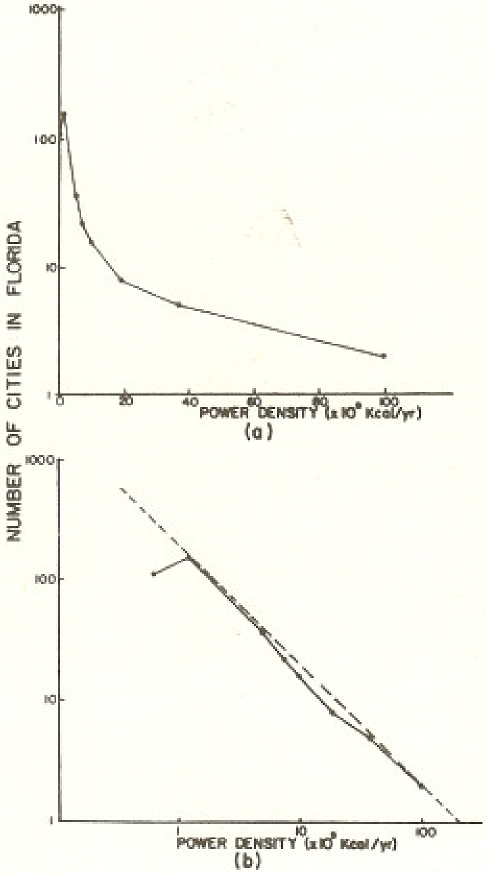

Figure 3. (a) Energy spectrum of cities in Florida graphed semilogarithmically, showing the trend of frequent occurrence of low power cities and less frequent occurrence of the very high power cities in the landscape. (b) Log-log plot of the energy spectrum of cities in Florida, after Zipf (1941), showing a negative slope of approximately 1.

Notes to Fig. 3.

Data on population of incorporated cities of the State of Florida are from the Bureau of Economic and Business Research, University of Florida (1978). The distribution of city power density was done graphically, where cities with similar power densities were grouped together and assigned a weighted average power density.

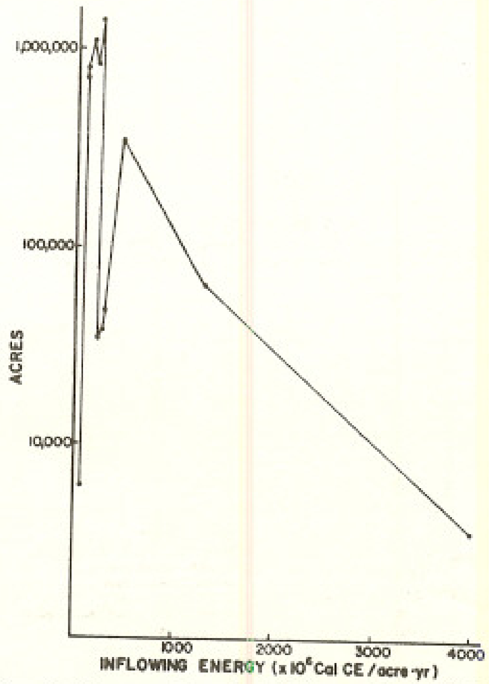

Figure 4. Energy spectrum of embodied energy in natural land production and urban land use power densities in the south Florida area, showing the spatial character of production of both natural and urban lands.

The composite energy spectra for south Florida in figure 4 is a graph of the power density of all input energies versus the number of acres of that particular power density. The graph is based on the spatial distribution of incoming energy, both natural energies and fossil fuel derived energies.

The energy spectrum in figure 5 shows the energy chain of increasing quality of energy as it flows from natural lands through the urban areas of the St. Johns River Basin and the Kissimmee-

Everglades Basin. This graph depicts the spatial character of energy chains, as there are large areas of low-energy lands to concentrate dilute low-quality energies and pass them up to the smaller yet very high-energy lands of the cities.

Regional Analysis

The Landscape of Cities within Regions

When an average power density was calculated for cities, there was a tendency for the cities to fall into the five classes of cities listed in table 1. Because of the large area of wetland ecosystems in the south Florida study area, the majority of cities of all sizes were sampled from the St. Johns area. It was felt that due to the extent of this wetlands coverage, and that developable land is confined to a very narrow strip along both coasts, the south Florida region represents a unique situation from a physical standpoint, and this inhibits the development of a complete array of city sizes.

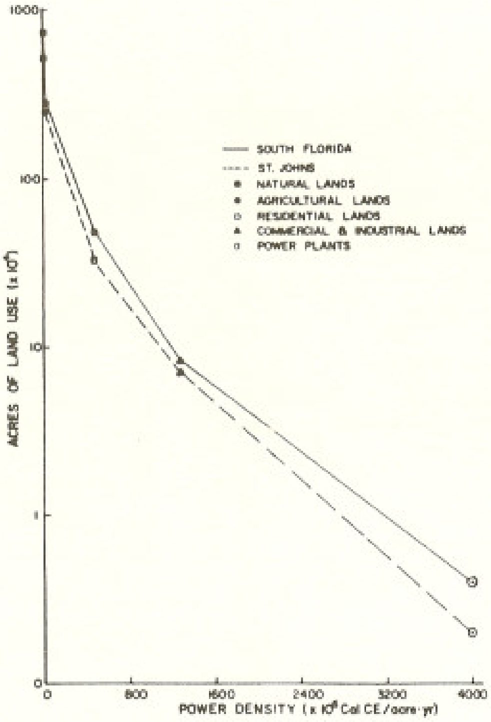

Figure 5. Energy spectrum of incoming energies to south Florida, showing the spatial distribution of both renewable and fossil fuel sources. All energies are expressed in Cal CE. Data on incoming natural energies (sunlight, rain, winds, tides, and waves) are from Costanza (1975). Data on incoming fossil fuel derived energies are from Odum and Brown (1976). The graph depicts the spatial character of inflowing energies. Because of the nature of the landscape and the inflowing energies, there are areas of concentration and areas of relatively sparse inflowing natural energy. Fossil fuel energies are somewhat point sources having very small areas of concentration. Therefore, the acreage of end use was used as the spatial distribution.

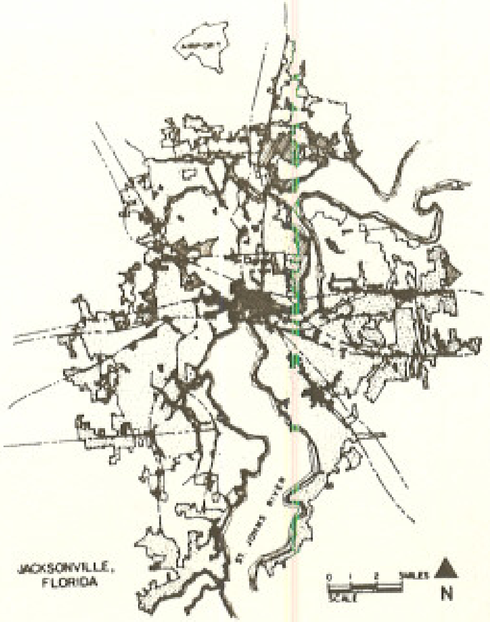

Figure 6. Generalized map of Jacksonville, Florida, a class 1 city; showing the three land use categories: commercial (black area), industrial (cross-hatched area), and residential (stippled area).

Shown in figure 6 is an example of a class 1 city (Jacksonville, Florida). Three types of urban land use are indicated and were used to calculate average embodied energy power densities.

The percentage of each land use for each of the city types were compared and are given in table 1. The extent that a city serves as a central place is indicated by the data as the percent of industrial and commercial land use increases. Thus, the class 1 cities (which includes Jacksonville and Miami) have a higher percentage of total land area in commercial and industrial uses than the other classes.

The areas of land use in each of the categories of commercial, industrial, and other uses are listed in table 2 with corresponding embodied energy power density. The percent of the total

Table 1. Urban land uses and population for 5 classes of cities in Florida.

City Class	Number of Cities	Mean Total Area (acres)	Mean Area Commercial Uses (acres)	Mean Area Industrial Uses (acres)	Mean Area All Other Uses (acres)	Mean Population
Class 1	1	988813.7	8003.9	8142.2	82667.6	504,265
Class 2	2	62877.5	4024.2	3521.1	55332.2	99,006
Class 3	5	13714.4	771.1	519.7	12423.6	37,177
Class 4	21	4584.1	244.9	151.6	4187.5	12,957
Class 5	116	692.9	29.7	9.6	653.6	1,754

Table 2. Areas of urban land use, embodied energy power density, and total embodied energy flow for five classes of cities in Florida.

	Commercial Land Use		Industrial Land Use		All Other Land Uses		
City Class	Area (acres)	Average Embodied Energy Power Density ($\times 10^9$ Cal CE/acre · yr)	Area (acres)	Average Embodied Energy Power Density ($\times 10^9$ Cal CE/acre · yr)	Area (acres)	Average Embodied Energy Power Density ($\times 10^9$ Cal CE/acre · yr)	Total Embodied Energy Flow ($\times 10^{12}$ Cal CE/yr)
Class 1	8004	11.1	8142	4.4	82668	0.7	182.4
Class 2	4024	8.7	3521	4.4	55332	0.7	89.0
Class 3	771	7.5	519	4.4	12423	0.7	16.7
Class 4	245	5.4	152	4.4	4188	0.7	4.9
Class 5	30	3.9	10	4.4	654	0.7	0.6

land area of each of the uses is also listed, and when compared for each class of city, indicates the extent that each city type serves as a central place. The percent of land use in commercial and industrial uses is highest for class 1 cities and decreases with each class.

The Flows of Energy in a Regional Hierarchy: Lee County

The flows of energy through, and the storages of energy within a regional landscape, while somewhat web-like in their organization, can be grouped by quality of energy and a hierarchy emerges. Given in figure 7 is an energy model of Lee County, Florida, organized as a regional hierarchy.

Figure 7 is a "heat energy" diagram, where all flows and storages of energy are evaluated in their chemical potential energy, or heat energy equivalents.

The regional hierarchy has two energy sources inflowing from the outside. The first is natural renewable energies that are the sum of all natural energies inflowing, including: sunlight, chemical potential energy associated with the purity of rainwater, potential energy associated with runoff of rains due to their elevation as they flow to sea level, potential energy associated with winds, potential energy in waves at the coastal margins, and the potential energy of tides over the estuarine areas. The second is the sum of fossil fuel energies inflowing and imported goods.

The renewable energies are cascaded through the regional economy and embodied in natural structure, agricultural structure, and urban structure, directly and indirectly into the higher quality components of governmental and educational structure and humans. Some of this embodied natural energy is exported in locally harvested and manufactured goods.

The inflowing fossil fuel energies and goods are the primary sources of energy for the urban structure and higher quality components. Much of this energy outflows as used heat energy, but is likewise embodied in the structure of the regional hierarchy.

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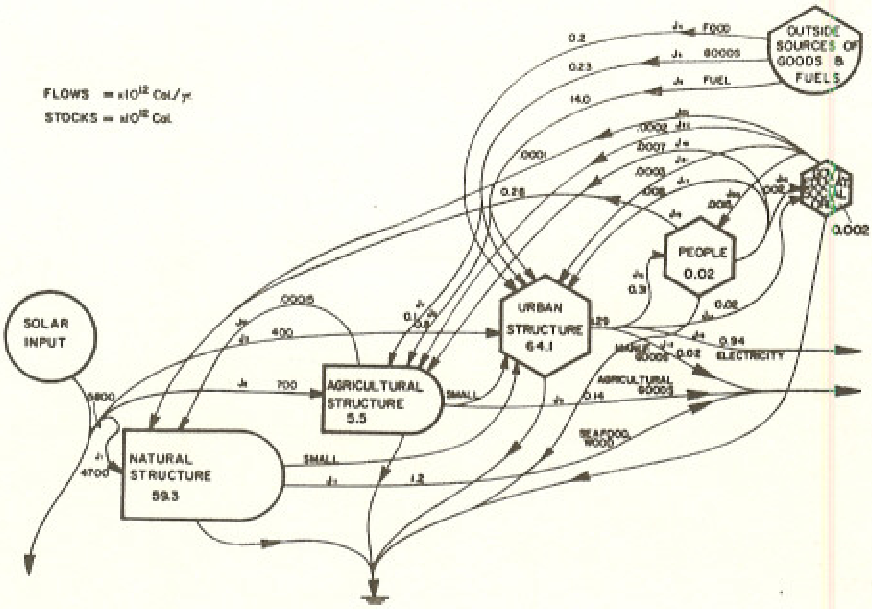

Figure 7. Energy circuit model of Lee County, Florida, organized as a regional hierarchy of components. Numbers are flows and storages of actual energy (heat equivalents). See notes for details of calculations.

Sometimes referred to as a "first law diagram," because the inflowing energies equal the degraded energies or heat losses from the system, figure 7 shows the sum of inputs equal to the outflows for each component as well as for the regional system as a whole.

Flows of energy decrease from right to left as more and more energy is dissipated as dispersed heat from components. In general, there are five orders of magnitude difference in energy flows from the inflows of natural energy to those of the feedbacks of human work; supporting the notion that there is a constant percent decrease from one component to the next in hierarchically organized systems.

When "heat" energies are converted to embodied energy Calories of coal equivalent, the values in figure 8 result. Figure 8 is an embodied energy diagram of the regional hierarchy, thus there is no energy outflowing as dispersed heat, but it is embodied in the next level components as energy is "concentrated" through the system. Comparison of figure 7 with figure 8 shows the very large flows of energy from natural sources, when expressed in coal equivalent Calories of embodied energy, as having nearly the same order of magnitude as those of fossil fuel sources.

Development Density and Imports/Exports

Development density (GDP/sq mi) was evaluated for various counties in the State of Florida, various states in the nation, and various countries. Then exports are evaluated using an export multiplier method for counties and states, and exports for countries were obtained from the literature directly. Development density was related to exports in a series of nomographs for the three different sized regions and are summarized in figure 9.

The nomograph in figure 9a is a log-log plot of development density versus export for the combined data from counties, states, and countries. Assuming a linear relationship between development density and exports and plotting an arithmetic scale gives the graphs in figure 9b. Statistical analysis using least squares regression gives the following equations for each set of data: (R^2 = 0.98)

$$\text{Counties: Ex} = 0.21 \times \text{Dev.} + 5.75 \quad (1)$$
$$\text{States: Ex} = 0.13 \times \text{Dev.} - 16.04 \quad (2)$$
$$\text{Countries: Ex} = 0.286 \times \text{Dev.} - 1.86 \quad (3)$$

where, Ex = Exports/sq mi, and
Dev. = Development density (GDP/sq mi).

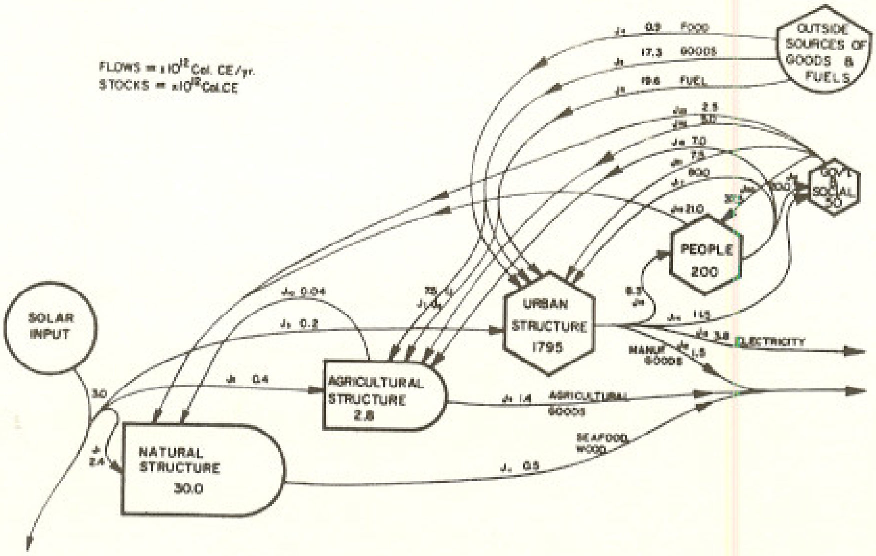

Figure 8. Energy circuit model of Lee County, Florida, evaluated in coal equivalent Calories of embodied energy.

When a regression equation is fitted to the combined set of data, the following equation is given for the line: ($R^2 = 0.83$)

$$\text{Combined Data: Ex} = 0.968 \times \text{Dev.} + 23.84. \quad (4)$$

Energy Flow and Structure in Urban Systems

The energy flow and structural characteristics of land uses were analyzed using 1973 data for two urban areas of Florida: Ft. Myers in southwest Florida and Gainesville in central Florida, and the data are summarized in table 3.

In table 3, the second column headed "fossil fuel power density" is defined as the power density that is from the direct use of electricity and other fossil fuels; and the column headed "power density of embodied energy in goods and services" is defined as the power density of the embodied energy that is consumed indirectly in the use of goods and services. All energy flows are expressed as a density function on a yearly basis; in this case, Cal/acre·year, rather than on a housing or commercial unit basis. The volume of enclosed space occupied by built structure.

Generally, the land uses are arranged in order of increasing power density from low density residential to the central business district (CBD). The volume of structure per acre increases with increasing power density as might be expected, with the exception of mobile home land uses, where energy use is high as compared with the volume of structure. In this land use category, living units tend to be small (from 600 to 850 sq ft), while the energy demands of the inhabitants are approximately equivalent to those of other residential land use types.

Industrial land uses are not very energy intensive on the average in the Florida urban landscape in comparison to other industrialized areas of the nation. For example, an average value for fossil fuel power density of industrial land uses for the nation derived from the Council on Environmental Quality (1979) is equal to approximately 4,600 x 10^6 Cal/acre·yr, or about 6 times that computed for the Florida industrial land uses. This is due primarily to the "light industrial" nature of Florida industry, and also to the fact that warehouse districts were included in this classification.

Two different densities of CBD were evaluated: those areas with an average height of two stories and those with an average height of four stories. Since energy use and therefore power density is strongly related to the volume of structure associated with a land use, it seems apparent that the power densities of these land uses will differ significantly from the very urbanized areas of the nation where CBD's might have heights as much as 10 times greater than those experienced in Florida.

Table 3. Power density and total volume of structure for selected land uses in Florida.

Land Use Type	Fossil Fuel[1] Power Density (x 10^6 Cal CE/acre * yr)	Power Density[2] Embodied Energy In Goods And Services (x 10^6 Cal CE/acre * yr)	Total Power[3] Density (x 10^6 Cal CE/acre * yr)	Total Volume[4] Of Structure (x 10^3 ft^3/acre)
Single-family residential				
Low density	70	328	398	42.0
Medium density	90	411	501	70.0
High density	110	463	573	85.8
Multi-family residential				
Low rise (2 stories)	340	1557	1897	302.0
High rise (4 stories)	570	2488	3058	664.4
Mobile home				
Medium density	122	597	719	30.6
High density	230	1086	1316	54.4
Commercial strip	680	441	1121	150.3
Commercial mall	3280	2052	5332	141.6
Industrial	760	548	1308	167.2
Central business district				
Average 2 stories	2380	1525	3905	528.5
Average 4 stories	4320	2789	7109	1102.8

[1] Energy consumption data from billing records of Florida Power and Light, Ft. Myers office for 1973. In general, a 10$ sample size of each land use classification was used.

[2] Goods and services consumed by each sector are from an input/output analysis of the Lee County analysis that gave total end use of goods and services by sector. Then that amount that was attributable to each separate land use within sectors was apportioned according to the same percentage of fossil fuel energies consumed by sector.

[3] Addition of column 2 and 3.

[4] Volume of structure is calculated by multiplying the square feet of structural area (obtained from property tax records) by average heights of buildings.

Simulation of Models of Hierarchical Organization and Energy Spectra

Results of the study of several hierarchically organized models are presented in this section, starting with a simple model and progressing to more complex examples. Differential equations to describe the behavior of each are presented along with time simulations of each model.

In general, the models are five compartment systems (having 5 state variables) and differ in kinetics of interaction between compartments as the models become more complex. The final model simulated is an aquatic food chain organized as a hierarchic system of energy flow, using data from Fontaine (1978) to evaluate each state variable and pathways of energy flow between variables.

Theoretical Models

Presented in figures 10, 11, and 12 are simulation results of a simple hierarchic chain of energy flow without interacting feedback pathways.

The steady state simulation results are given in figure 10 and then the results of various perturbations of the model are presented (figs. 11 and 12). In all cases, pathway coefficients are held constant in each simulation run, changing only those coefficients indicated in the models in the figures. When the initial conditions for state variables are set low and the system allowed to grow to steady state values (fig. 11), damped oscillation is exhibited by compartments Q1 and Q2, with less noticeable oscillation in "upstream" compartments.

In a final simulation of the simple chain model, pathway coefficients were adjusted so that turnover times for all compartments were equal. The simulation results are given in figure 12. Without the dampening effect of increasing turnover times for each compartment (as was the case in the simulation presented in fig. 11), increasing oscillatory behavior is exhibited by each component. The energy source has been increased twofold, acting as stimulus to the system.

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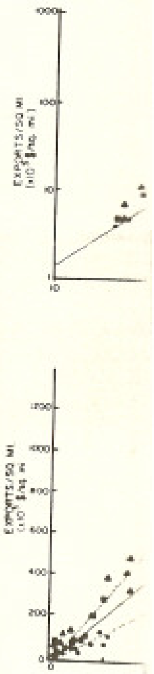

Figure 9. Graphs
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A feedback pathway is added between compartments acting as a multiplicative interaction in the next simulation, which is shown in figure 13. The model has the added feature of a second energy source that is multiplicatively interacted with compartment Q3, using a switching function, so that the model first runs in a steady state and then at time = 10, the second source is turned on. The interaction of the second source changes the distribution of energy within the system, with Q1 attaining a lower overall value, and Q2 and Q3 higher values. The graphs in figure 14 give the energy spectral distributions for the steady state solution, and as a result of the second source.

Aquatic Food Chain

Given in figure 15 is an evaluated aquatic food chain organized as a hierarchy of energy flow. The data used in the model given are a summary of Fontaine's (1978) data for Lake Conway in central Florida. Compartments were summed together into trophic levels based on primary energy source in the following manner: Q1 = Phytoplankton, Macrophytes, and Epipilec Algae; Q2 = Zooplankton and Benthic Invertebrates; Q3 = Primary and Secondary Level Fish; Q4 = Tertiary Level Fish. A fifth compartment was added as a top carnivore, and values of storage and flows estimated.

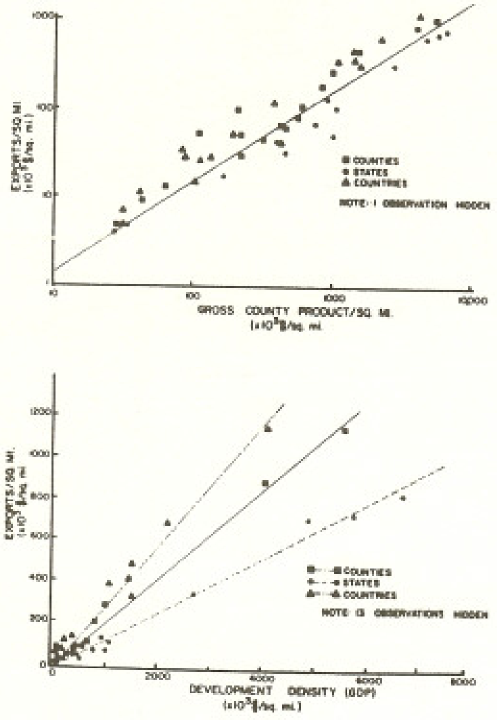

Figure 9. Graphs of the relationship of exports to gross domestic product when expressed as spatial functions for the combined data of counties in Florida, states in the United States, and countries. (a) Log-log plot as a nomograph; (b) arithmatic plot showing regression lines for each set of data.

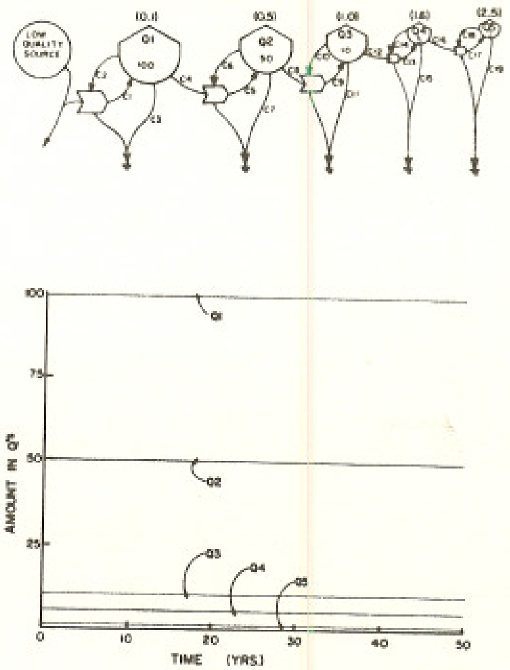

Figure 10. Model and steady state simulation results for a simple hierarchic system of compartments, with no feedback between compartments. Values in parentheses above each compartment are turnover times, values in each storage tank are steady state values, and differential equations are as follows:

$$JR = Jo/(1+KQ1)$$

$$\dot{Q}1 = C1JRQ1-C2JRQ1-C3Q1-C4Q1Q2$$

$$\dot{Q}2 = C5Q1Q2-C6Q1Q2-C7Q2-C8Q1Q2$$

$$\dot{Q}3 = C9Q2Q3-C10Q2Q3-C11Q3-C12Q3Q4$$

$$\dot{Q}4 = C13Q3Q4-C14Q3Q4-C15Q4-C16Q4Q5$$

$$\dot{Q}5 = C17Q4Q5-C18Q4Q5-C19Q5$$

The major differences between the aquatic food chain hierarchy and the previous models are the addition of a sixth compartment that represents a pool of detritus and nutrient storage that is recycled from the other five compartments, the additive pathways of energy flow up the food chain, and the additive feedback path-

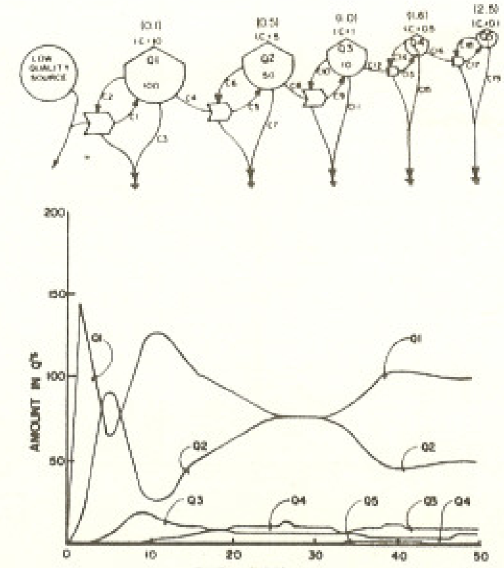

Figure 11. Simulation results of the simple chain when initial conditions are set low, as indicated above each compartment. Note that there is a difference in the vertical scale from the graph in figure 10.

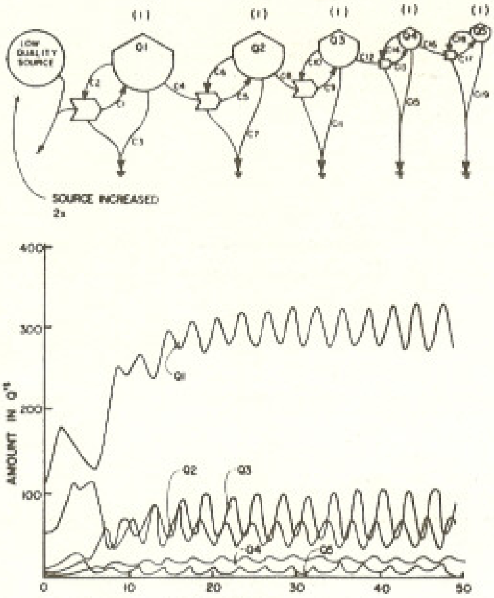

Figure 12. Model and simulation results when the turnover times of each compartment are adjusted so that they are equal. Numbers in parentheses above each compartment are turnover times. Adjustment of turnover times was achieved by rescaling inflows and outflows for each compartment so that they were equal to the steady state value.

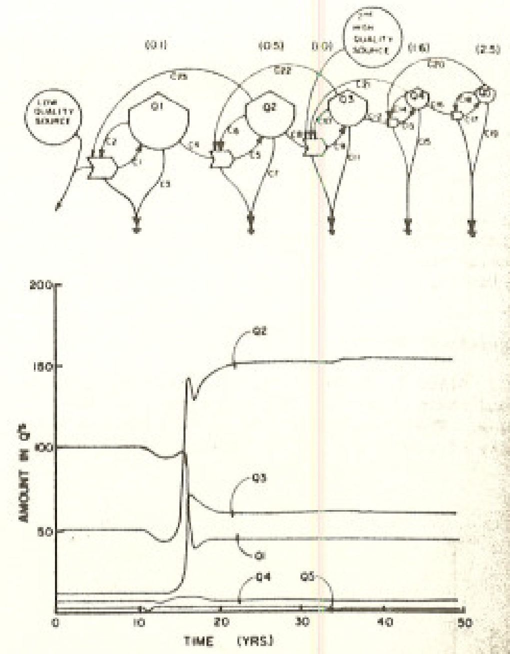

Figure 13. Model and simulation results for a hierarchical energy chain with interactive feedback and a second energy source. The simulation is first run in steady state conditions until time = 10, then the second source is switched on. Differential equations are as follows:

$$JR = Jo/[1+K(Q1+Q2)]$$

$$\dot{Q}1 = C1JRQ1Q2-C2JRQ1Q2-C3Q1-C4Q2Q2Q3$$

$$\dot{Q}2 = C5Q1Q2Q3-C6Q1Q2Q3-C7Q2-C8Q2SHQQ3Q4-C23JRQ1Q2$$

$$\dot{Q}3 = C9Q2SHQQ3Q4-C10Q2SHQQ3Q4-C11Q3-C12Q3Q4Q5-C22Q1Q2Q3$$

$$\dot{Q}4 = C13Q3Q4Q5-C14Q3Q4Q5-C15Q4-C16Q4Q5-C21A2SHQQ3Q4$$

$$\dot{Q}5 = C17Q4Q5-C18Q4Q5-C19Q5-C20Q3Q4Q5$$

ways of control action flow from higher level compartments to lower ones.

The model given in figure 16 shows the energy source as a smooth sine wave that represents the variation in sunlight from summer to winter. The graphs in figure 16 are the steady state solution, where the effects of dampening of the fluctuations in energy source are obvious. Since Q2 draws most of its energy from the large stable pool of detritus, very little oscillation is observed. Q3, on the other hand, draws much of its energy from the first compartment (Q1) and shows oscillation, but damped from that of Q1. Yearly variation in standing crop in the higher compartments (Q4 and Q5) is relatively small due to the dampening of upstream compartments.

The model in figure 17 was simulated to test the effect of control actions by the highest level compartment. This last compartment has an additional input pathway driven by a sine wave with amplitude varying from +1 to −1, and frequency equal to the turnover time of the compartment (5 yr). The input pathway acts as both positive input and drain, causing the compartment to oscillate.

The oscillation set up in compartment Q5 is passed on to downstream compartments through feedback pathways C28 and C29, and is passed further downstream through feedback pathways C23, C24, C17, C18, and C11. Because of differences in scaling on the graph of the vertical axis for each compartmnt, the differences in the magnitude of oscillation of each compartment are not apparent. The percent change from minimum to maximum values for each compartment is given in figure 17. A general trend of decreaseing magnitude of oscillation from the highest level compartment to the lowest level compartment is observed.

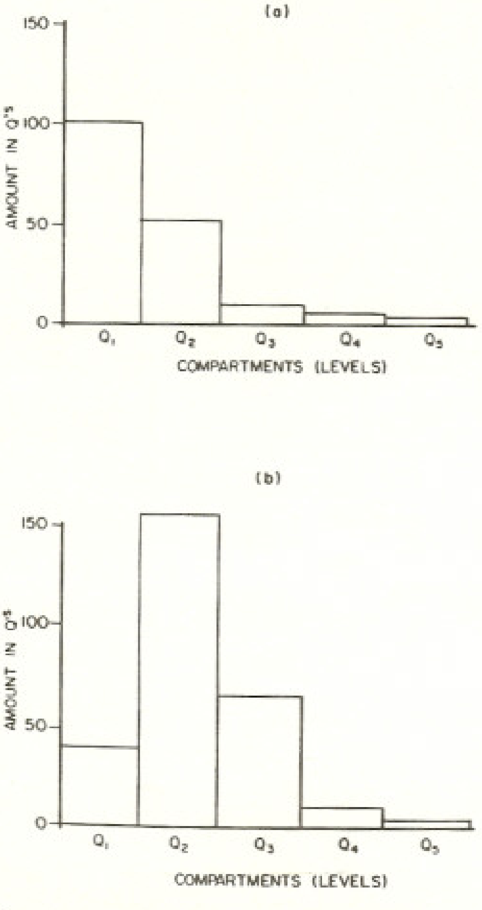

Figure 14. Graphs of the energy spectral distributions of compartments in the simulation model in figure 13 where a secondary energy source was introduced into the system. (a) The distribution achieved with single low quality source; (b) the distribution achieved with the addition of a secondary high quality energy source.

In all, many simulations of the various models reported here were conducted; testing various organizations and perturbations to each model. Different kinetic organization, energy sources and magnitudes were tested for the theoretical models. The aquatic food chain was simulated testing different sources (constant and pulsing), effects of harvesting of each compartment, and the effects of a secondary energy source as a stocking function. These simulation results are reported in Brown (1980). Reported here are some of the highlights of those initial investigations.

DISCUSSION

Analysis of regions, urban systems, and smaller ecosystems showed many manifestations of hierarchy that were related to supporting energy flows. Simulated models were able to duplicate many of the observed features of hierarchical organization. This evidence supports a theory of energy control of the organization of systems of man and nature.

Pathways of energy flow were shown to be greatest, hierarchically, in the highest components of urban and regional landscapes. Here components were found to be largest in size, fewest in number, to have larger time constants, and have greatest potential control of the overall systems processes.

Hierarchical Principles of Landscape Organization

From the measurements and models, principles may be formulated for relating parts to whole landscapes and as guidelines for regional planning.

Energy Quality and Spatial Effect

While the number of components decreased in successive levels of hierarchies, the spatial area over which their effect was spread increased. The nomographs of development density versus exports suggested this relationship, for as the density of human activity increased, the total exports to other regions increased.

Energy Convergence in Landscape Hierarchies

The evaluated models of regional and ecological systems and data on regional land uses and spatial distribution of incoming energies showed the pattern of convergence of energy flows to higher and higher quality components in smaller

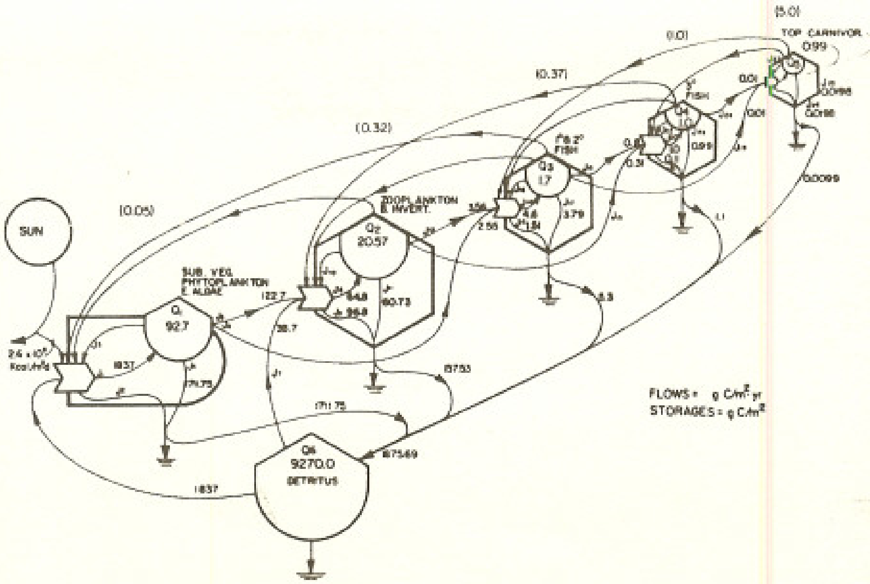

Figure 15. Model of an aquatic food web organized in a hierarchic fashion. Data are from Fontaine (1978). Numbers in parentheses are turnover times of the state variables.

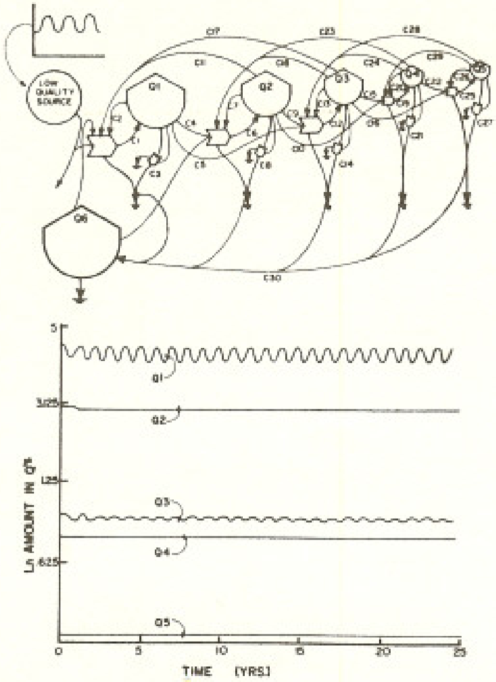

Figure 16. Model and steady state simulation results of model in figure 15, where the energy source is generated sine wave representing seasonal fluctuation of sunlight. The vertical axis on the graph is the natural log of the value in compartments. Differential equations are as follows:

JR = sine wave

$\dot{Q}1$ = C1JRQ1(Q2+Q3)Q6−C2JRQ1(Q2+Q3)Q6−C3Q1−C4(Q1+Q6)Q2(Q3+Q4)−C5(Q1+Q2)Q3(Q4+Q5)

$\dot{Q}2$ = C6(Q1+Q6)Q2(Q3+Q4)−C7(Q1+Q6)Q2(Q3+Q4)−C8Q2−C9(Q2+Q1)Q3(Q4+Q5)−C10(Q2+Q3)Q4Q5−C11JRQ1(Q2+Q3)Q6

$\dot{Q}3$ = C12(Q2+Q1)Q3(Q4+Q5)−C13(Q2+Q1)Q3(Q4+Q5)−C14Q3−C15(Q2+Q3)Q4Q5−C16(Q3+Q4)Q5−C17JRQ1(Q2+Q3)Q6−C18(Q1+Q6)Q2(Q3+Q4)

$\dot{Q}4$ = C19(Q2+Q3)Q4Q5−C20(Q2+Q3)Q4Q5−C21Q4−C22(Q4+Q3)Q5−C23(Q1+Q6)Q2(Q3+Q4)−C24(Q1+Q2)Q3(Q4+Q5)

$\dot{Q}5$ = C25(Q3+Q4)Q5−C26(Q3+Q4)Q5−C27Q5−C28(Q1+Q2)Q3(Q4+Q5)−C29(Q2+Q3)Q4Q5

$\dot{Q}6$ = C30(C3Q1+C8Q2+C14Q3+C21Q4+C27Q5)−C31(Q1+Q6)Q2(Q3+Q4)−C32JRQ1(Q2+Q5)Q6 spatial extent. Incoming energies, low in quality and spatially dilute, were transformed into higher quality energies, many as storages, as energy flows converge from many low quality components to fewer and fewer high quality ones.

Energy Divergence (Dispersion) in Landscape Hierarchies

Energy is not only concentrated and converged in landscape processes, but much is fed back in dispersing actions of recycle and control. Spectral distributions of incoming energies and power density of land uses, as well as the distributions of cities within regional landscapes indicated that dispersion of high quality energy from centralized sources follows a hierarchical distribution.

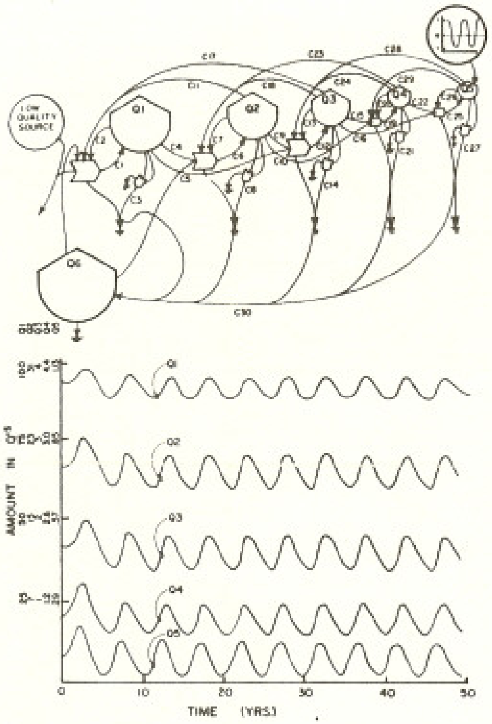

Figure 17. Model and simulation results of the aquatic food chain when compartment Q5 is caused to oscillate from an input pathway driven by a sine wave with amplitude +1 to -1. The oscillation is passed onto lower level compartments with decreasing amplitude (decreasing amplitude is not graphically apparent due to different vertical scales for each compartment on the graph). The percent change from minimum to maximum values for each compartment is as follows:

Q1 = 6.9%
Q2 = 15%
Q3 = 22%
Q4 = 42%
Q5 = 80%

Differential equations are the same as in figure 16 except for the sine wave input to compartment Q5. The equation for Q5 is as follows:

$$\dot{Q}5 = C25(Q3+Q4)Q5+SW-C26(Q3+Q4)Q5-C27Q5-C28(Q1+Q2)Q3(Q4+Q5)-C29(Q2+Q3)Q4Q5$$

Control Actions of High-Quality Components

Evaluation and simulation of hierarchically organized models suggested that the highest quality pathways were those associated with the highest level component in the hierarchy, and suggested a general principle of hierarchic organization and control action feedbacks. The greatest control effect was achieved with the highest quality pathways, since their overall cost was large and their effect must at least be equal their cost. In the simulations of the aquatic ecosystem, greatest overall effect to the system was achieved when the final compartment was perturbed.

Primary and Secondary Energy Sources and Their Effect on Hierarchies

The landscape is a mosaic of natural lands, agricultural lands, roads, cities, and people related through pathways of energy flow and exchange. When viewed as a whole system of processes, it was seen that energy sources inflowing support the processes of the entire system. Systems that are sustained by one energy source such as the evaluated aquatic ecosystem, develop relatively smooth distributions of energy between components as energy is cascaded up the hierarchy supporting fewer and fewer components. Secondary energy sources of higher quality inflow at levels in the hierarchy where their quality nearly matches, with additional energies for support at these levels, greater structure was developed and the hierarcy was shifted somewhat in the relative distribution of energy between levels.

Stability Through the "Filtering" Actions of Hierarchies

The term stability has been applied to a number of concepts. Orians (1975) distinguishes seven different concepts of stability. When models of hierarchies were simulated, stability was greatly enhanced if turnover times were adjusted so that turnover increased with each level in the energy chain. When the turnover times were set equal in all compartments, oscillation was exhibited, since any perturbation in one compartment was passed on to the next.

A Theory of Regional Boundaries Derived from Place in the Landscape Hierarchy

A method that may have significance in determining the regional boundaries of systems was suggested by the results of the nomographs of exports versus development density of regions. The nomographs showed that the propensity to export (and therefore to import to maintain balance of payments) was greater as the density of development increased for regional systems of all sizes. In essence, this relationship suggests that the greater the density of development the more an area relies on external areas for sources of primary goods and energies. And, to carry it one step further, since primary goods require large areas of the landscape for their production (i.e., they are low in quality and occupy large spatial area), the greater the density of development, the greater the size of the region required for support.

ACKNOWLEDGMENTS

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