Zonal Organization of Cities and Environment*

A Study of Energy Systems Basis for Urban Society

by

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A Report to the
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on the Taiwan-Amerian project:
Ecological Energetic Evolution of Urban Systems: Cross Comparison of Chinese and American Societies#

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1. Introduction

In our time, cities of the world have become the centers of the intense activity of a technological civilization, with rapid changes in land uses, transportation, population distributions, and quality of life. The results have not always been good, and many cities are in a disastrous state, with bankrupt finances, collapsing utilities, and stressed with social problems. For the older cities of Europe, with buildings of permanent stone construction such as Rome, Italy, all the new development had to be fitted in and around the old structures. For the American cities, where there was a cultural priority on free use of automobiles, great sections were displaced for the super-highways, leaving many areas dysfunctional. In recent decades, Asiatic cities, especially on the rim of the Pacific Ocean, have accelerated growth, and questions were raised as to how these cities would develop, and if the results would be any better than those where the technological revolution was older.

A Taiwan-American Research Project was conducted to compare Chinese and American cities and investigate the basis for the observed trends of development. This report is Part I of the results of the joint project between the Graduate Institute of Urban Planning, National Chung Hsing University, Taipei, Taiwan, and the Center for Environmental Policy, Environmental Engineering Sciences, University of Florida, Gainesville, Florida, sponsored by the Chiang Ching Kuo International Scholar Exchange Foundation, Taipei, Taiwan.

For centuries, human society has been organized around cities as centers of industry, commerce, communication, information, government, and control. In earlier agrarian society, cities were supported by the products of environment converged into the centers, with most people living outside (Figure 1). Then in the last two centuries, using the available energies of fossil fuels, a surge of growth of the human and technological civilization of all over the world was concentrated in huge urban centers with most people living inside (Figure 2). To understand the modern cities, it was clear that we had to learn how the hierarchy of landscapes centered in cities is changed by the huge technology and information and its ultimate basis in resources.

Since the availability of the resource which fueled city change are already beginning to decrease, any understanding of city patterns over time must include projections and planning for a period of descent in concentration toward a more agrarian base once again.

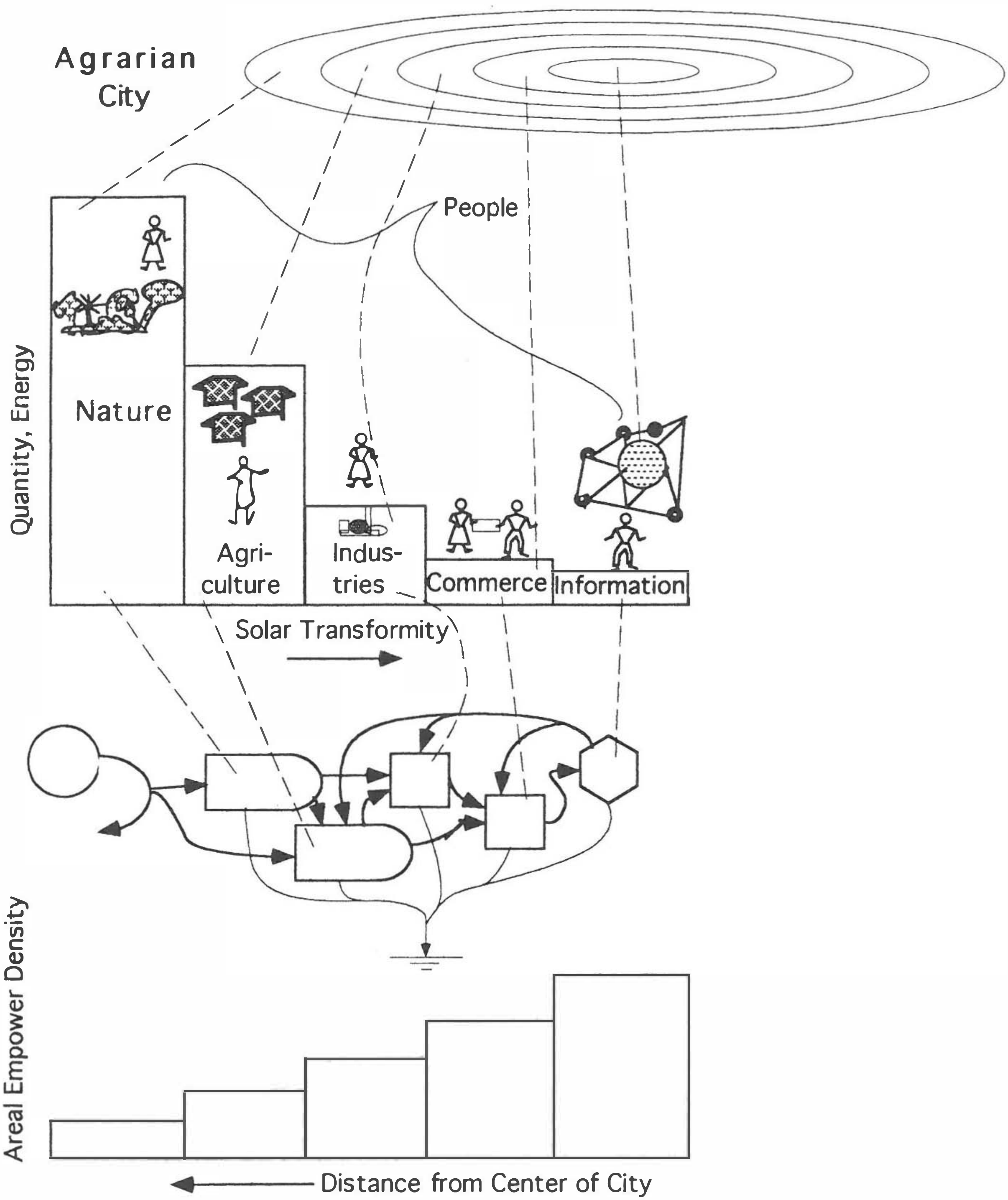

Figure 1. Model for zones of a city in an agrarian landscape, with hypothetical distribution of energy and empower.

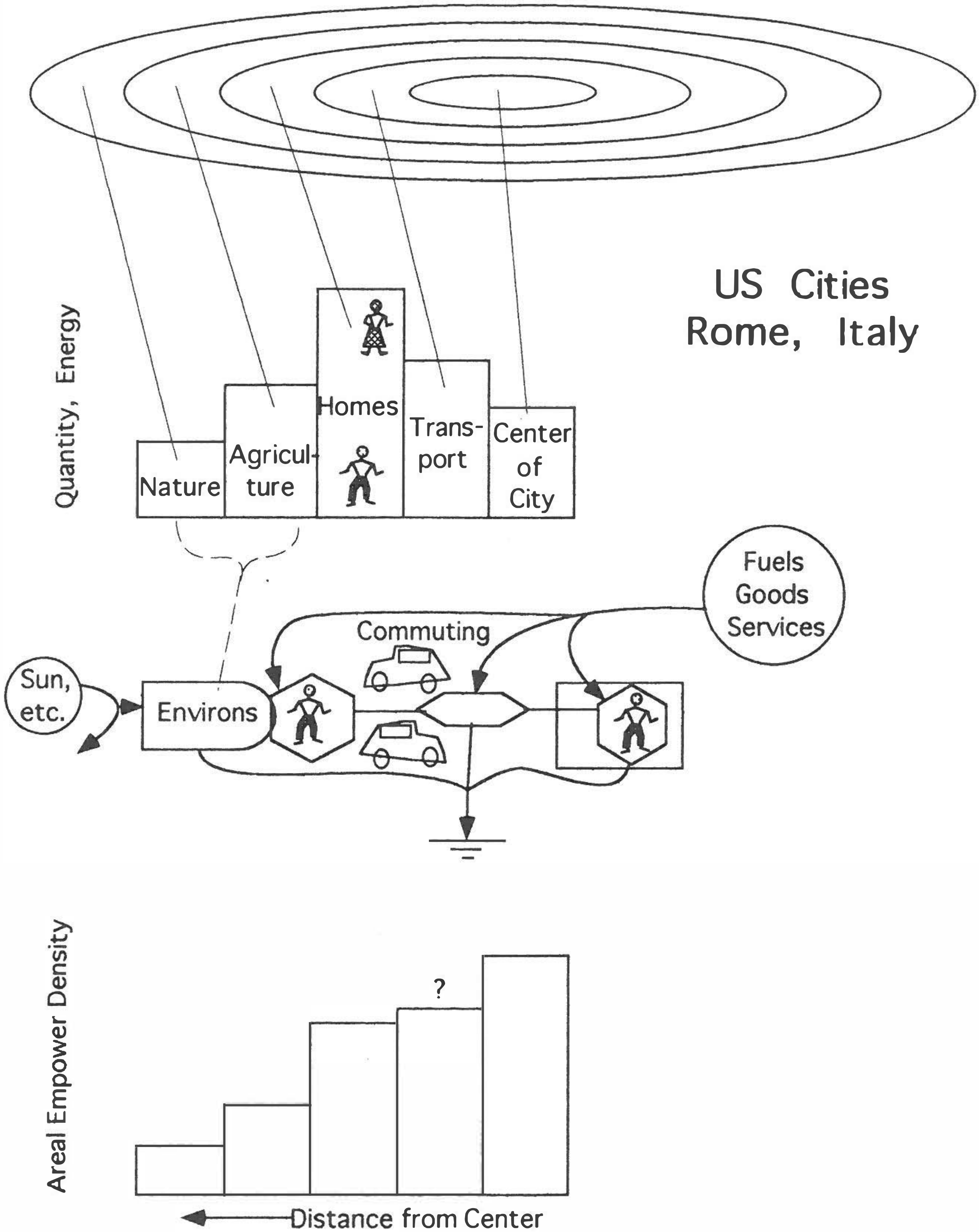

Figure 2. Model for zones of a city in a fuel-based Urban landscape with hypothetical distribution of energy and empower.

Emergy Evaluation. In order to put all resources and human work on a common basis, we have included evaluations of EMERGY, spelled with an "m", a measure of real wealth. Although there is energy in everything including information, we recognize that energies of different kinds are not equal, but can be compared by expressing everything in units of one kind of energy required. In this way, human services are found to require thousands of times more energy of ordinary kinds than do agricultural processes or industrial processes. The EMERGY production and use per unit of time is called Empower. For example, the total EMERGY use per year is the annual empower of a city. Emergy and empower include all inputs, fuels, electricity, environmental, people, etc.

The EMERGY of one kind of energy required to generate a product or service of another kind of energy is the transformity. The more energy transformation steps there are, the higher the transformity. Since everything is related to everything else according to how much was required in the making, transformity measures relative position in a scale of increasing wealth. Since self organizing systems only retain transformations which have an effect commensurate with what into them, transformity measures power to accomplish and control.

EMERGY may be expressed in the dollars of the gross economic product for which that wealth is responsible. Dollars of buying power calculated from EMERGY evaluations are called emdollars. In the Appendix are further definitions and explanations of procedures for calculating Emergy, transformity, empower, and emdollars.

Theory of EMERGY and Landscape Hierarchy. Because ability of energy to do work is used up in any energy transformation, items in the universe can be arranged in a series according to how many transformation steps are used from one item to another. In other words, there is a hierarchy of energy. We believe that this energy hierarchy explains the landscape hierarchy with cities at their center. Chapter 2 on Spatial Organization presents these concepts. These new measures provide ways of representing city functions as derived from converging resources.

In an agrarian landscape, the resources of agriculture and nature are converged to support small cities (Figure 1). Although the total energy flows and land areas may be less in the city, the areal concentration of empower and transformity increases to the center. In the fossil fuel driven landscape, the cities are driven by the use of fuels, minerals, electric power and goods and services generated from these resources. However, these resources only generate their best contribution to wealth when they interact with the environmental resources so as to be mutually amplifying. The city processes reach out to the surrounding zones in their interactions (Figure 2). For example, people with jobs based on industry in the city move out further to live where there is environmental quality, commuting to the city.

The intense use of fuels for excess requirements of individual transportation have distorted American cities, creating a transport-zone that is hardly livable. In Rome, the solution has been to fit more small cars into the spaces available, retaining more of the housing, not displacing people and the buildings of antiquity with highway construction. People going to work appear to spend as much time in transport as they do in American cities, but for shorter distances.

One of the concepts of the energy systems approach to cities is that systems ultimately organize so as to maximize empower production and use. Is the pathology of some American cities, and now appearing in Rome, a result of use of distorted use of fuels by individualistic priorities on cars and freedom of individual transportation, without consideration of what is required for the maximum function of the larger system of all people?

Zonal Concept of this Report. Our energy systems models based on EMERGY hypothesis for the determination of cities and their zones showed promise as being able to generate the patterns of city growth and decline. Hence, the work of this project was concentrated on surveying the zones of cities and then simulating their characteristics for various conditions such as increasing and decreasing availability of fuels, the inflow of information, or immigration. Figures 3 and 4 show hypotheses about city gradients.

Whereas wholly aggregated city models have some utility in dealing with total resource uses, total populations, total trade, etc., the science of urban and regional science has generally directed its efforts toward understanding the landscape structure of the city and its environs. Although there are many spatial models being attempted with Geographic Information Systems, complexity is very high with spatial detail. Perhaps, at this stage of the science, a more attainable, less ambitious objective is to aggregate the city into about 5 units, each representing a concentric zone. In gathering data, transects can be used and averaged. Or lines estimating a concentric zone can be traced, bending the line in an irregular fashion so as to include the items for which the zone is defined. For example, the natural zone (nature zone including wilderness) can include the parks that are on the city periphery, bending the line to include mountains and coastal marshes.

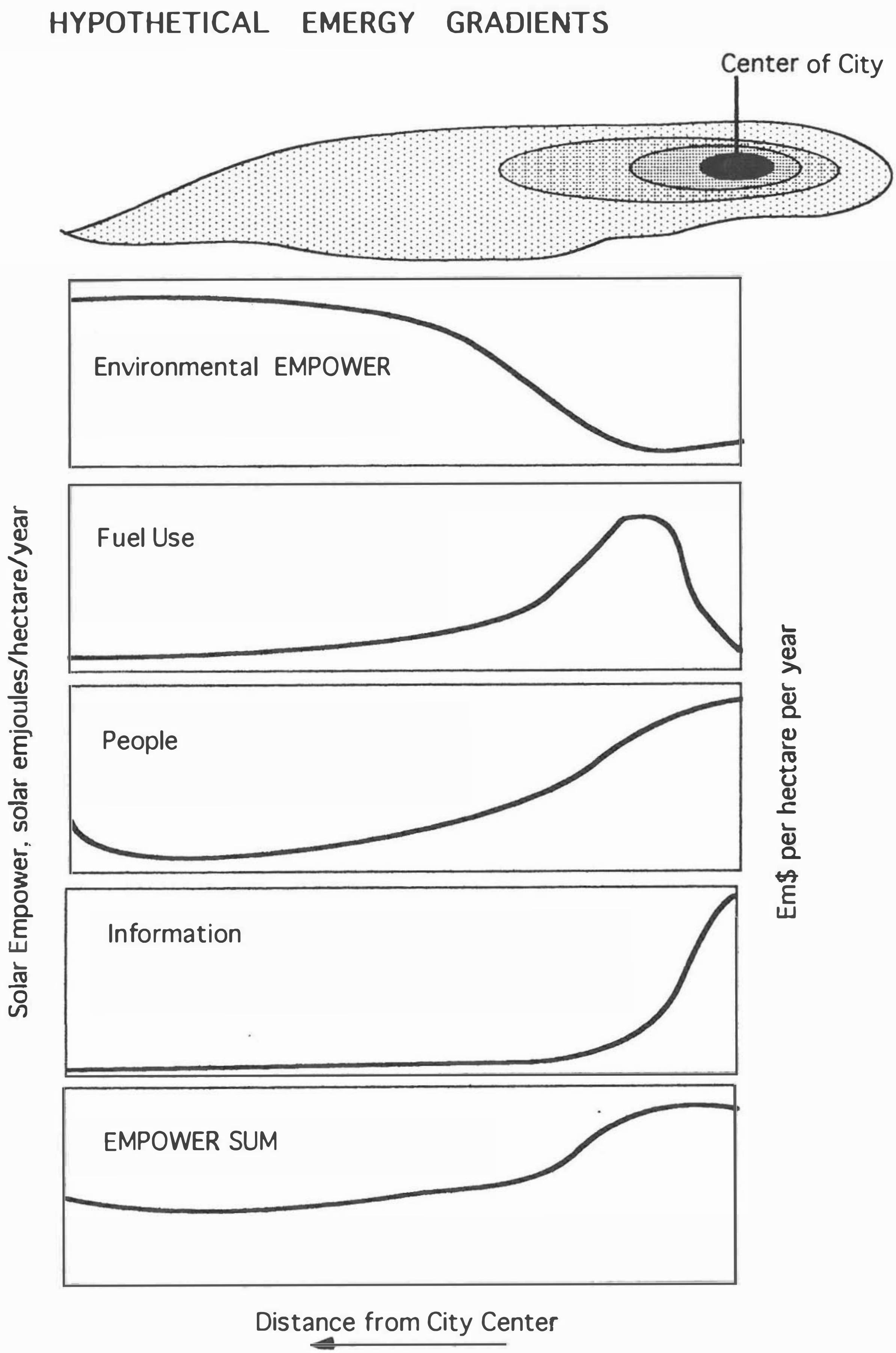

Figure 3. Hypothetical gradients in zonal properties around a city.

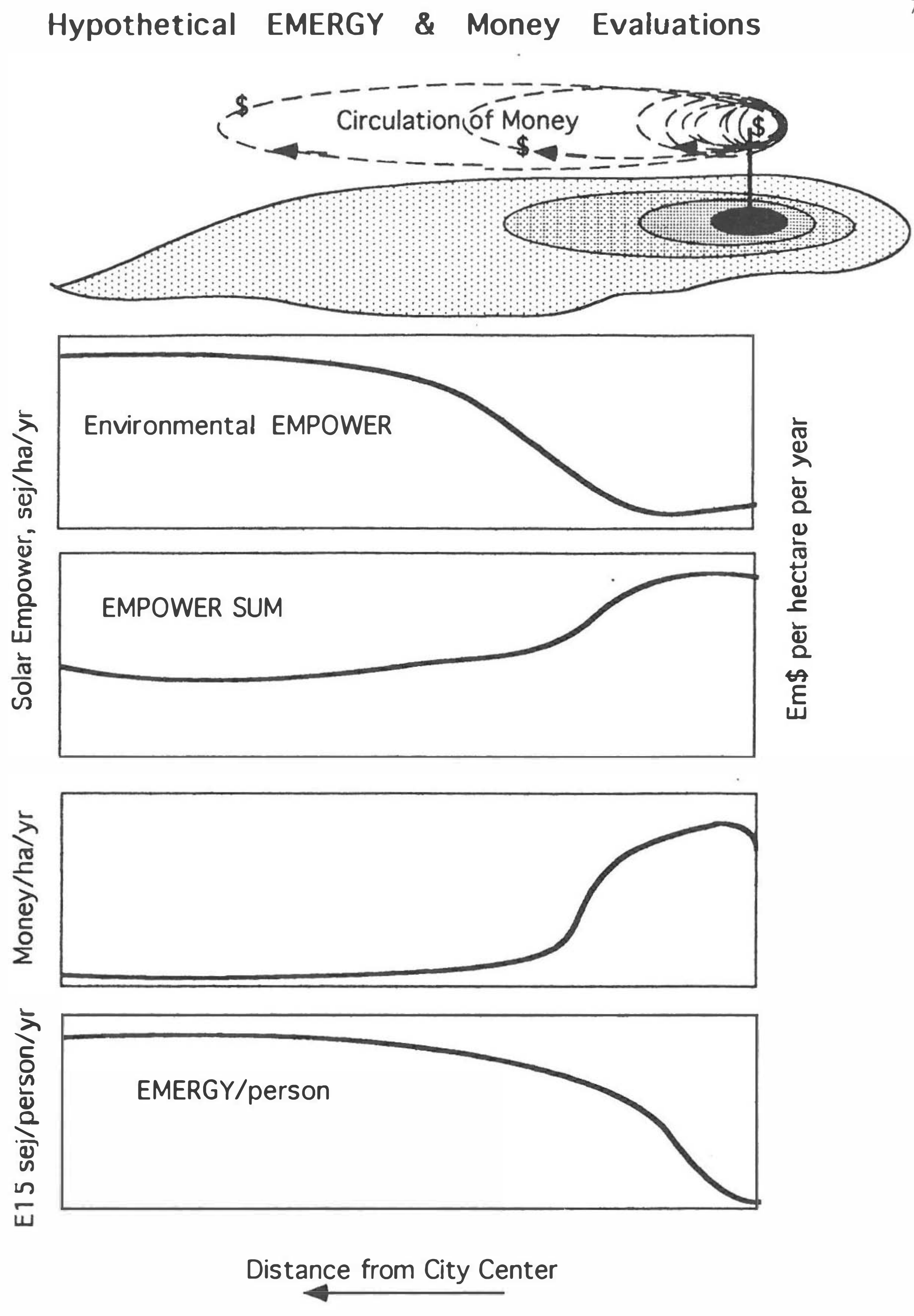

Figure 4. Hypothetical gradients in zones properties around a city.

Chapters 3, 4, and 5 include studies of the transects through Jacksonville and Miami, Florida, and three more northern cities. Transects or literature data were assembled showing changes in population, car use, electric power etc. Then transformity and the concentration of Emergy flows per unit area were evaluated for transects. These were compared with our initial hypotheses (Chapter 2), in which transformity and areal empower density increase towards the center of hierarchy and increase with the total empower inputs to the urban system.

At the same time, study of cities requires that they be compared with the larger state and national systems in which they are a part. Overall EMERGY evaluations were made for Miami, Florida, in Chapter 6 and San Juan, Puerto Rico, in Chapter 7. Both are at one end of an island or peninsula, and in this respect are like our comparison city, Taipei, Taiwan.

City Models. Computer simulation of city models has a long history. Earlier reviews (Mohan, 1979; Batty, 1976) found most models built up from relationships of a few of the parts such as human behavior, employment, population trends, economic data, and land use. Aggregated models of the city as a whole, such as Forrester (1969), without spatial zones, were criticized as leaving out the spatial organization causally dominant.

Transportation is inherently hierarchical, with many small trips toward the center converging successively to larger and larger flows to the center, like a river. Return transportation diverges on these successively branching pathways. The hierarchical correlation of time and space is inherent in many small trips over short time, contributing to fewer longer trips over a longer time. The pattern relating city transportation function to hierarchy was called Ekistics by Doxiadis (1969).

Transportation is one of the main ways energy supports city function. Data on the role of cities in larger landscape were mapped by Batty(1976) by plotting black vectors with width in proportion to transport miles per year, thus showing graphically the inter-zonal flows of EMERGY. The concentration of inter-zonal transport per area was a maximum at an intermediate distance from the center. The excessive use of fuels for transportation changed these middle zones of cities into zones too intensive for optimal living. Any simulation of cities has to include the transport function and its relation to the whole city energetic hierarchy.

A Zonal Simulation Model. In Chapter 8 a city simulation model was made with 5 zonal units, each with production and assets as expected for units hierarchically connected with general systems relationships, as in a food chain (Figure 5). Each zone block draws resources from larger areas in the next zone outward, a feedback from the next zone inward as well as from direct trade input from outside the system. Each zone block can pull land from the zones on either side, depending on the assets in each. The model is spatially hierarchical, since the outer zones have larger areas than the center zones in initial calibration. The simulation showed some features of city growth, such as expansion to incorporate agriculture and natural areas, building an information center. When fossil fuels are added, this process is accelerated. When fuels are made more costly, the landscape returns to a more agrarian zonation.

There are different views on how to use this class of energetics model. The thermodynamic view is that the zones, areas, population, and assets will self organize in the series of autocatalytic models as in the real world, with people changing their culture as needed to fit the models' performance. By this view, the basic pattern and calibrations should not be modified by small scale considerations. The assumption is that the small scale will adapt to the performance of the large scale.

A more humanistic viewpoint modifies the model according to cultural tradition. For example, in the U.S. there is a tendency to put more resources in intra-city transport than is optimum. Do people in Asian cities tend to stay where there are social ties? Special properties can be included by adding special pathways or changing coefficients. Some of the results of model modification are given in Part II (Huang et al., 1995).

Quality of Assets and Catastrophes. One of the differences between cities is the EMERGY that is stored in buildings. Except for the downtown centers, American cities have less permanent housing: more frame houses, brick-front, trailers, and other construction of about 50-100 years turnover time. In other words, the construction, like that of rapidly colonizing ecosystems is a bit weedy, requiring more rapid replacement. Part of this is because the individualistic culture seeks individual, and thus less costly, structure for homes. The old cities of Europe have more of the permanent stone buildings that last centuries, although the insides have to be replaced at 50 year intervals or sooner. The new Asiatic cities may be intermediate, with more EMERGY in housing, although it is shared among more people.

As hurricane Andrew showed in its destruction of Homestead and Florida City (southern Miami, Chapter 6), the flimsy housing of individualistic American housing was mostly destroyed and had to be replaced at great expense. There are two strategies: (1) one to use more energy to resist damage; (2) to put energy into quick reconstruction rather than in resisting catastrophe. Both mechanisms are observed in ecosystems. Transformity may be helpful in classifying structure that is best for one strategy versus the other. More permanent housing shared by more people may be a better solution for winds of a hurricane belt.

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2. Spatial Organization*

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In order to understand how city systems are developing and are expected to change in the future, theoretical concepts about landscapes are set forth in this chapter. Later chapters relate observations and simulation models to these principles and hypotheses.

As part of maximizing system functions, self organization develops geographical patterns. Designs form that process energy and recycle materials between sparse areas and concentrated centers. Landscapes become hierarchical with consumption pulses in the centers. To be successful, human policy and planning of landscapes must follow these geographical principles. By these patterns of organization there is maximizing of empower (rate of EMERGY production and use).

Spatial Pattern for Production, Consumption and Recycle

Wherever we place the window of attention we can find systems of production, consumption, and material recycle (Figure 2). Where the source of energy is entering the system evenly spread out on a broad surface, the production that uses this energy has to be broadly dispersed too. After energy is transformed into more valuable products, these converge spatially to be used by consumers in a center as drawn in Figure 1. For example, in many agrarian landscapes, before the industrial revolution, agriculture around a city supplied food for people and hay for the horses in the center.[1] Although the energy reaching the consumers was much less than the original solar energy, it was higher quality as measured by its higher transformity. The products reaching the city consumers were concentrated as they were converged towards the center.

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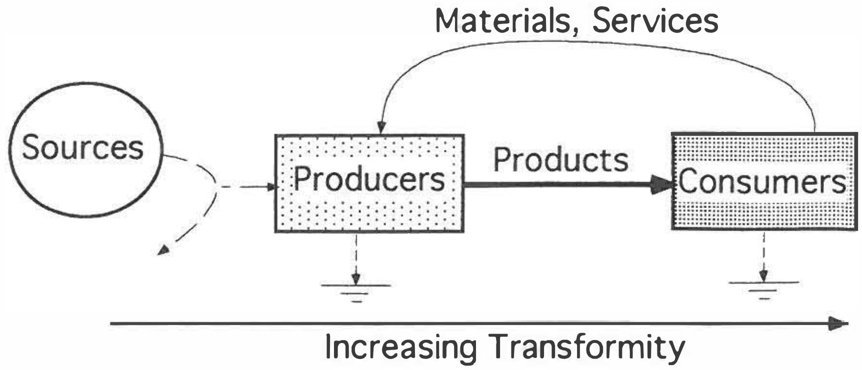
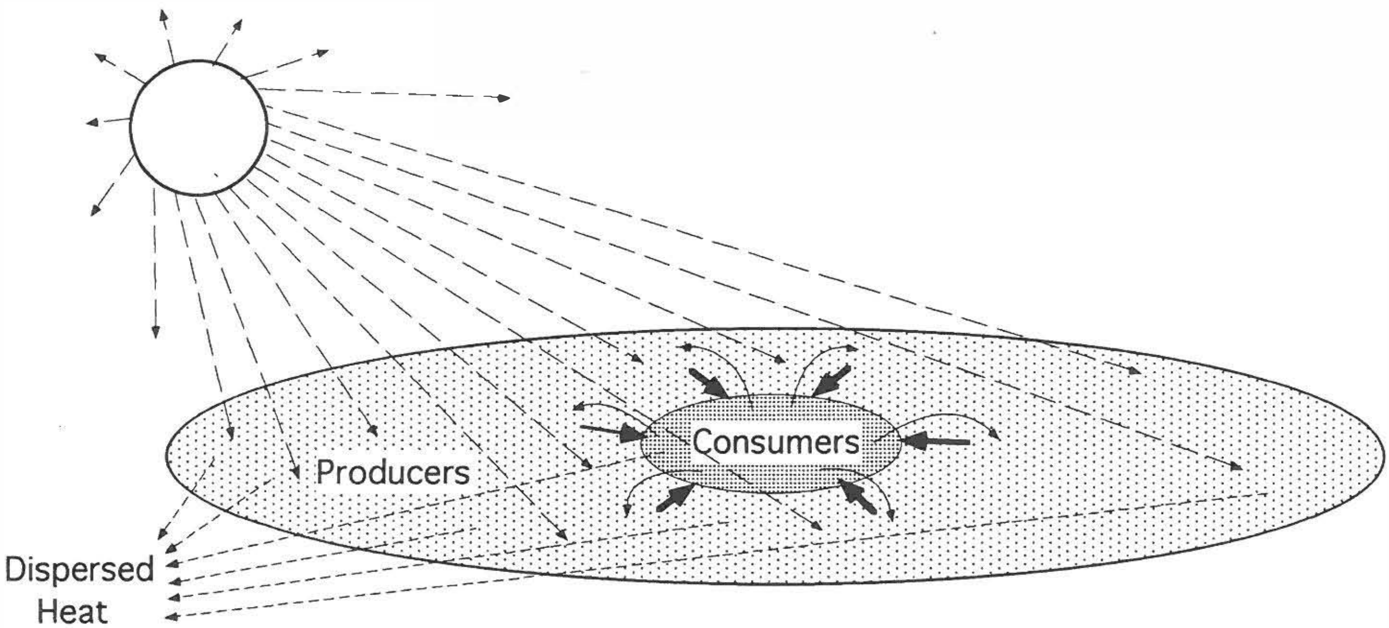
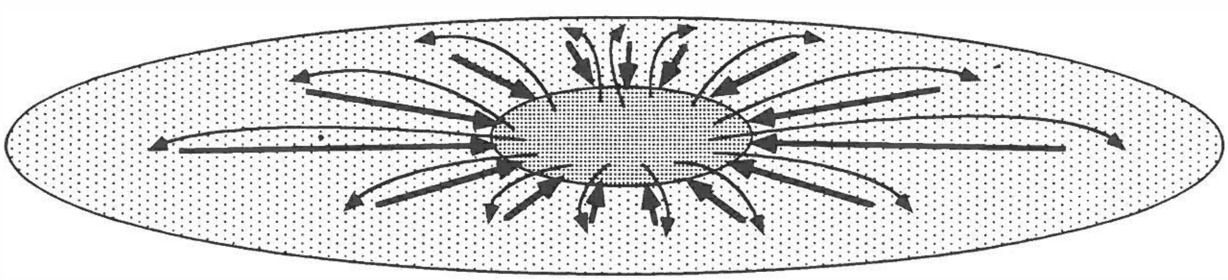
*From "The Prosperous Way Down" (Odum and Odum, 1995)



(a) Systems model



(b) Energy Flow



(c) Converging and Diverging Materials

Figure 1. Spatial arrangement of a system of production and consumption. (a) systems model; (b) geographical view of energy flows; (c) geographical view of material cycle.

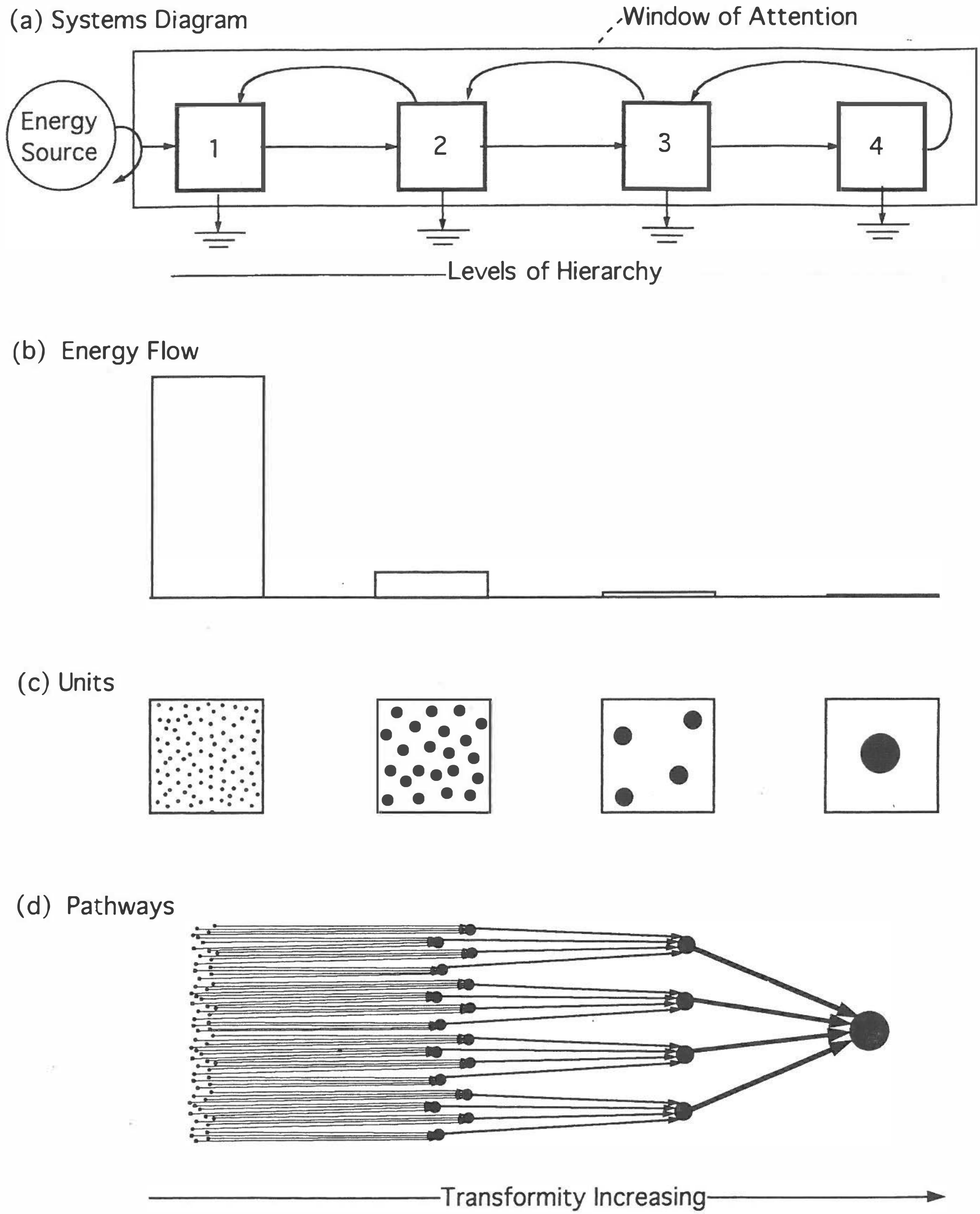


Figure 2. Properties of a system with 4 levels of hierarchy. (a) systems model; (b) energy flow; (c) numbers and sizes of units; (d) energy flows passing up the hierarchy. Not included here feedback flows can be represented similarly but with arrows reversed.

As required for maximum performance, the central consumer part of the system returns services to reinforce the rural system. For example, day laborers and equipment moved from city to the farms. Consumer centers also returned materials released during the consumption process. The agrarian city returned horse manure back to the surrounding farms. Figure1 shows the materials from the center flowing outward to the producers in diverging, dispersing pathways, thus closing the cycle of materials necessary for continued production. Production and consumption are symbiotic; they are cooperatively linked by the products converging to the center and services and by-products diverging back.

This converging and diverging design is observed in many kinds of systems. Cumulus clouds are the centers of converging and diverging airflows. Some reefs of animals are the consumer centers where waters bring products from plants in the surrounding seas, carrying back out the by-products of consumption. Volcanoes are the centers where heat and lavas converge from surrounding areas and are dispersed back outward when there are eruptions.

Good policy for planning a landscape is to arrange to converge and diverge materials in complete cycles. Expenditures on diverging and dispersing wastes back to the rural systems may be as important as those spent to bring products into the centers of an economy. Examples are the recycle of waste waters to forests and transportation arrangements that converge people to the center of cities and recycle them back to their dispersed homes again.

Window of Attention on Multiple Levels of Hierarchy

With a model production-consumption the window of attention is on two levels of hierarchy (Figure 1a). But the real world has many scales of size and time. Each level receives products converging from smaller units spread out over larger areas. Each level in turn produces products for the more concentrated center at the next higher level.

Whether you use the words "Producer" or "Consumer" depends on your window of attention. For example, within an ecological window of interest, fishes are consumers receiving energy from smaller, dispersed producing organisms. The window of attention for a family living off fish sees the fish as the producer and the family as the consumer. On yet a larger scale with a window of attention of economic use, fishermen are the producers and the people in the towns are the consumers. The energy chain in Figure 2 shows the way the energy decreases through successive levels, but the transformities of the products increase. Here sunlight supports phytoplankton, that support zooplankton, that support small fish.

Four levels of energy hierarchy and size are represented in Figure 2 to show the spatial pattern that emerges. From left to right in Figure 2c units get larger and fewer with larger territories of influence, longer turnover times, and higher transformities. Examples are the food chains of aquatic ecosystems, the ecological organization of land ecosystems, and the spatial organization of farms, villages, and cities in an earlier agrarian economy. As with a two level window, the transformity increases with each step from geographically dispersed small units on the left to more centralized units on the right. The total energy flows decline, but the converging pattern brings highly concentrated flows of high EMERGY into the centers. Figure 2d shows the convergence of the pathways passing up the scale of hierarchy. The reinforcing, return feedbacks (shown in Figure 1c and 2a) follow similar patterns except with arrows in reverse direction.

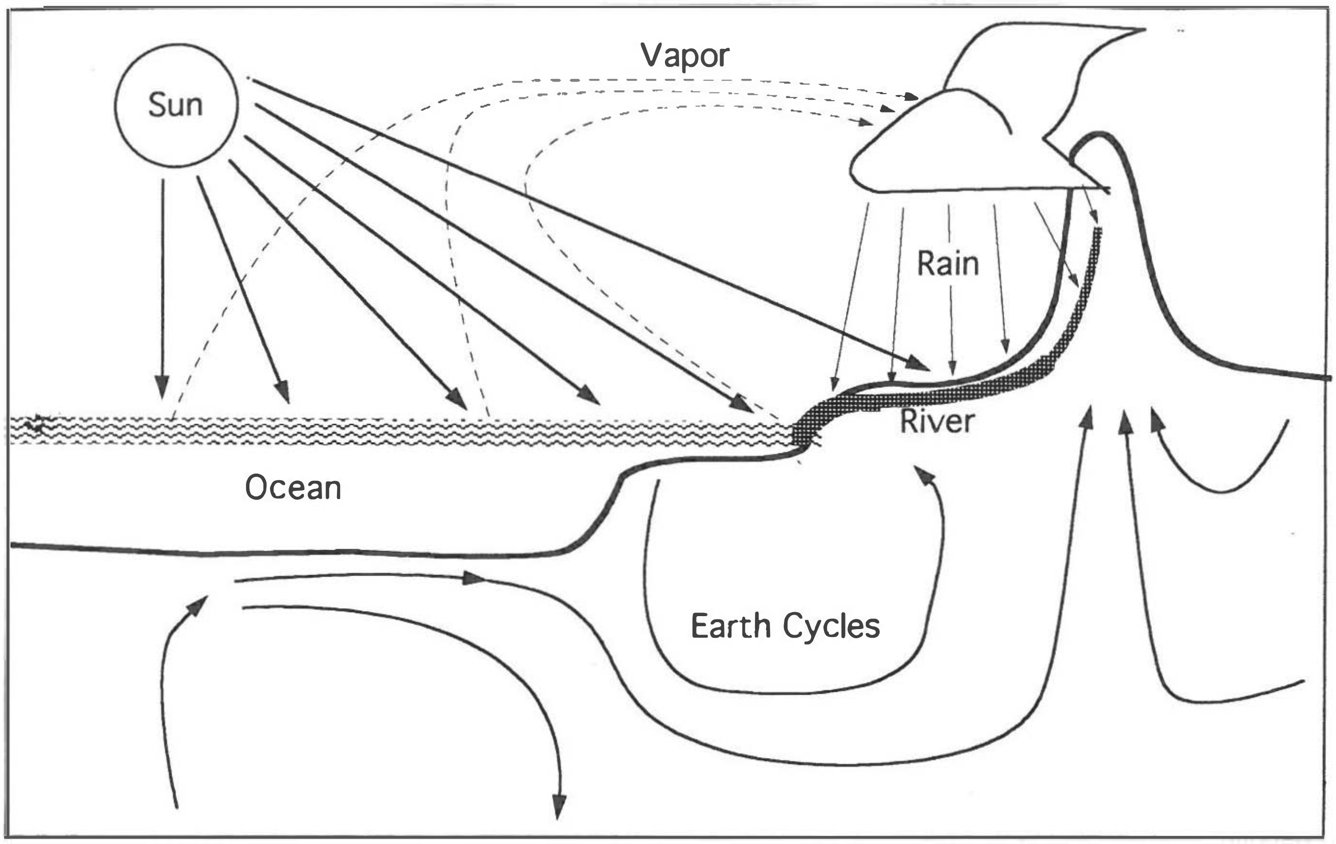
Global Energy Basis

For the planet earth as a whole, there are three main outside sources of energy: the direct sunlight, the tidal energy transferred by means of the pull of gravity of sun and moon with sea, and the intense concentrations of heat deep in the earth from radioactivity and other sources. Since the inflows from these sources are broadly distributed over the earth, the processes of atmosphere, oceans, and geological cycles as they interacted with each other organized a hierarchical spatial pattern that generally fits the basic spatial plan shown in Figure 2; many small units supporting fewer large units.

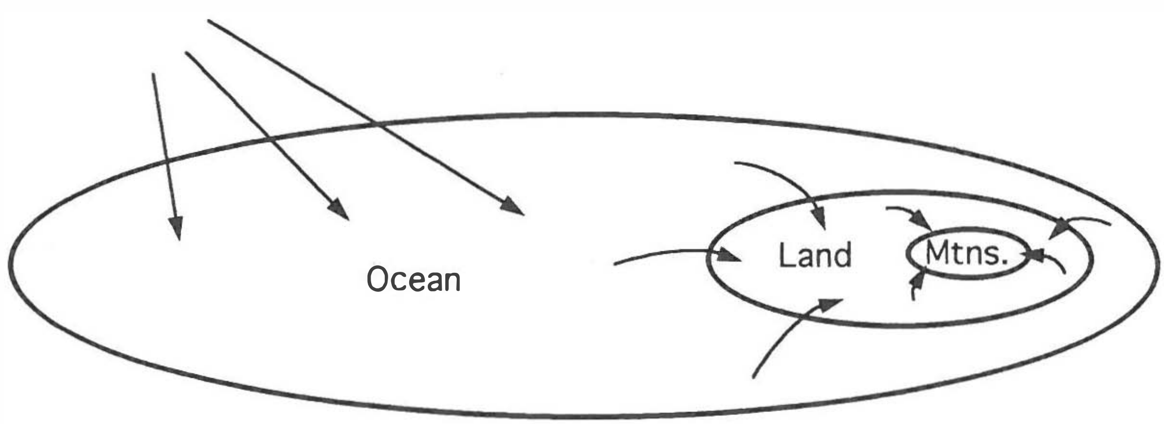
The energy hierarchy of the earth (Figure 3) starts with absorption of sunlight over the globe, especially the seas; its heat transformed into winds, storms, and ocean currents, water vapor converging to land; the falling of freshwater rain and snow over the lands, and the large scale slow cycle of the land driven by the rivers from above and the earth heat from below. The transformities and usefulness of the environmental products to humans tend to increase in the order of this transformation series from left to right.

Geographic Role of Environmental Energy Concentrations

In the places on earth where the natural processes of wind, water, and earth converge, the transformities and concentrations of resources



(a)



(b)

Figure 3. Biogeosphere and its hierarchical organization. : (a) Sketch view in cross section showing circulation of water and earth; (b) areas of the earth showing the hierarchical converging of EMERGY to the mountain centers.

increase. In low energy times of the past, conditions were best for human societies to develop in these places because highest quality resources were located there on which to build a high quality society. Policy for locating developments in the future can be aided by maps of concentration of EMERGY use[2] and transformity so that these beneficial areas can be found.

Rains and snows already have a moderately high transformity when they fall on the land, and they are concentrated (transformed) further as waters run together to form rivers or accumulate as ice flows. Much of the earth surface is organized by the streams and glaciers that sculpture the landscape (Figure 4). In some places the waters converge, as in the example of many tributary streams converging to form the Mississippi River at New Orleans. In other places the waters diverge, as in deltas or waters flowing down and out from conical volcanoes.

In many river systems the upper streams converge. Not only is water flow increased, but valuable substances are joined, especially sediment and organic matter. Transformity is highest at the places where waters and their contents converge most, and here the EMERGY of the whole watershed is available. Here navigation, fisheries, and use of water for urban development is easy. Little wonder that the great cities of the pre-industrial past tended to develop at the end of the hydrologic hierarchy: Cairo and Alexandria on the Nile, Vienna on the Danube, New York on the Hudson, and Shanghai on the Yangtze.

In the lower part of the watershed the physical energy of water running downhill is used to spread water out in flood plains, delta marshes, and agriculture, where it stimulates productivity of the land. An important hypothesis is that geomorphologic self organization of the landscape gets reinforced so that the geopotential of elevated waters can help maximize productive uses of fresh water. Chemical potential energy is the property of fresh water that is used to make plants grow as they transpire the water. Any plans to divert upstream river waters must also evaluate values generated by the lower flood plains and deltas which may be lost. Damming the Nile caused loss of land and estuarine fertility in the delta.

Too often economic development diverts high quality energy without regard for the role these energies have in the landscape as a whole. As a general policy rule:

> Before diverting environmental resources into new economic uses, existing EMERGY contributions of

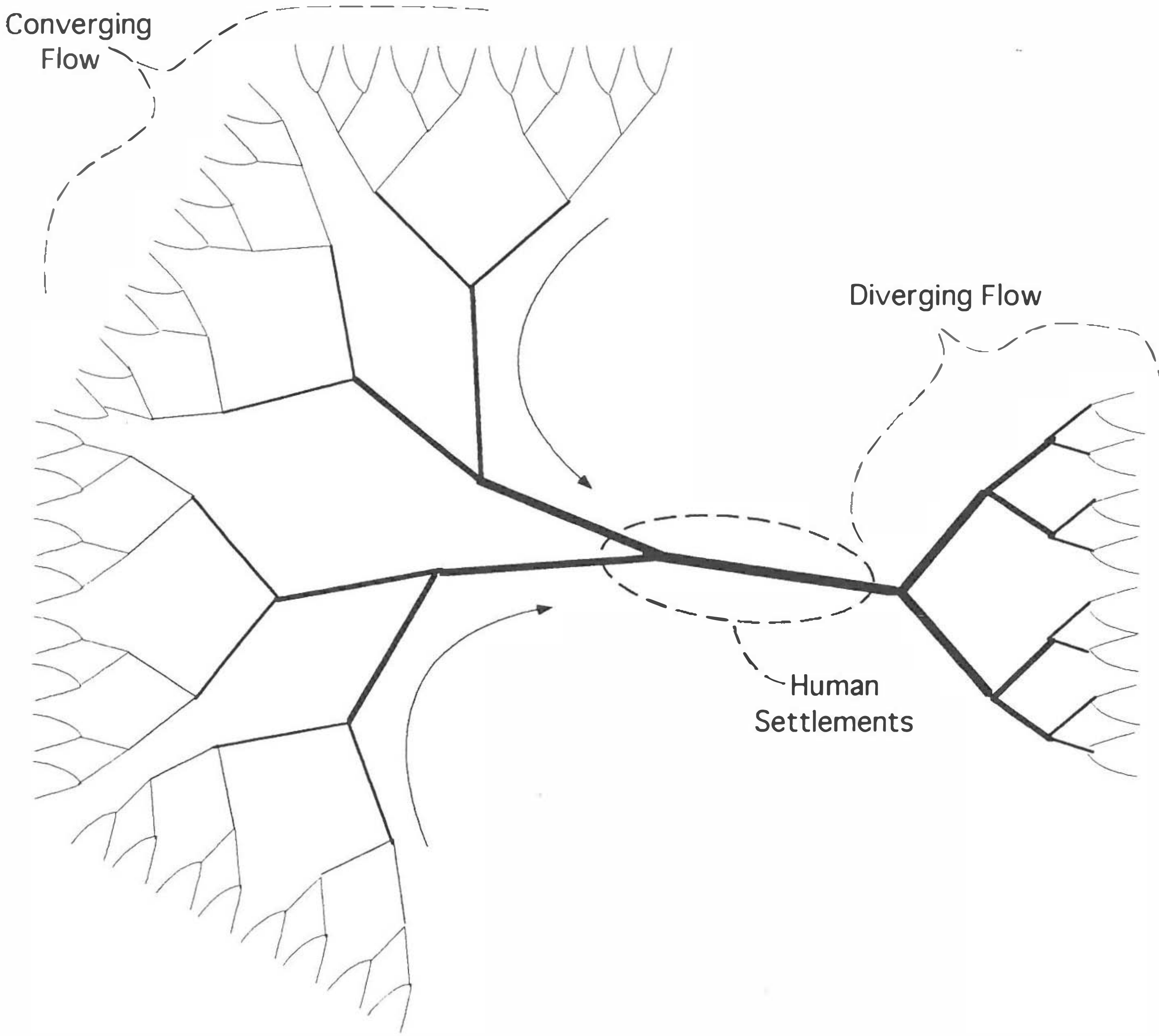


Figure 4. Converging and diverging river network showing historical location of cities in zones of highest transformity and EMERGY availability.

environmental processes should be compared with those to be obtained by development.

Another place were energy flows of the planetary system converge is at the sea coast where the action of water waves and sediments interact to form beaches. Lagoons behind the beach help to convert tidal energy into fisheries. Economic development develops along coastal strips, another example of attraction of high energy areas.

Some energy transformation series are laid out spatially, their hierarchical branching easily recognized like the river system in Figure 4. More often the components of an energy transformation hierarchy are together in the same area, giving a complex view with many small items and large items together. See the landscape sketch in Figure 5. This sketch represents energy hierarchy, since the energy flow through the smaller components is larger than that through the centralized components they support.

Spatial Organization of Human Settlements

The spatial and hierarchical organization of human settlements in agrarian landscapes was recognized early-on[3]. Scattered rural people supported a village and received trade and services back; villages supported towns; towns supported cities. Large, low-transformity energy flows of the rural system were transformed to higher transformity villages whose products were further transformed to higher levels in towns and cities. Transportation and utilities were effective when organized hierarchically, converging toward the centers of higher transformity. People and products were circulated into these centers along converging roads and then returned, diverging again along the same corridors.

The hierarchical distribution of human settlements and the economy on the landscape is summarized with Figure 6. People and information are more concentrated in the centers where transformities are higher. More money circulates in the centers than in the rural areas. The EMERGY/money ratio is highest in the rural areas, where money buys more real wealth, since many environmental resources can be used directly there without use of money. In the city centers, nearly everything for people's needs has to be brought in to be purchased. Money buys less there because a higher proportion of the purchased wealth consists of human services for which payment is required. Knowledge and information is concentrated in centers. Money, materials and information converge as they circulate in and diverge as they circulate out.

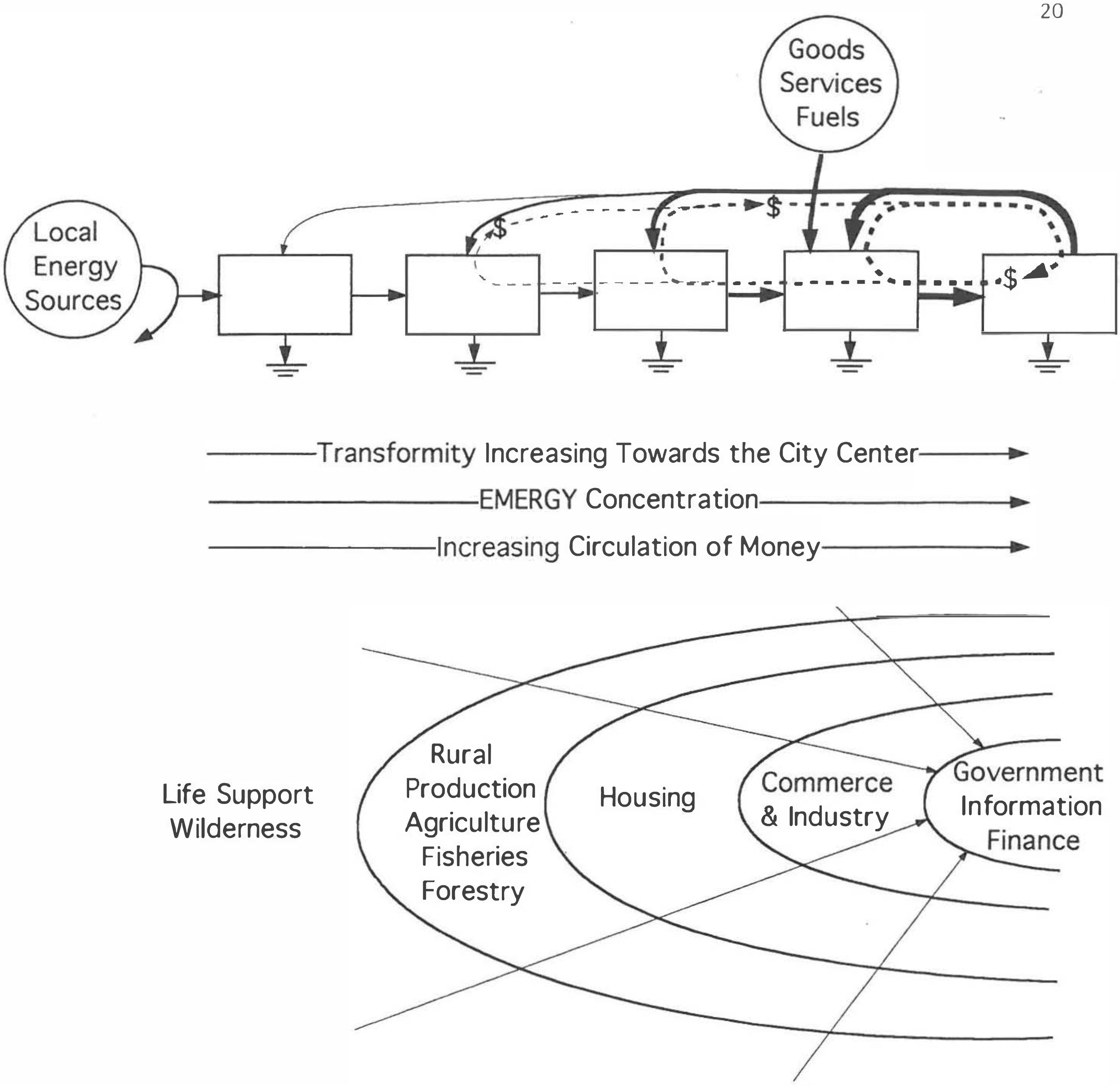


Figure 5. View of the convergence of properties to urban centers showing hierarchical concentration of EMERGY, population, and circulation of money.

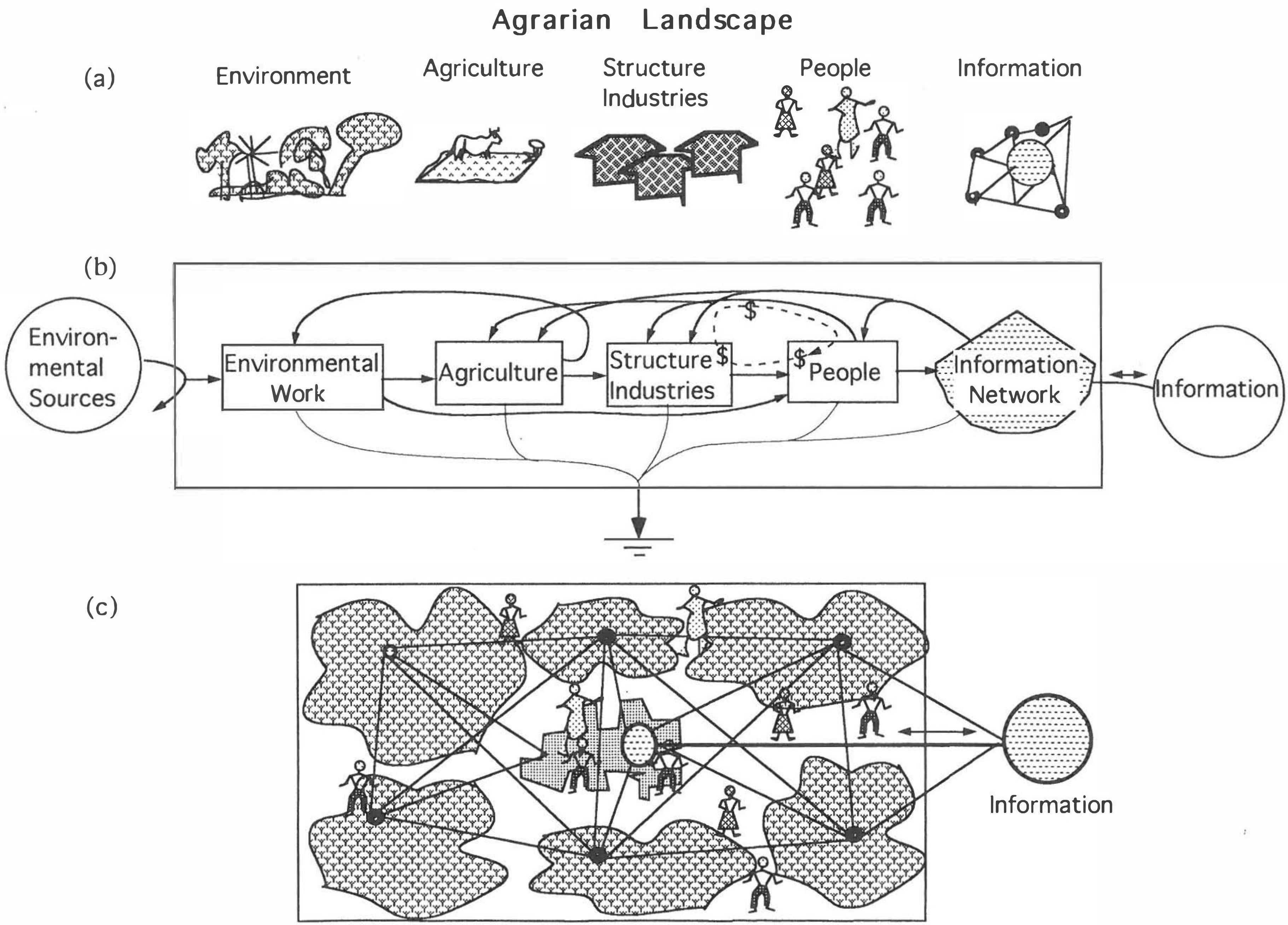


Figure 6. Model of the agrarian landscape of the past mostly running on renewable energies: (a) five zonal areas; (b) energy systems diagram of the zones from rural environment to center; (c) complex view when examined from aerial view

A Model of Environmental Zones Around Cities

Even in the landscape of the agrarian economy two centuries ago, there were zones of increasing concentration and transformity that a traveler would pass in going from wilderness (where it existed without people) inward to small cities. One way to study complex landscape systems is with detailed maps (geographic information) on a scale that includes environmental systems and the economy.

For simplified policy thinking, the zones can be aggregated into a chain of blocks. For example, Figure 5 has 5 zonal blocks: wilderness, agriculture, town housing, industry-transport, and the center of information and finance (including business, banks, libraries, government). Increasing toward the center are the concentrations of EMERGY use, circulation of money, and transformity. In order to assemble data from a complex real map for the simplified chain model, irregular lines can be drawn on a map to separate activities according to the 5 categories of the aggregated model.

For an agrarian landscape, most of the high concentrations, EMERGY, and transformity originated from the broadly distributed, renewable environmental resources being converged into the city. The sketches in Figure 6 represent the agrarian economy of the past that may come again as part of the long range cycle (Chapter 2). Although information has usually had processing centers, its territory is the whole landscape from which information is drawn and fed back. With larger territory and EMERGY content, the turnover time and time between pulses is longer than the zones further out (at lower level in energy hierarchy). In many agrarian areas, such as Sweden in 1650[4], rural exchange was mostly by barter, whereas silver coin was used within the cities. Human settlements that self organized over centuries functioned well with natural patterns of energy hierarchy. Good policy in restoring ailing cities may come from re-establishing the spatial hierarchical patterns that maximize empower.

Transformity Matching

As explained in Chapter 1, maximum empower requires a network of reinforcing feedbacks. In other words, each flow must interact in a multiplicative way with another resource of different transformity either an order of magnitude higher or lower. In this way each pathway amplifies or is amplified. Figures 1 and 2 show the way feedback intersections look when diagrammed. Reinforcing interactions link the zones of the city (Figure 5). For example, humans feed back their services to control and facilitate agriculture; information from the city center is fed back from the central city to control and facilitate industry. We suspect that the interaction between levels in the energy hierarchy is most effective with the adjacent level. Information in organizations tends to cascade down one level at a time, and is not so effective in skipping down several orders of magnitude.

Geographic Reorganization with Fossil Fuels

Starting in the 19th Century, the pattern of spatial organization was profoundly changed by the technology and availability of rich fossil fuels and minerals for development. Since these resources form slowly, they were essentially non-renewable for the window of attention of economic development. Accelerated by a competitive race to develop these fuels, the geographic pattern of economic activity was no longer restricted to those areas where the earth energies could converge a series of transformations. Instead of high transformities of human society coming up from the renewable earth energies, development could take place anywhere with access to the fuels and minerals, providing matching interactions could be arranged with lower transformity resources. Figure 7 sketches the patterns of life in the fuel driven hierarchy for comparison with the sketch of the environmental driven agrarian landscape in Figure 6.

With sea transportation and pipelines, fuels were carried directly to develop the cities. Because of the high net EMERGY yields, growth and development was far beyond what was possible from the original regional resources. High levels of people and information developed in the city, putting a strain on the environmental resources of air, land, and water with which fuel use required interactions. Streams of air and water were required for raw materials and waste dispersal. Green spaces were required in matching interaction with human life. Capitalistic investments helped draw in environmental resources in relative short supply. Political power which originally had a rural base was replaced with urban predominance based on the intense fuel and information EMERGY in use there.

Fuels enter the city along with other imported products made abundant because of the availability of cheap fuels (Figure 7). Fuels and derived products then exchange outward for use over the surrounding landscape. A factor in the feasibility and location of development is the necessary matching of the free resources of environment with the

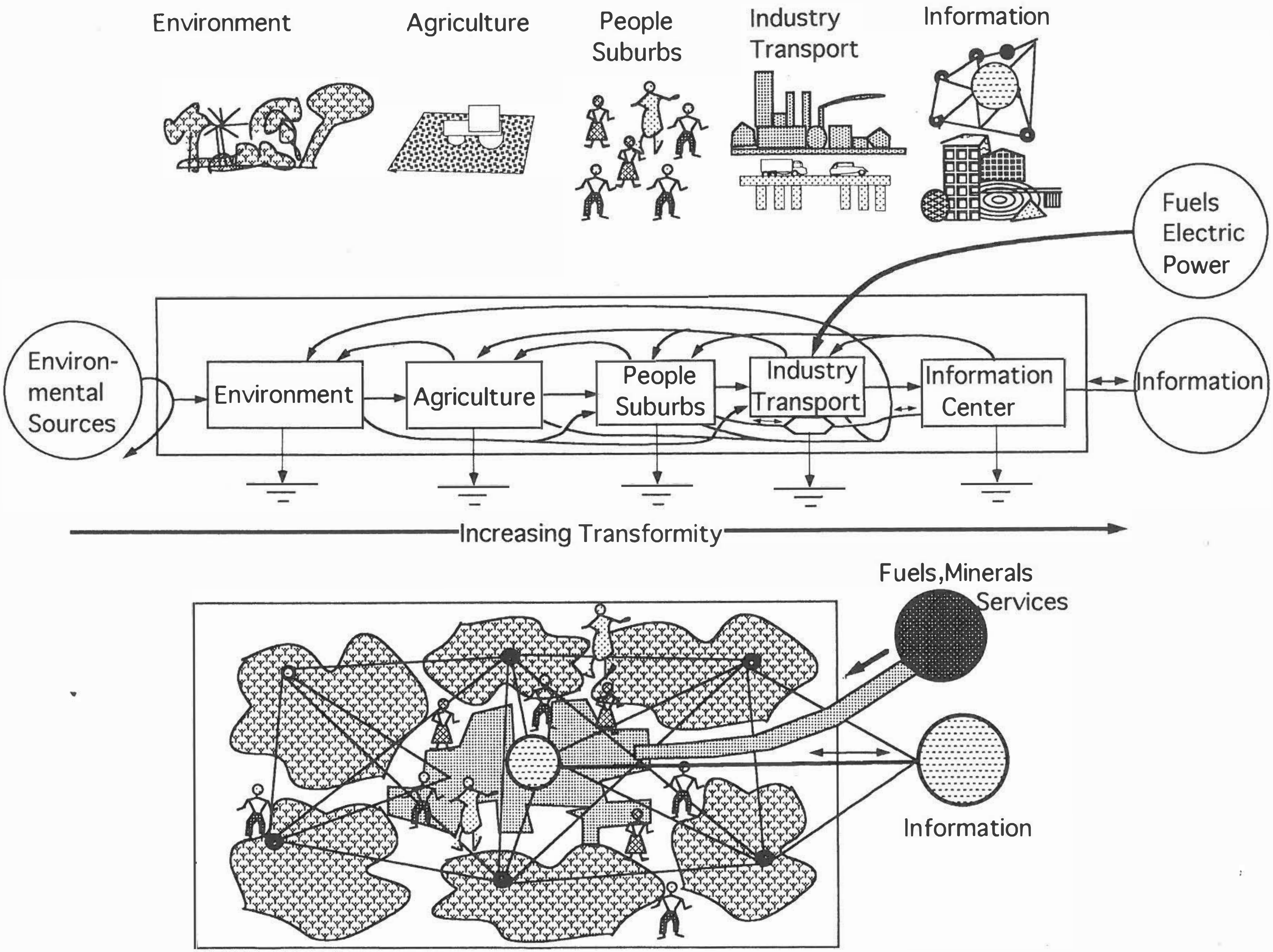


Figure 7. Model of the fuel-based landscape of urban America: (a) five zones with suburban populations outside of the fuel-using transport-industrial areas; (b) energy systems diagram of the zones from rural environment to center; (c) complex view when examined from aerial view.

purchased fuels and other resources from outside the local area. The Investment Ratio is useful for evaluating the ratio of these two inputs. If too much has to be purchased compared to what is locally free, then the activity is not economical. An economic activity in an area cannot compete well if its investment ratio is higher than in the surrounding area. The investment ratio is high in the center of cities and low in the rural lower energy areas outside. Maps of investment ratio can be useful to find appropriate areas for economic activities of different intensity. For example, you could expect to make money by putting a copying business with a high investment ratio in the city center but not in a rural area with low ratio.

Electric Power, Information, and Night Lights

Although such books as Toefflers' Third wave dramatize the accelerating global development of information systems (Bucky Fuller's doing more with less through information), there is little mention of its energy basis or of resource limits. Electric power is required to support city people, operate information in computers, educated professionals, business transactors, government leaders, university researchers, medical support, television celebrities, etc.). Electricity has moderately high transformity, intermediate between that of the fossil fuels and the information. It has great flexibility in its uses and has become the main intermediate method of supporting higher levels of human society, especially those concerned with information. With fuels cheap and transportable, electric power plants to support cities and information have been installed everywhere.

All over the earth in the 20th Century, self organization of economic society with available resources has generated a spatial organization of cities running at their center with electric power and information. In Figure 7 note the typical zonation of the energy hierarchy around the modern, high information city. People and information are shown at the top (to the right).

Information that is shared by many people has a large territory and the highest of all transformities on earth. Its means of duplication and processing through the centers of television and computer networks is based on electric power. Spatially, people and the information they process are concentrated in the urban centers. Increasingly, in those countries which are at the hierarchical center of the world system, people and technology are reorganizing around centers of information processing and storage. Part of the learned information of human society is becoming globally shared.

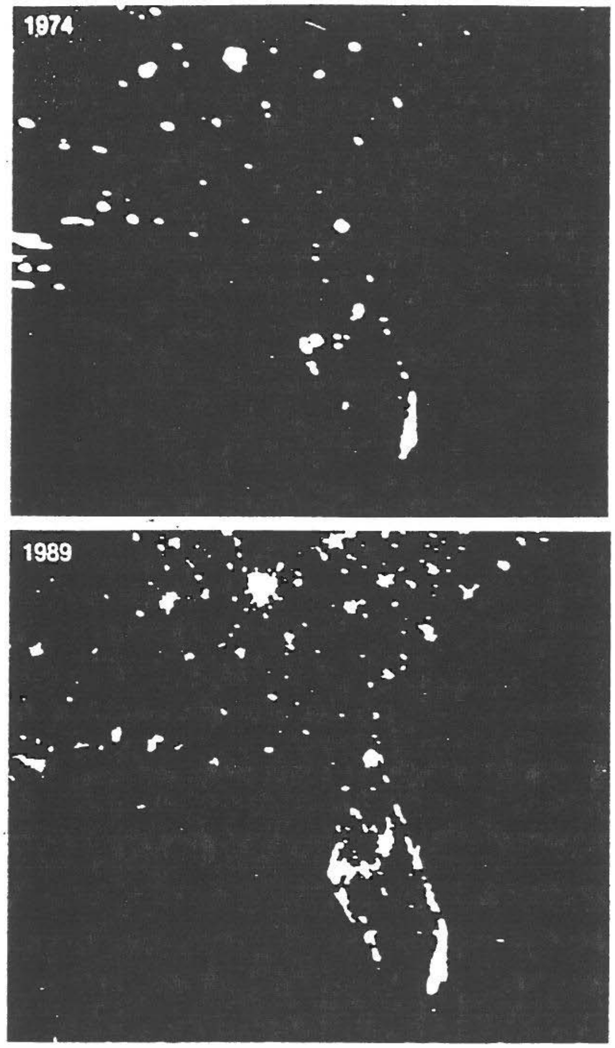
A very dramatic view of the spatial hierarchy of our high energy world systems comes from satellite photos of the earth at night (Figure 8). Each town, city, and metropolitan center is vividly shown by the night lights. The pattern of smaller centers of light of towns around larger areas of large cities shows the spatial patterns of energy hierarchy. Maps of the distribution of population are very similar to the night light photographs. Night lights are one of the ways the urban civilization maximizes its functions by extending the hours when operations can continue. The photograph shows the way the main urban functions of our civilization are derived from electric power.

But electric power, with its transformity about four times that of the fossil fuels, requires huge fuel flows, and diversion of much of the energy of the mountain rivers that used to support other productivity. With less fuels available in the future, availability of electric power may control where the centers of information will continue. In fuel-scarcer times ahead, there may be advantages in locating information centers near hydroelectric power. There may be advantages to those with proximity to mountains with high rain and snowfall.

High EMERGY of Genetic Information

Humanity and the green cover of the earth are also based on the global network of genetic information in the species of plants, animals, and microorganisms. Maintaining biodiversity and global genes has been difficult as the areas are displaced for urban development and the insatiable market demands for environmental products. Opportunity exists to retain the corridors of nature and wildlife by combining them with the corridors of the economic system, such as the riparian borders of waterways, the margins of highways, the lands under power lines, and the other utility strips.

As some of the fuel based information of human society has to be moth-balled, the genetic information diversity in the environment and agriculture neglected in our recent age of growth again becomes more important for maximum empower in the down cycle ahead. For example, agricultural varieties that require less fuels and chemicals will be needed, although they are lower yielding. Conversely, the high yielding agricultural varieties that require high energy inputs need to be kept in



(a)

(b)

Figure 8. Night Lights of Florida from U.S. Air Force satellite (a) 1974; (b) 1989.

genetic banks until they are useful, when there are high energy pulses in the future.

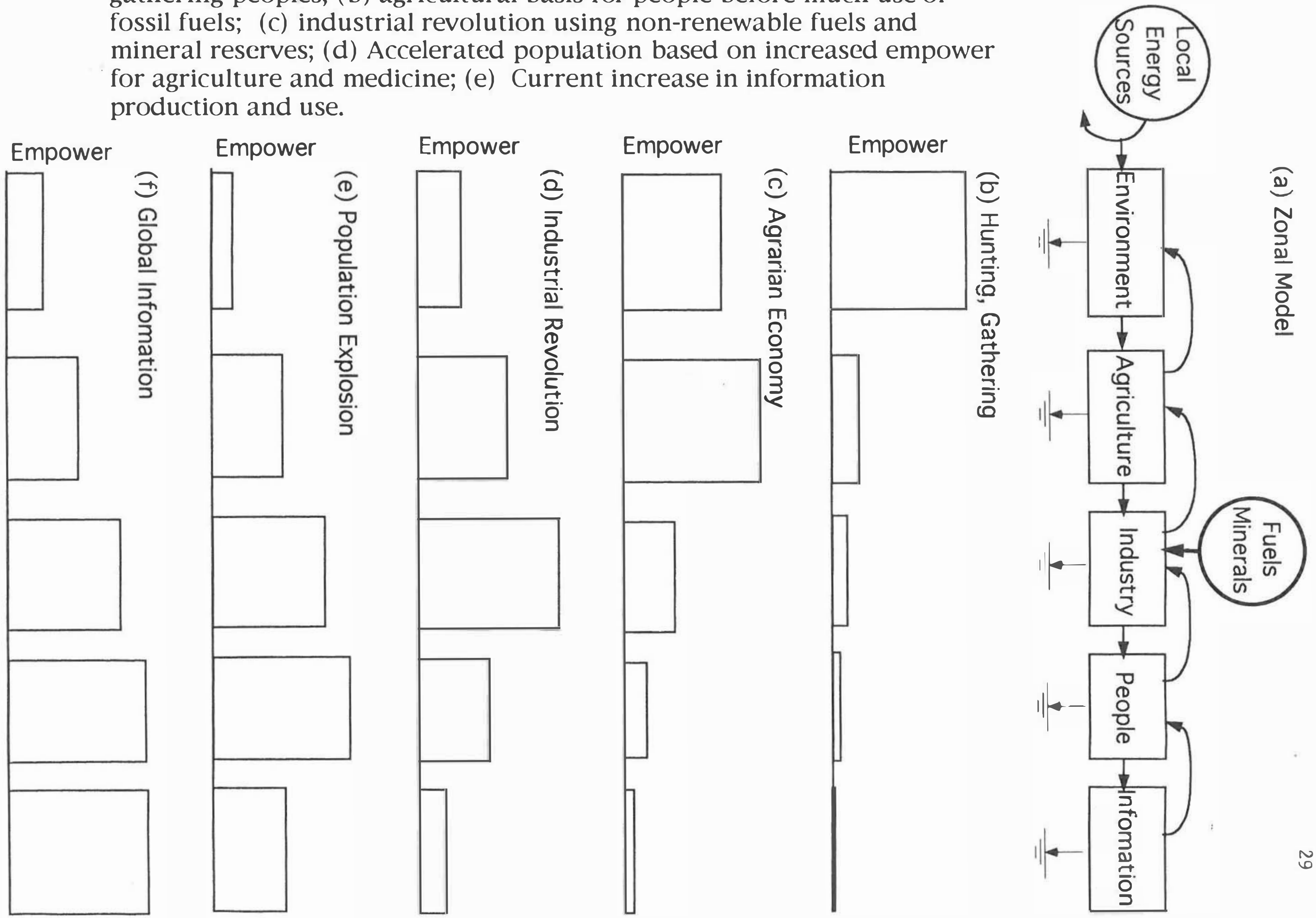
Gaps, Concentrations, and EMERGY Waves

Wherever an area is in a low part of a growth cycle, it appears as a gap in the better developed areas around it. For example, wherever trees are recently down in a forest, there is a gap in the forest cover. Because there are many small, fast growth oscillations and fewer large, slow oscillations, there is a similar distribution in the locations of the gaps. Many studies in geography, landscape ecology, oceanography and other fields have observed the geographical property of many small gaps and few large ones. If one walks along a line passing from gaps to areas in other stages, the ups and downs can be thought of as oscillation over space, the spatial equivalent of pulsing.

The hierarchical centers of consumption in cities have had sharp pulses of growth and decline over history. If a person could have watched from a satellite over centuries, the pulses of light rising and falling, first in one place and then in another, would be like a Christmas tree with flashing lights as civilizations rose and declined. Looking out to space over eons, there are the even longer periods of pulsing of even greater centers of consumption, the stars.

Many urban centers are still growing in their levels of consumption, information, and lights, even though the availability of resources to bring to these centers is already beginning to decrease. The development progression in this century has been an EMERGY wave moving up the energy hierarchy (Figure 9). First was agrarian agriculture, then use of fuels and minerals for the industrial revolution, next a population explosion, concentration of EMERGY in the cities, and finally a world wide sharing of information. Soon the climax recedes, either crashing or descending prosperously, depending on how well we educate the world to share common purpose and information on how to take the staircase down.

Figure 9. Zonal distribution of empower for five stages in the history human development: (a) Environmental systems containing hunting and gathering peoples; (b) agricultural basis for people before much use of fossil fuels; (c) industrial revolution using non-renewable fuels and mineral reserves; (d) Accelerated population based on increased empower for agriculture and medicine; (e) Current increase in information production and use.



Endnotes for Chapter 2 Spatial Organization

1 Stanhill (1977) quantitatively evaluates the system of highly productive agriculture supporting Paris, France in the last century, with horses, transportation, and recycle of horse manure to the land.

2 The measure of concentration of EMERGY use is "areal empower density", which can be represented in units of solar emjoules per acre per year.

3 Spatial hierarchy was recognized by Christaller(1933) with hexagonal polygons of support and influence around villages and towns in agrarian landscapes of Europe before the industrial revolution. We observed them from airplane near New Delhi, India in 1970.

4 An EMERGY evaluation was made of the Swedish empire of the 17th Century with its economic and military power based on the EMERGY of its forest and mineral resources (Sundberg et al., 1994).

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3. Emergy Analysis of the Spatial Resource Distribution of Urban Land Uses for the City of Jacksonville, Florida

Douglas F. Whitfield

Introduction

The City of Jacksonville was studied to develop a better understanding of how a low density land use pattern can impact the type and amount of resources consumed by a society. This study focused on the level of resources in urban infrastructure and the contribution of renewable natural systems for a representative set of land uses. Two concepts were central to this analysis of urban systems. The emphasis on general systems theory and the use of emergy to define community resources.

Development Density

Urban development produces many benefits to a community. However, as cities consume more land area, negative side effects become evident. The phenotypes of increased area and low density create larger burdens on infrastructure, energy consumption and the environment. The "life support system" of a city is in particular adversely impacted by removal and fragmentation of natural landscapes. Environmental benefits such as air quality, recreational amenities and harvested natural systems can be diminished as they are degraded. A significant loss in the total value of a community can result if these intrinsic resources are eliminated.

The density of development and the amount of area developed should be that which maximizes the local and regional wealth of the society. Once this density is determined, microeconomic solutions can take place to optimize the developable land. That is what successful comprehensive planning is about. However the tools currently applied in comprehensive planning emphasize identifying and categorizing important resources. No solution can precipitate out of the planning process if a common yard stick is not used to evaluate important resources.

Theoretical Considerations

A central concept in this study was that cities are definable as coherent systems. Systems are a series of interrelated parts exchanging and relating to each other to from a recognizable whole. Systems such as cities are complex because they change in seemingly unpredictable, nonlinear ways. Much of contemporary science has emphasized deconstructing complexity to define simple relationships that can be reduced to linear equations. This contemporary thought has created an emphasis on linear problem solving which can only be applied under simple conditions. However, this linear viewpoint is beginning to change. Recently a great deal of research has been generated on nonlinear systems, i.e. complex systems. Mathematics and Ecology among other disciplines have developed modeling techniques to define complex systems. These new concepts come under many names such as Complex System Dynamics, Dynamical Systems, Systems Ecology, Quantitative Ecology, and Chaos Theory. These new fields have developed rigorous mathematical techniques to investigate nonlinear systems. One of the implied central tenants in these fields is that the general behavior of complex systems can be modeled and analyzed. The complexity can be aggregated and simplified for understanding. This new emphasis on real world systems presents planners with new tools to define cities.

Another important point is that modeling complex systems is not about prediction. Urban planners are often given the task of predicting the course of growth in a community. Plans are developed that quickly become dated. We all have come to realize that the process is the most important product and not the plans. Plans form a conceptual frame work to understand our communities. So too, the science of complex systems is not an attempt at prediction, but rather an additional tool to enhance our understanding.

Units of Measurement

All complex systems have unique difficulties relating to their particular scale. One advantage most scales of analysis have is that we can quantify the elements involved in a system in common units. In physics, energy is the common unit; in economics it is the dollar. Unquantifiable community resources have always thwarted analysis of urban systems. Many community resources have been unquantifiable in traditional economic terms up to this point. The interface between nature and human enterprises has perhaps been the most difficult to evaluate. For this reason, this analysis uses the concept of emergy to relate significant community resources and evaluate them mathematically in emergy units. The ability to evaluate diverse sets of resources is the central strength of emergy analysis. There is no side stepping the issue of common units if a complex system such as a city is to be understood.

A resource is defined broadly as any material or process that contributes to the continuing existence of the system. Resources range from information to forest products. By emphasizing resources, this study includes natural and economic values. The intended result is a blend of human and ecosystem values to measure the eventual impact of resource decisions.

It is important to realize that the common unit used to evaluate community resources has a significant impact on what the quantitative results are. In economics money is a value used to measure human effort. The cost of gasoline pays for the human effort to pump it out of the ground, transport it, and market it. This cost is different from the value of the heat content of the gasoline. If the human effort to take petroleum out of the ground exceeds the benefit to human society then the value measured in money rises, essentially limiting gasoline use in the system. The value of gasoline measured in energy units does not change. Money measures human effort. Money feeds back to humans. A well designed car results in humans being paid by other humans. The environment is seldom rewarded.

The real difference in these techniques is by what the values are based on. Economics is pliable, it changes as our understanding of our world broadens. Economic conditions are always quick to adjust to new situations, that is its strength. The principle weakness in economics is its inability to define systems beyond human parameters.

Society needs a fundamental understanding of how human and natural systems behave that is based on a more basic foundation. Emergy is the value used in this study to achieve a fundamental understanding of urban systems. Emergy analysis is based on basic science principles and as such provides a unique perspective on the inter workings of urban systems.

Economics has a fantastic way of adjusting and evolving to solve immediate problems facing society. The cost of gasoline continues to change, day to day, year to year. The emergy of gasoline however does not change. Many of the basic components measured by emergy have constant values that do not significantly fluctuate. Emergy analysis provides a measure in a longer time frame for the impact of a resource. This analysis relies less on our current knowledge of the value of a system and therefore relies on fewer short term assumptions subject to cycles in the economy.

As two different techniques, each having strengths and weaknesses, economic and emergy analysis provide unique perspectives. The use of both kinds of analysis together can be a powerful form of analysis. In other quantitative fields, several different analytical techniques are used to gain information about a problem. For example, in statistics, hypothesis testing uses a series of test statistics to summarize the significance of experimental factors. Each test statistic has strengths and weaknesses. The power of the test statistic is based on those strengths and weaknesses. Economic and emergy analysis must both be viewed with a complete understanding of the benefits and limits in their use.

Emergy measures what went into a product and is also a measure of what that product should contribute to the economy if its use is to justify its production (Odum, 1989). In the self organizational process of economies and environmental systems, products that require more work in their manufacture either contribute more to the system commensurate with what is requires to make them, or the production is discontinued (Odum, 1989). Emergy analysis attempts to measure resources in the broadest way possible. Physical properties of energy and matter form the foundation of this technique of tracing the flow of intrinsic value a product or process has for a system. For this method of analysis to be effective, thorough modeling of the system and its significant components must be undertaken.

Criteria for Successful Urban Planning

This leads to the question of developing a workable set of criteria for planning a city. We must first have realistic expectations. Complex systems are open systems, they are exchanging resources with outside systems and are not entirely finite. They lean toward more consumption and transformation. A balance sheet is never complete because once one process is complete, planning is taking place for the next process. A land use plan typically becomes out of date quickly due to ever changing economic conditions. Some problems in developing criteria may arise from the engineering concept of "optimization" or "efficency" which can only be successfully applied to linear systems.

Complex systems as open systems have been explained as exisiting between a state of chaos and structure (Langton, C. 1992). Complex systems derive their adaptibility by being on an edge between these two states. This edge however is a plane with unlimited possibilites (Langton, C. 1992). This study proposes that criteria for sucess should not require structure without some form of flexibility to deal with the chaos of life.

Nature accomplishes fitness by building on sucessful subunits. Complex systems are part of a hierarchy of subunits. These subunits have undergone evolution to a point were they met the critea for survival and then were used as building blocks for more complexity in a never ending attempt to further maximize resource use, maximum empower principle (Odum, 1989). The evolution of the human body is a good example of building complexity from subunits. Cells in the human body share many of the same cellular structures as single cell microrganisms.

So how can one set a realistic criteria for a complex system? This study proposes starting by improving the type and distribution of land uses. To develop criteria for managing the growth of a city, we must first focus on understanding the building blocks of cities, in most cases the individual land uses.

Methods

This study evaluated the major land uses in Jacksonville, Florida between 1986 and 1992 and developed a composite land use distribution. For each land use the dominant resources were evaluated and quantified in emergy terms.

Description of Study Area

Located on the St. Johns River, Jacksonville started as a small port town and has gradually grown to compete with the port towns Savannah and Charleston for servicing the southeastern seaboard of the United States. Along with the port, Jacksonville has a significant insurance and financial sector as well as a large military presence. Incontrast to most Florida cities, tourism is not a significant industry in Jacksonville making the city more typical of other Amercian cities.

The topography of Jacksonville's landscape is relatively flat, with a majority of the land area having a slope of less than four percent Jacksonville Planning Department (J. P. D., 1991). The low topography, combined with an average annual rainfall of 52 inches causes frequent flooding. The St. Johns river supports a large flood plain and scattered freshwater wetlands (J. P. D., 1991). Low elevations along the Atlantic coast support a large estuary (Figure 1.0). The transportation system is based on a centralized road system radiating from downtown with two main freeways, Interstate 10 and 95. Commercial land uses are found along freeways and major arterials with residential land uses filling in between the highways.

System Diagram of Jacksonville

Emergy analysis, a method using emergy for the evaluation of processes, uses general systems principles. The city is viewed as a system of flows and storages (Figure 2.0). Resources committed to different urban functions are identified and related to the larger context of the whole urban system. In this simplified diagram, Duval County is taken as the system boundary and flows of resources are traced through the system as they are processed and exported for profit. Money is then used to purchase more resources to supplement natural resources within the county.

Of particular interest is the relationship between the commercial and residential sectors of the system (Figure 2.0). Workers commuting between these sectors consume a significant amount of resources, the largest of which is fossil fuel. Fossil fuel is shown in the diagram by a flow of fuel crossing the system boundary and splitting between the commercial sector, and the transportation process (Figure 2.0). Another important relationship is between renewable sources, such as the sun and river, and natural systems. Only the environmental sector is able to process these renewable sources which can then be matched with purchased resources (Figure 2.0).

Urban growth in Jacksonville is driven to a large extent by the flow of people moving into the city, increasing resource flows into the commercial and residential sectors. Economic growth in the past has also been driven by the Naval bases. The systems diagram is used in this study as a frame work for better understanding how the various land uses interelate.

Transformities and emergy to dollar ratios

The following resources were evaluated in this study; nonrewable energy, building materials, goods and services, the environment and human labor. Data on resource flows and storages for Jacksonville was collected from various sources and translated to potential energy equivalents or monetary terms. The transformity of individual flows and storages (Table 1.0) were used to convert energy values to emergy values. Transformities are derived by summing the cumulative energy invested in a flow or storage traced back to solar energy as emergy and divided by the energy flow or storage measured.

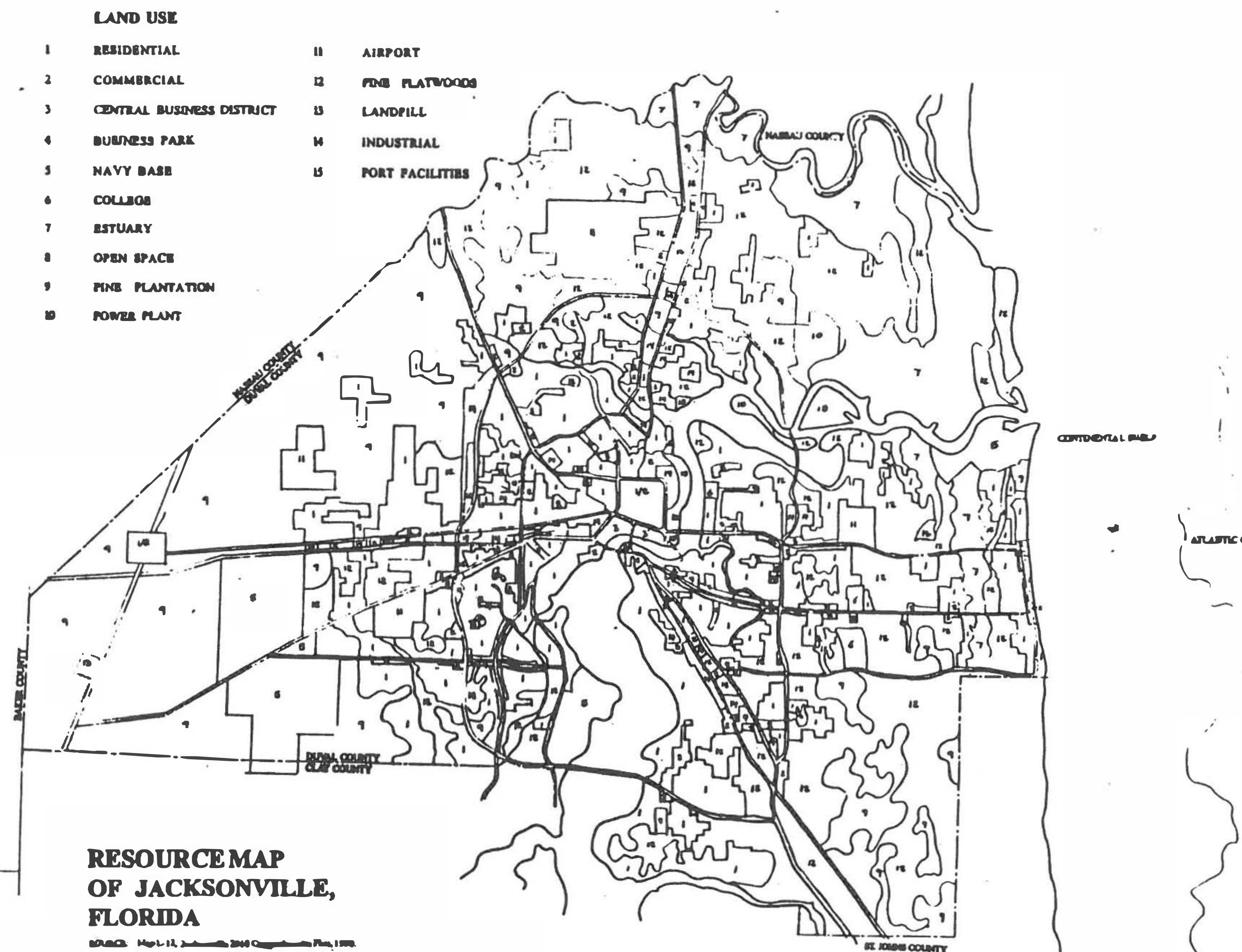

Figure 1.[illegible] Map showing the set of land uses evaluated and their distribution in the landscape.

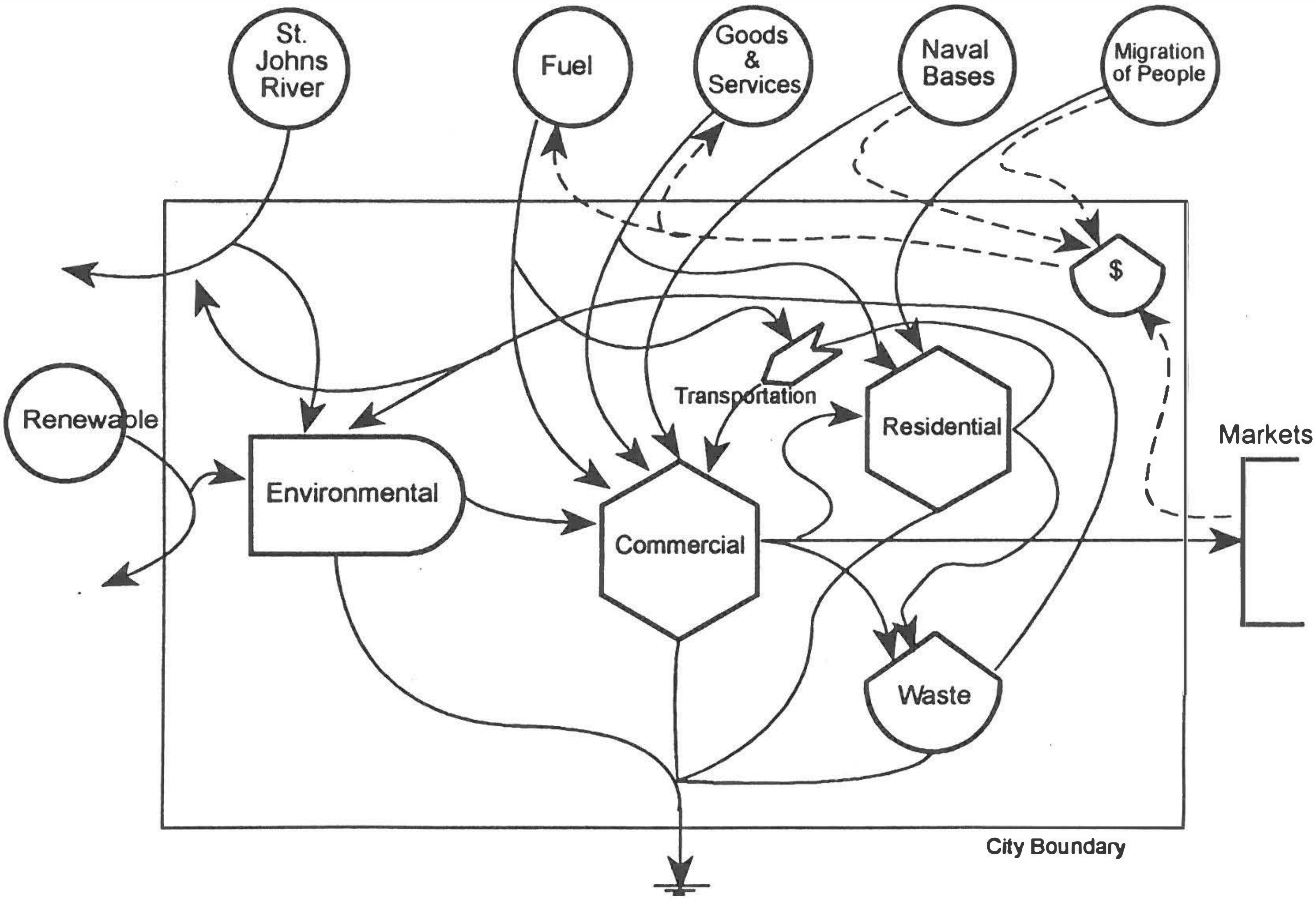

Figure 2.0 Generalized diagram of resource use for the City of Jacksonville, Florida

Transformities allow a comparison of the cumulative invested energy of different resources. Emergy analysis techniques define the earth's biosphere as a system boundary. Because solar energy is the primary energy source crossing the biosphere boundary it is used as the unit of measurement for evaluations. Deep heat in geologic processes is also included in global transformities. In contrast to economic studies that are based on the "willingness to pay" approach, emergy analysis tracks the cumulative solar energy and geologic energy invested in a process.

Emergy to dollar ratios are used to convert monetary values to emergy values. Emergy to dollar ratios for the United States are developed by identifying the annual emergy use and dividing it by the Gross National Product (GNP) for that year (Table 2.0). The result is an emergy value equivalent for each dollar circulating in the system. The resource use of Jacksonville was analyzed by using transformities and emergy to dollar ratios. A thorough discussion of emergy analysis techniques applied to planning is by (Huang, S. and H. T. Odum, 1991).

Emergy Evaluation of Land Uses

Three broad land use classes were evaluated; residential, commercial and environmental. For each land use electricity and fuel, water, goods and services, human effort, and renewable sources were each quantified in emergy terms (Figure 3.0). In order to obtain comparable data, each land use class used a slightly different scheme.

Natural systems used transpiration rates for mixed ecosystems as a measure of renewable use (Figure 4.0). The chemical potential energy of rainfall was the largest source of energy to terrestrial ecosystems in the city. The flat topography of Jacksonville limits the physical potential energy of rainfall and the kinetic energy of wind relative to rainfall is small. For terrestrial ecosystems, run in or runoff was accounted for by the transpiration rate of the vegetation. The estuary was dominated by the physical and chemical potential energy of river water and the physical energy of tides. Because of the way environmental transformities were evaluated from world energy budgets, the emergy inflow from rain and runoff includes that of sun, wind, and geologic contribution (Odum, 1994).

Residential land uses evaluated several flows (Figure 3.0). Renewable sources were estimated with a transpiration rate of 0.8 m3/m2-year for urban landscapes. Electricity was directly measured from Jacksonville Electric Authority (J. E. A. 1991) data. Water use was obtained from the Florida Statistical Abstract and was allocated on a population density basis. Human effort was estimated as four hours per person per day used on personal services. An emergy delivery rate per year was used to convert labor to emergy terms. The emergy delivery rate is the time of information delivery, the metabolism per unit time, and the solar transformity estimated for that persons education and experience level (Odum, 1993).

Transpiration values were used to measure renewable contributions on commercial land uses. Electricity and water use was taken from direct data. Labor

Table 1.9 Transformities for global energy flows from Brown, M. T. and J. Arding (1991).

Item	Solar Transformity semj/J	Solar Transformity semj/g	References
RENEWABLE SOURCES			
Sunlight	1		
Wind, kinetic	1496		
Rain, geopotential	10489		
Rain, chemical	18189		
Tide	16842		
Waves	30550		
Ground Water	41000		
River, geopotential	27806		
River, chemical	48460		
Topsoil formation	73750		
Earth flux	1.01E+09		
NONRENEWABLE SOURCES			
Water storage	15400		
Wood	34900		
Pulpwood	1.80E+05		D(p.145)
Pulp product	2.60E+05		D(p.145)
Coal	40000		A(Fuel:79)
Groundwater	41000		
Natural Gas	48000		A(Fuel:79)
Liquid Motor Fuel	66000		A(Fuel:79)
Topsoil erosion	73750		
Electrictiy	200000		A(Fuel:79)
Consumer water	665714		
Dirt in solid waste	1.80E+09		
RENEWABLE PRODUCTS			
Corn	95000		
Grains	68000		
Wheat	68000		
Agricultural Products	200000		
Bananas	530000		
Nitrogen fertilizer (NH3)	1.59E+06		A(NH3:66)
Nitrogen (N) as NH3	1.70E+06		A(NH3:66)
Meat	1.71E+06		
Cattle	1.73E+06		
Food waste	1.80E+06		
Cotton	1.90E+06		
Fisheries	2.00E+06		
Livestock; poultry	2.00E+06		
Potassium fertilizer (Potash)	7.02E+06		B(rev:449)
Phosphorus fertilizer	5.99E+07		A(+new)

Table 1.0 Continued

NONRENEWABLE PRODUCTS

Item	Solar Transformity semj/J	Solar Transformity semj/g	References
Paper, cardboard	2.15E+05		
Asphalt	3.47E+05		
High quality logs	3.11E+06		
Textiles	3.80E+06		
Bauxite	1.27E+07		
Pesticides	9.78E+05		
Phosphorus rock (mined)	4.43E+07		A(Phos:68)
Machinery		6.70E+09	
Cement		7.48E+08	C(p.36)
Concrete		9.26E+07	C(p.36)
Plastics		3.80E+08	
Glass		8.40E+08	
Ferrous metals		9.20E+08	
Iron/steel from raw mtl.		2.64E+09	B(p:432)
Refined steel		4.65E+09	B(p:432)
Iron and steel end-product		1.25E+10	B(p:432)
Rubber		4.30E+09	
Motor Vehicle		6.70E+09	

References: Most of this data is from a Table Compiled from; Brown, M. T. and Arding. 1991 Transformities Working Paper. Center for Wetlands, University of Florida, Gainesville, F

A- Odum, H. T. In Press

B - Odum, H. T. et al. Energy Analysis of Nations (1983)

C - McClanahan, T. R. et al. Emergy Analysis perspectives of Thailand (1990)

D - Christianson, R. Energy Perspectives on a Tropical Forest Plantation (1984)

Table 2.0 Solar Emergy to dollar ratios for the United States between 1974 and 1992.

Year	Solar Emergy/$ (E12 semj/$)	Year	Solar Emergy/$ (E12 semj/$)
1974	5.70	1983	2.40
1975	6.00	1984	2.20
1976	4.80	1985	2.00
1977	4.40	1986	1.90
1978	4.00	1987	1.80
1979	3.50	1988	1.75
1980	3.20	1989	1.70
1981	2.70	1990	1.65
1982	2.50	1991	1.60
		1992	1.55

1974 to 1988 Emergy to dollar ratios from Odum (1992).

1989 to 1992 Emergy to dollar ratios based on 3% annual inflation

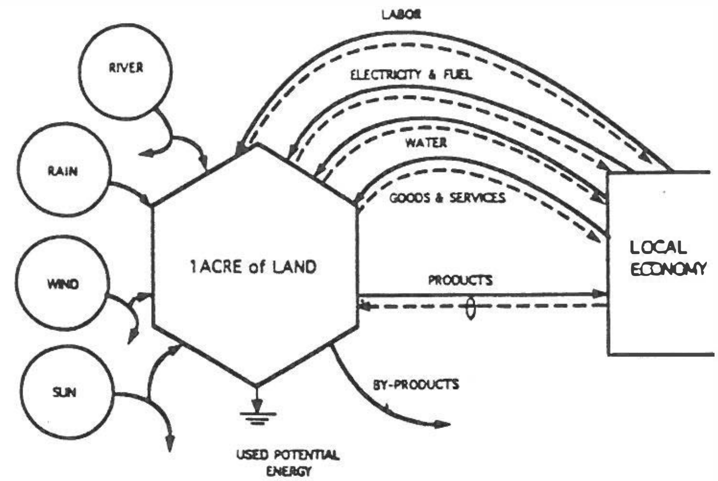

Figure 3.0 Generalized diagram of resource flows evaluated for each land use on a per acre basis. Human effort, direct energy in the form of electricity and petroleum fuels, consumer water, renewable contributions from rainfall, wind, river and solar radiation and the remaining goods and services derived from outside the city were each evaluated as inputs into land uses.

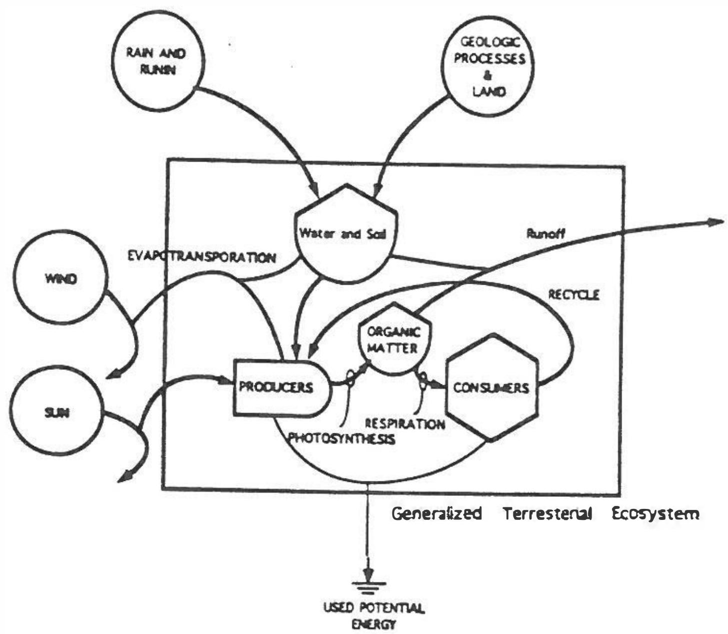

Figure 4.0 Generalized terresterial ecosystems diagram of material and energy flows. Transpiration was used to determine the emergy use from solar, wind and geologic processes. Because environmental transformities were orginally evaluated from world energy budgets, the emergy inflow from rain and runoff includes that of sun, wind, and geologic processes.

was evaluated in emergy terms by using the emergy delivery rate of human labor for an 8 hour work day. An average education level between high school and college graduate was used for business park and the central business district (CBD) land uses. For strip commercial land uses, businesses located in ribbons along major arterials, a high school level emergy delivery rate was used.

Goods and Services

Goods and serivces were combined into one category due to the difficulty in separating the two resources. Inorder to get and estimate of goods and services for each land use this study had to rely on economic values derived in dollars. To avoid double counting money flows, this study developed a careful definition of the goods and services to be evaluated. Therefore only goods and services derived from outside the city boundary were evaluated in dollars. Other goods and services originating from within the city were not evaluated directly, and were considered part of the human service, nonrenewable energy, building materials and natural resources that were evaluated.

Goods and services derived from outside the city boundary were estimated with a combination of empirical data and theoretical relationships. Outside goods and services for the residential sector were estimated by logically evaluating the source for different classes of goods and services bought by consumers. The United States annual consumer expeditures for 1992 (U. S. Department of Chamber of Commerce Table No. 703 for the South) served as model. Categories of expediture were classified as either derived from within or outside Jacksonville. The estimated total for consumer expeditures from outside Jacksonville was then divided on a per capita basis.

Inorder to estimate the commercial goods and services from outside Jacksonville the total money crossing the city boundary had to be estimated. This concept is based on the idea that the more money circulating within a city, the higher the proportion of money crossing the city boundary (Brown, 1980). Equation (1) represents a regression analysis of cities and regional economies at varying scales of economic output. First the development density for the city was determined by dividing the county earnings by the area of the city. Then exports per square mile was determined by using Equation 1 (Brown, 1980).

Exports/Square Mile = 0.21 x Development Density + 5.75 (1) (Brown, 1980)

Exports per square mile was then multiplied by the city area to get the total exports or money crossing the city limits.

With the total money crossing the city limits an approximate balance sheet was developed to estimate the share of money ending in the commercial sector. This estimate was then distributed on the basis of earnings by sector.

Infrastructure Resources by Land Use

For each land use; building, road, natural and miscellaneous interior assets were determined. 1990 Property Appraiser Aerials were used to measure road, buildings, and vegetated area per square foot for each type of land use. Building structure was estimated by weight per square foot for wood and concrete structures from Dodge (1973), the chemical potential energy of concrete and wood was from Odum (1979) and road weight per square foot from Brown (1980). The chemical potential energy of asphalt and rock sub-base was from Odum (1979). Natural structure was estimated from the soil chemical potential energy aggregated from data on Florida by Regan (1977). The formation time of Florida's soil was estimated as 375 years from Regan (1977). Urban system soil formation time was assumed as 10 years for this study.

The materials used in transportation corridors were evaluted with data from an emergy analysis of Florida highways by Guy McCrane (1994). Fill material, limerock, lumber, asphalt, steel and gasoline were evaluated with emergy values.

Empower Transformities for Land Uses

For each land use, a transformity of resource use was determined. The resource use divided by the chemical potential energy of structure within a land use area was the transformity of resource use. In other words, the transformity of a land use is the amount of resource processing a unit of structure can accomplish per area. As a result, transformities are a kind of measure of quality. Theoretically, a higher quality land use can transform more resources into products.

Transformities for each land use were calculated by multiplying the annual resource use by 50 years and dividing by total chemical potential energy associated with the structure for that land use. 50 years of resource use was used as an estimate for the turnover time of the average land use.

Emergy Analysis Maps

Jacksonville Planning Department maps were used to evaluate the spatial distribution of land uses. Fifteen land use categories were aggregated from the 1990 Existing Land Use Map from Jacksonville's 2010 Comprehensive Plan. The emergy maps were used to get an overview of the existing land use pattern and identify relationships between individual land uses.

A summary emergy signature of Jacksonville's landscape was evaluted along sixteen transects bisecting the central business district (CBD). The relationship between land use resource use resource use and distance from the center of town was statistically summarized with a linear regression analysis.

Results

Goods and services derived from outside the city limits were estimated as 2 billion dollars per year or a per house hold expediture of $7,383 per year (Table 3.0).

Table 3.0 Consumer goods and services expeditures from outside city.

Item		Goods and Services:		Other:	Natural
Food:		Locally	Out of Region	Energy Source	Resources
	Food at home:				
	Cereals		$133		
	Bakery products	$249			
	Meats	$670			
	Dairy products				
	Fresh milk and cream	$125			
	Other diary products		$145		
	Fruits and vegetables:				
	Fresh fruits		$112		
	Fresh vegetables	$115			
	Processed		$930		
	Food away from home	$1,550			
Housing:	Shelter	$4,423			
Utilities:	Natural gas			$156	
	Electricity			$954	
	Fuel oil and other fuels			$51	
	Telephone	$624			
	Water and other public services				$248
Household operations					
	personal services	$238			
	other household expenses	$237			
Housekeeping supplies					
	Laundry and cleaning supplies		$119		
	Other household products		$217		
	Postage and stationery	$102			
Household furnishings, equipment			$1,054		
Apparel and services			$1,540		
Vehicle purchases			$2,193		
Gasoline and motor oil				$1,021	
Other vehicle expenses		$1,873			
Health care		$1,711			
Entertainment		$1,285			
Personal care products/services		$396			
Reading		$134			
Education		$369			
Tobacco products			$295		
Miscellaneous		$4,233			
Life and other personal insurance			$395		
Pensions and Social Security			$2,169		
Personal taxes			$2,557		
Totals		$18,334	$12,109	$2,182	$248
Totals (without taxes and Social Security)			$7,383		
Total Expenditures		$32,873			
Total Goods and Services		$25,717			

Goods and Services: Percent Local 71% Percent from Out of Region 29%

Total Goods and Services from Outside City: $2.05 in billions

Data is based on annual consumer expenditures for the United States for 1992 from the United States Department of Commerce, 1994 Table Number 703. Items considered out of region have little or no processing by the local economy. Expenditures are per consumer unit. Values used for this table are for the region defined as the South as compared to the Northeast, Midwest and West

Outside goods and services composed 21% of all consumer expeditures (Table 3.0). The relationship of the total economic output to area was analzyed using a previous regression equation (1) to determine the total money crossing the city boundary, 4.67 billion dollars. From this economic data a balance sheet for the money flows in Jacksonville was proposed and used to determine the money ending in the civilian commercial sector, 440 million dollars (Table 4.0). This total was then used to quantify outside goods and services expeditures per employee (Table 5.0) and finally per land use in emergy terms.

The main purpose of this study was to identify the resource distribution of the existing land use pattern. To that end, the emergy per acre of land use over the course of a year was used as a summary value for analysis. Total resource use for the collection of land uses was found to be dominated by the central business district with an aereal empower of 604E16 semj/acre-year (Table 6.0). The next closest land use was the regional power plant at 224E16 semj/acre-year. A suburban land use with similar activities as the CBD is the business park, which had a resource use of 177E16 semj/acre-year. The two analyzed residential land uses ranged between 169E16 semj/acre-year for the high density land use (30 D.U.'s) to 21E16 semj/acre-year for the low density land use (2.7 D.U.'s). The level of resource use in low density residential is important because this land use consumes almost 70% of the exisiting city area.

The highway system was a major resource consumer at 103E16 semj/acre-year for freeways and 40E16 semj/acre-year for arterials. When the collection of land uses are graphically portrayed, the dominance of the CBD (Figure 5.0) is evident. Two land uses that intuitively might have seemed to consume more sigificant resources per acre than reported was the Jacksonville Naval Air Station and the Jacksonville International Airport. The large land area supporting these latter two land uses functions to reduce the net aereal empower.

Breaking down the analysis into the components analyzed, we can see the most prominant intensity of resource use was human labor in the CBD at 525E16 semj/acre-year. The other large labor resource use occurred in business parks 153E16 semj/acre-year and colleges 78E16 semj/acre-year. Direct energy in fossil fuels and electricty were consumed at the highest intensity at the regional power plant 220E16 semj/acre-year and freeways 62E16 semj/acre-year. Infrastructure use was heavest in arterial roads 16E16 semj/acre-year and port facilities 10E16 semj/acre-year. Outside goods and services were consumed the most in the consumer sector with high density residential at 42E16 semj/acre-year followed closely by the CBD at 32E16 semj/acre-year.

Renewable resources had the most intensive use in natural landscapes. Pine flatwoods, representing upland systems, appeared the most intensive natural resouce at 4E14 semj/acre-year. Low density residential land use had a surprisingly large natural resource use at 2E14 semj/acre-year similar to wetlands.

The physical assets found in land uses were referred to as the infrastructure of resource processing. Similar to how the physical presence of roads facilitate transportation resource use, so to does building and soil structure act as the basic infrastructure of resource processing. On a human scale, infrastructure appears as

Table 4.0 Balance sheet for 1992 money flows in Jacksonville, Florida

Money Crossing Boundary (In Billions):		
Energy*	$0.72	
Goods & Services	$3.95	
Total	$4.67	
End Use Consumption of Goods and Services Crossing Boundary by sector (In Billions):		
Total	$3.95	
Residential*	$2.05	
Commercial	$1.90	
Commercial to Military*		$1.46
Commercial to Civilian		$0.44
Gross Commercial Consumption Within City (In Billions):		
Commercial Energy*	$0.35	
Net Commercial Goods and services*	$1.90	
Commercial Taxes paid*	$2.00	
Payroll*	$9.66	
Income to investors-1	$1.72	
Depreciation of Assests-2	$1.37	
Total*	$17.20	

*-Data from source or prior calculation
1-Income to investors estimated as 10% of investment per year.
Therefore 10% of gross product used to generate value.
2-Estimate from Total

Table 5.0 Commercial goods and services derived from outside the city as cash flow estimate per employee

Sector	Duval County Payroll (Millions)	Percentage of Total	Goods & Services (In Millions)	Employees	Goods & Services Per Employee
Agriculture	$36.10	0.76%	$3.36	3,045	$1,102.76
Mining	$0.94	0.02%	$0.09	172	$508.35
Construction	$443.60	9.38%	$41.26	28,430	$1,451.36
Manufacturing	$658.95	13.93%	$61.29	32,120	$1,908.26
Transportation	$403.81	8.54%	$37.56	27,275	$1,377.12
Wholesale Trade	$576.51	12.19%	$53.62	25,737	$2,083.58
Retail Trade	$635.09	13.43%	$59.07	65,268	$905.10
FIRE	$715.26	15.12%	$66.53	42,558	$1,563.30
Services	$1,260.08	26.64%	$117.21	98,239	$1,193.09
Total			$440.00	322,844	

1989 Duval County Payroll from U. S. Department of Commerce, 1992
Outside Goods and Serivces from Equation 1 in text.
Employment from Jacksoniville Planning Department, 1992

Table 6.0 Intensity of resource use by land use. Resource use expressed as Emergy per acre and year (aereal empower E16 semj/acre-year).

Land Use	Direct Energy	Water	Human Labor	Infrastructure	Outside Goods & Services	Renewable Energy	Total Aereal Empower
Residential							
Low Density	3.3	0.3	12.4	1.5	3.8	0.02	21.4
High Density	21.6	2.5	98.9	4.1	42.1	0.008	169.2
Commercial							
C.B.D.	39.2	2.2	525.0	5.7	32.2	0.001	604.2
Shopping Centers	11.7	0.4	49.9	6.2	4.0	0.003	72.2
Strip Development	10.1	0.4	47.2	9.4	7.7	0.002	74.8
Business Park	11.4	0.6	153.0	3.3	8.6	0.016	177.0
Colleges	2.2		78.3	1.0	3.1	0.02	84.7
Industrial	18.7	0.1	37.6	4.1	5.9	0.006	66.3
Port Facilities	18.7	0.1	37.6	10.1	4.6	0.001	71.0
Pine Plantation	0.0005		0.06			0.04	0.1
Transportation							
Freeway	62.3		31.2	10.0		0.004	103.5
Major Arterial	16.3		8.2	15.6		0.002	40.1
Jacksn. Int. Airport	0.2		0.4	1.6	0.5	0.02	2.8
Jacksonville NAS	3.4		9.7	4.5	2.6	0.02	20.2
Landfills					1.1	0.02	1.1
Power Plants	220.8		1.6	0.9	0.9	0.03	224.3
Terrestrial Ecosystems							
Pine Flatwoods						0.04	0.04
Wetlands, Fresh						0.02	0.02
Salt Marsh						0.00002	0.00002

Total Aereal Empower is the sum of each column by Land Use.
The following notes describe the methods for enumeration of potential energy unless otherwise noted.
Potential energy was then converted into EMERGY by the appropriate Transformity in Table 1.0.
Note that "Employee/Resident" notation means Employee or Resident

Resource Category	Notes and Sources
Direct Energy	=(Annual Kwh per Customer)*(Density of Buildings/Homes per Acre)* (3.6E6 J/kWh) Annual kWh from Jacksonville Electric Authority, 1991 Density of Buildings per Acre of Land Use from J. P. D., 1985
Water Use	=(Volume of Water)gal/y*(1m3/264.2 gal)*(1E6 g/m3)*(5J/g) Volume of Water =(Per Capita Water Use)*(Employees/Residents per Acre) Per Capita Water Use = (Total Water Use for Sector)/(Employees for Sector) Water Use for sector from Florida Abstract 1991 Employees for Sector from J. P. D., 1992 Employees per Acre from J. P. D., 1992

Table 6.0 Continued

Human Labor	Reported in EMERGY units as follows: =(Human Labor per acre)*(EMERGY Delivery Rate of Human Labor)semj/yr EMERGY Delivery Rate per Year (based on education) from Odum, 1993 Employees per acre =(Office Space)*(Employees per Office Space)/(Land Area) Office Space from Jacksonville Chamber of Commerce (J. C. C.), 1992 Employees per Office Space estimated from J. P. D., 1993 Land Area from J. P. D., 1985
Infrastructure	Data reported in grams for concrete and potential energy for wood and furnishings. Potential energy divided by estimated turnover time to get final flux value. =(Building Area)s.f*(Concrete weight)lbs/s.f.*(454.5g/lb) =(Building Area)s.f*(Wood weight)lbs/s.f.)*(Potential Energy of Wood)J/lb =(Building Area)s.f*(Metal/Plastic mass)gm/s.f.)*(Potential Energy per Item)J/gm =(Road Area)s.f.*(Mass per area)lbs/s.f.*(Potential energy of material)J/lb =(Potential Energy of Soil Flux)J/m2-yr*(.0929 m2/sf)*(Time of Formation)yrs. Building and Road Area for each land use from palimeter reading by this study. Building Weight from Dodge, 1973 Potential Energy of Wood from Odum, 1987 Potential Energy of other Items from Odum, 1987 Transpiration Rate of Vegatation from Golkin, K. R., et al, 1984 Formation Time of Soil estimated from Regan, 1977 Potential Energy of other Items from Odum, 1987
Outside Goods and Services	Data reported in 1986 dollars. =(End Use Consumption per Resident/Employee)$*(Resident/Employee per Acre) End Use Consumption per Resident/Employee from estimate based on Table 4.0 and Population for Residents, and Table 5.0 and estimate of dominant sector for land use.
Renewable Energy	Data reported as potential energy of rain. =(Transpiration per year)m3/m2*1E6g/m3*(Chemical Potential Energy of Water relative to Salt Water)J/g*4.046E3m2/acre*(% Vegetation Coverage) Transpiration per year = 0.8 m3 estimated Chemical Potential Energy of Water Relative to Saltwater = 4.9J/g Odum, 1987 % Vegetation Coverage from Duval County Property Appraiser Aerial Maps

the most prominent emergent property of land uses. Counter intuitively the regional land fills had the largest assest in infrastructure as a function of discarded materials 303E16 semj/acre (Table 7.0). Overall the emergy of infrastructure was similar to what may be predicted by other forms of analysis, with the commercial land uses having the largest assets per acre.

The level of environmental loading from urban systems was related with the emergy investment ratio from (Odum, 1993). As expected the CBD had the largest enviromental loading 1E22 followed by the port facilities 1E21 (Table 7.0) Of the other commercial land uses the strip commercial land use was the largest at 3E20.

In summarizing the resource use of individual land uses, the transformity relates the aereal empower per potential energy of resource use. The tranformity of a land use is another form of ranking the intensity of resource use of a land use. The transfromity most directly relates to the fundemental potential energy of the land use and therefore is prehaps the most objective measurement. When land uses are ranked by transformity, the hierarchial distribution of resource use becomes apparent. The commcerical and high density residential land uses have the highest transformities (Figure 6.0) as centers of converging and consuming resources. In contrast to the cities' overall hierarchial form, suburban land uses have fairly similar transformities ranging from 1900E5 semj/j to 1000E5 semj/j.

The relationship between Jacksonville's CBD and the suburbs is one of the primary emergent properties of how the collection of land uses are used. This relationship begins to answer the question of how the existing land use pattern impacts the type and amount of resources being consumed in Jacksonville. Resource maps were developed using emergy values to investigate the spatial distribtuion of resources.

The annual resources per acre map depicts Jacksonville as a fairly complex system with centers of activity responding to several structures in the landscape, principally the St. Johns Rivers and the interstate freeways (Figure 7.0). The highest resource use is in the CBD which clearly functions as the center of the land use pattern, Other centers of resource use stretch along the radials of the freeway system feeding downtown. Development along the atlantic ocean appears to be a secondary center of resource use. The infrastructure facilitating resource use was referred to as emergy storage and mapped (Figure 8.0). The urban area has filled in almost completely between the freeway circling the city and the CBD. However, large gaps still remain where natural landscapes coexist with seemingly leap frog development on the outskirts of town. The emergy storage of the city appeared more evenly distributed than did the aereal empower where centers of activity are more identifiable.

The map of transformity indirectly integrates the first two maps with its values derived from the aereal empower per unit of potential energy of structure. Two of the most valuable land uses for the city pop out in this map, the CBD and the port facilities (Figure 9.0). Also the important relationship between the St. Johns river and the CBD and port becomes evident.

In order to summarize the land use distribution analysis and explore the relationship between the CBD and the suburbs, emergy signatures along transects

Table 7.0 Emergy evaluation of infrastructure storage,
Emergy investment ratio and transformity for individual land uses

Land Use	Infrastructure Storage (E16 semj/acre)	EMERGY Investment Ratio (E16)	Transformity (E6 semj/J)
Residential			
Low Density	52.1	1150.1	100.7
High Density	123.0	20954.0	1476.7
Commercial			
C.B.D.	283.5	1047216.2	19243.5
Shopping Centers	187.3	21444.3	1357.7
Strip Developmen	188.3	32620.0	1917.1
Business Park	100.4	11236.2	804.6
Colleges	30.9	3663.6	7.1
Industrial	163.0	10273.6	801.2
Port Facilities	252.4	123130.9	3116.1
Pine Plantation	13.4	1.8	0.01
Transportation			
Freeway	199.1	25621.1	1024.4
Major Arterial	234.0	18518.9	646.4
Jacksn. Int. Airpor	48.4	129.7	0.2
Jacksonville NAS	135.1	1133.2	3.4
Landfills	303.0	45.2	0.6
Power Plants	28.4	6967.4	16.9
Terrestrial Ecosyst			
Pine Flatwoods	13.4		0.002
Wetlands, Fresh	21.6		0.001
Salt Marsh	4.9		0.000002

Index	Notes and Sources
Infrastructure Storage	Potential energy was converted into EMERGY by Transformities in Table 1.0.
EMERGY Investment Ratio	=(Purchased Aereal Empower)/(Renewable "Free" Aereal Empwer) Purchased Aereal Empower from Table 6.0 as Direct Energy, Human labor, Building Materials, Outside Goods and Services and Water Consumed Renewable Aereal Empower from Table 6.0
Transformity	=((Total Aereal Empower)*(50 years))/(Potential Energy of Structure) Total Aereal Empower from Table 6.0 Potential Energy determined as per Table 6.0

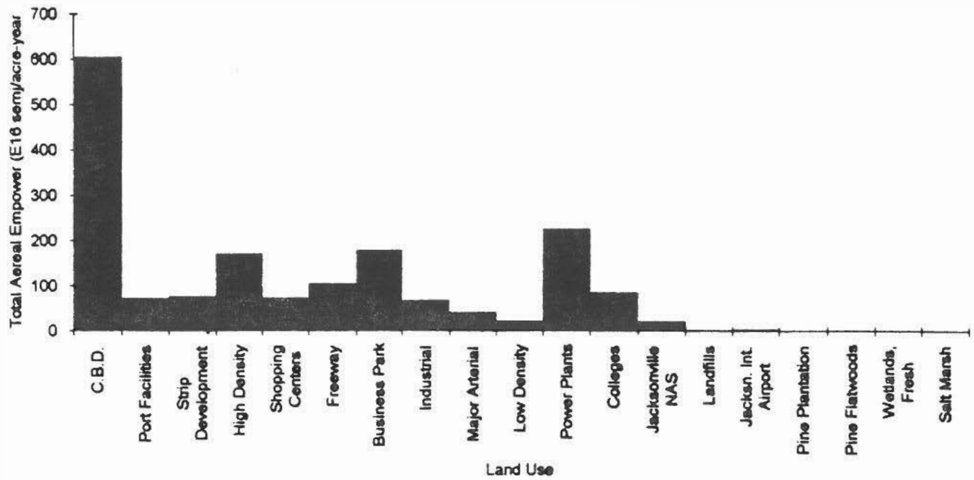

Figure 5.0 Distribution of aereal empower for the collection of land uses in Jacksonville, Florida.

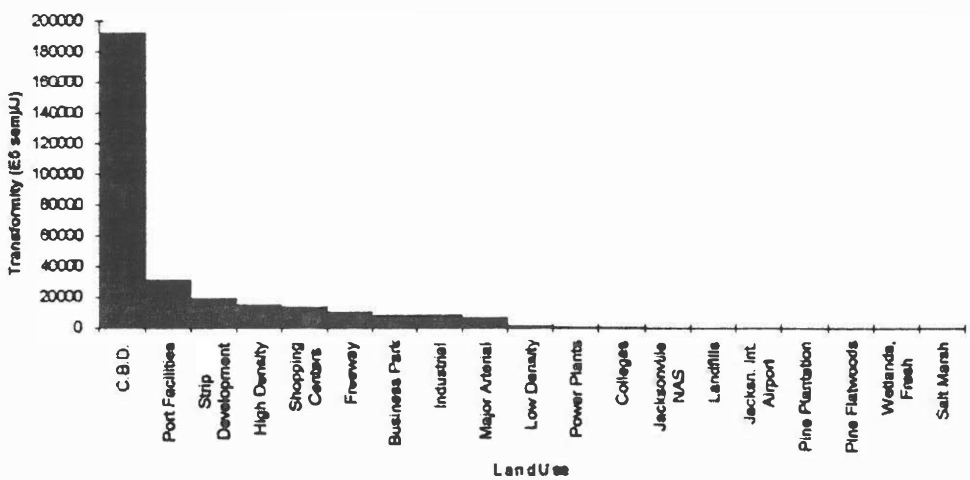

Figure 6.0 Distribution of transformites for individual land uses in Jacksonville, Florida.

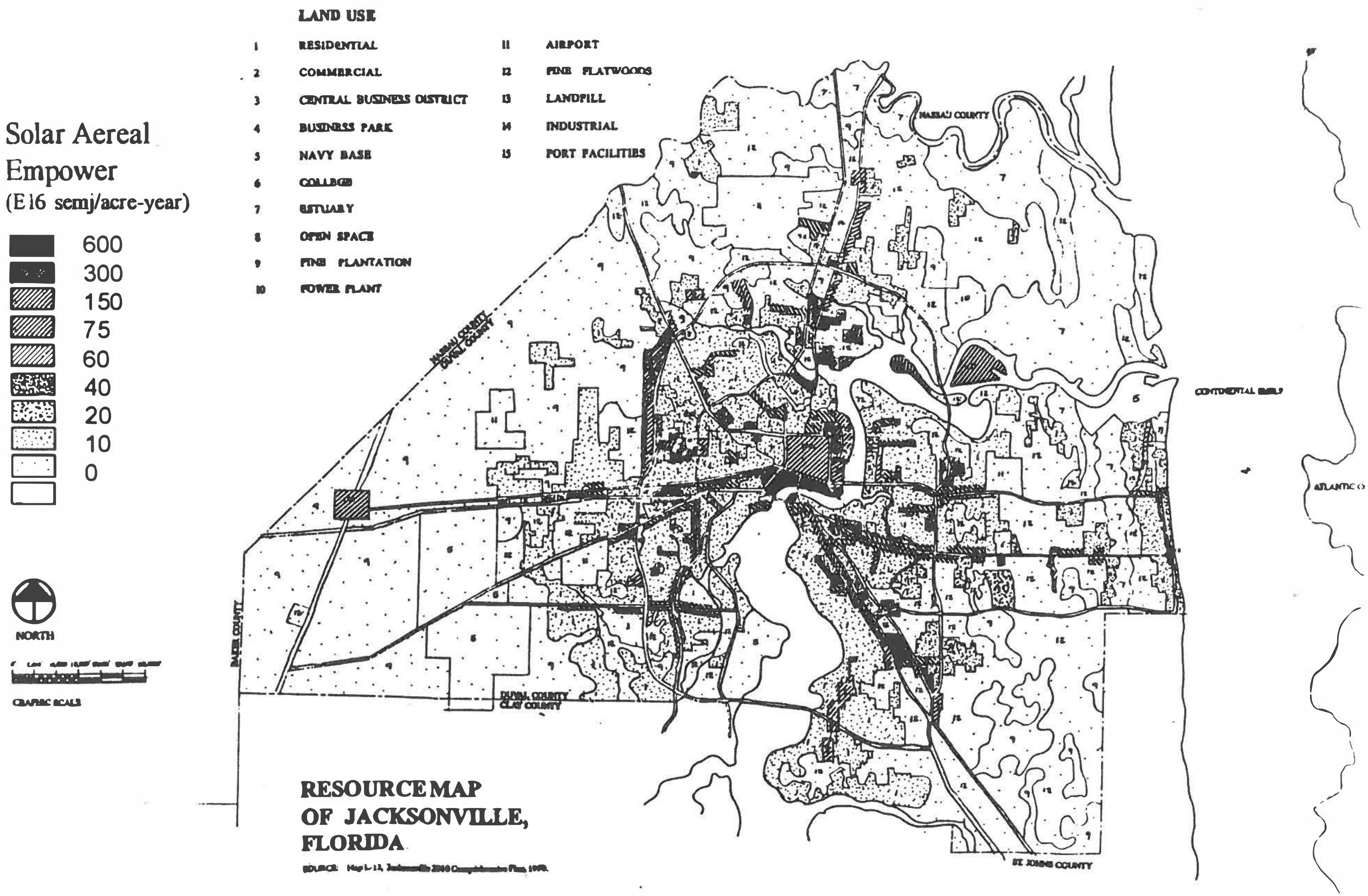

Figure 7.0 The solar aereal empower for the Jacksonville, Florida land use pattern.

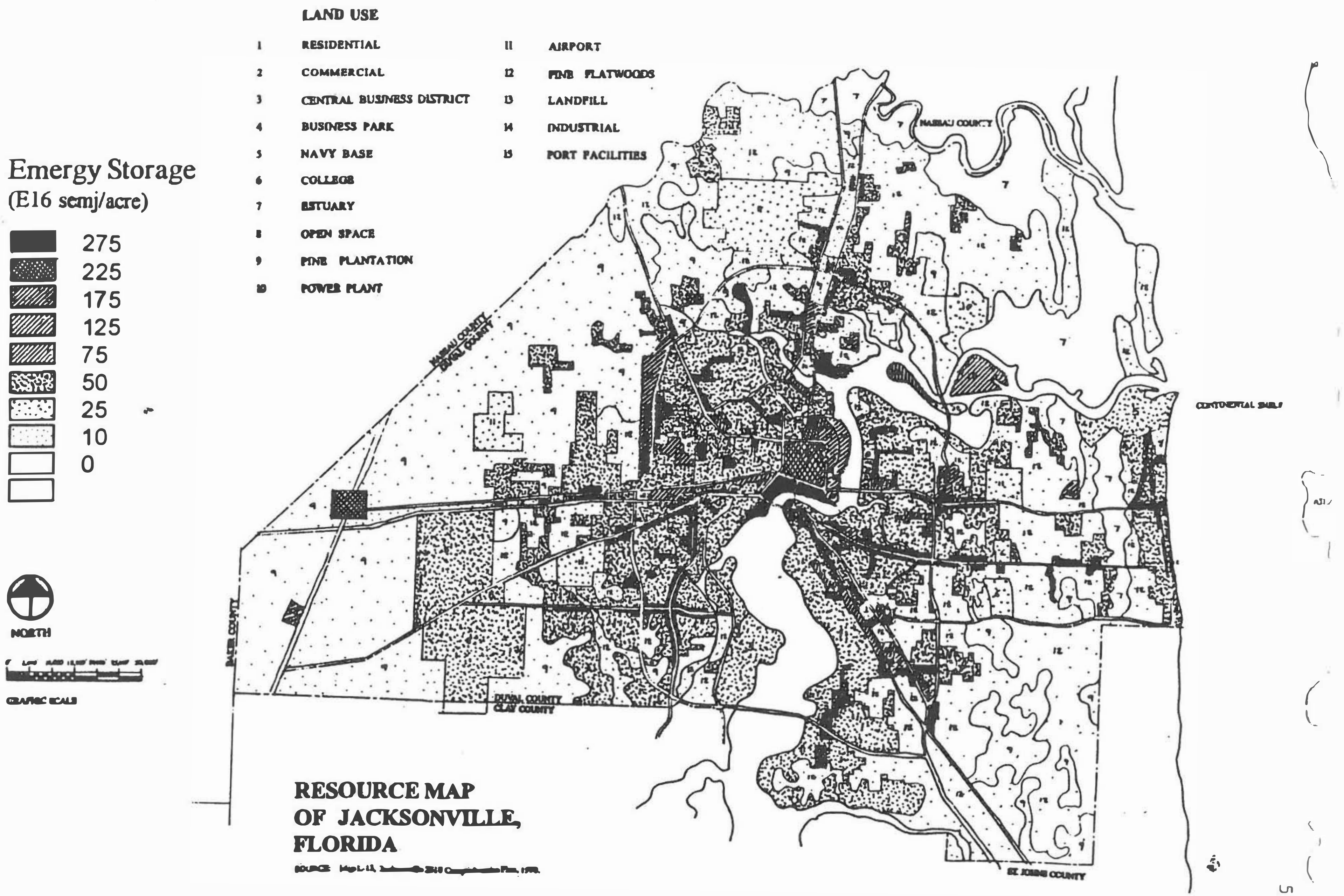

Figure 8.0 The emergy storage for the Jacksonville, Florida land use pattern.

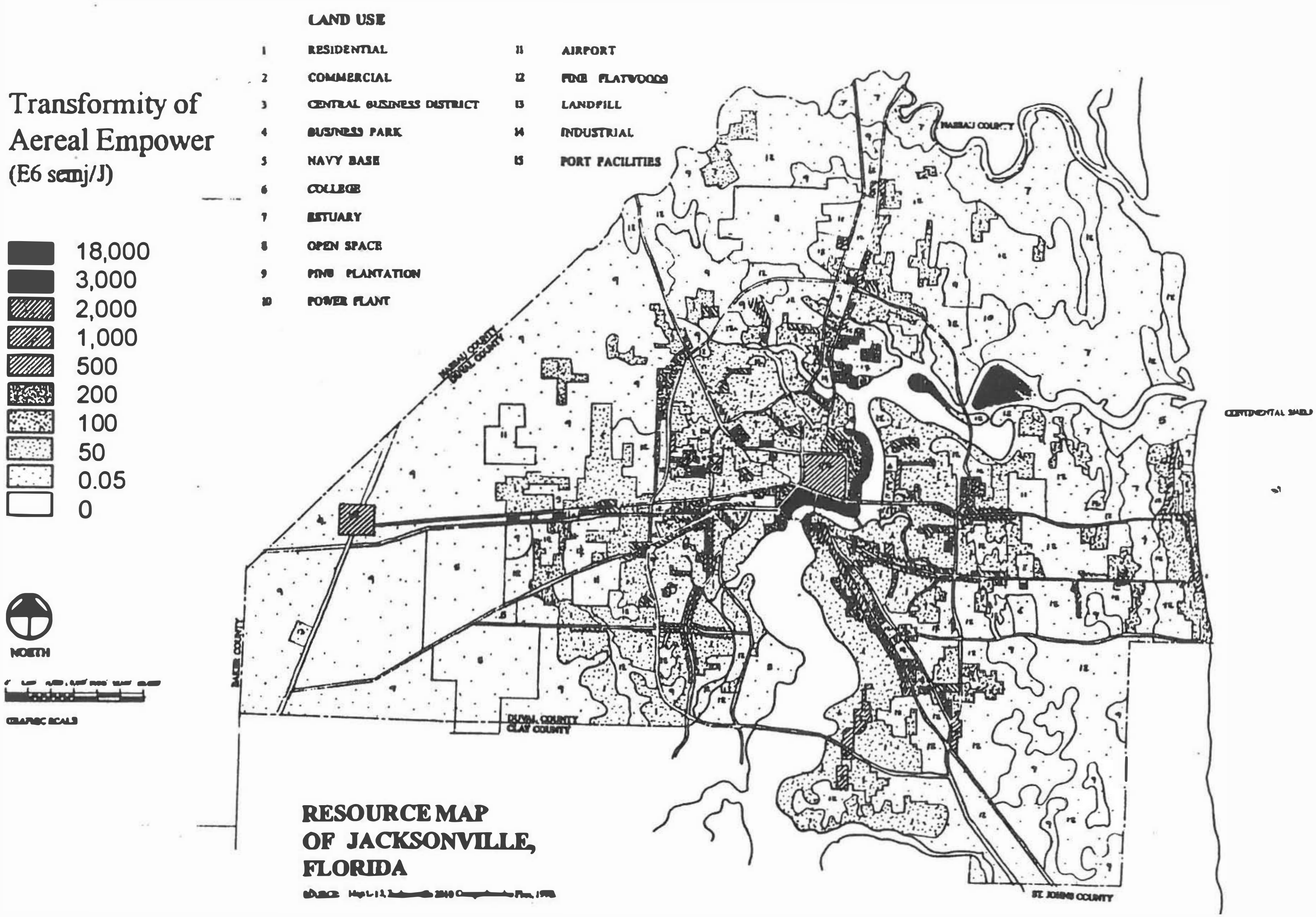

Figure 9.0 The solar transformity of aereal empower for the Jacksonville, Florida land use pattern.

between the CBD and the suburbs were developed. The total resource use peaks in the CBD and drops dramatically into the suburbs (Figure 11.0). The three types of land uses become obvious; urban, suburban and natural. The first ring of urban resource use was six orders of magnitude larger than the suburbs. And the suburbs are three orders of magnitude larger than natural landscapes. The suburban area extends across approximately twice the crossectional area than does the urban area. Renewable resource use increases linearly from the center of town (Figure12.0). The resource use in labor peaked in the CBD depicting the prominance of human labor as driving the organization of the city (Figure 13.0). Direct energy consumption was more widely distributed with multiple peaks approximately located at the CBD and the freeway circling the city (Figure 14.0). The total infrastructure of the city was evenly distributed in the suburbs with a prominant peak in the CBD (Figure 15.0). The ratio of infrastructure between urban and suburban land uses was approximately three to one.

A linear relationship between total resource use and distance from the CBD was statisitcally significant on the log base 10 transformed resource use and was summarized with the following equation:

$y = -0.12x + 2.31$ ($P<0.001$)
y = Total resource use per acre-year log base 10
x = Distance from city center in 5,000' increments

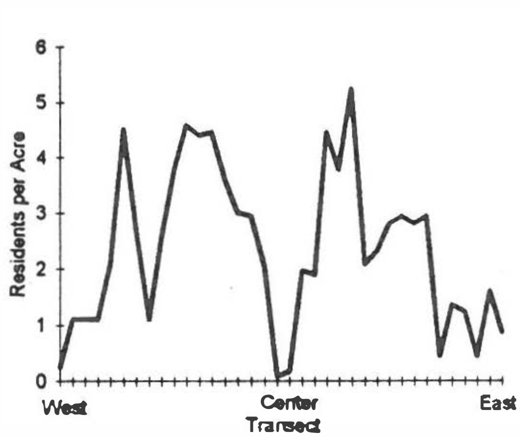

Figure 10.0 Residential distribution across a mean cross section of the city. Transect starts from the western boundary and extends through the city center ending at the eastern boundary.

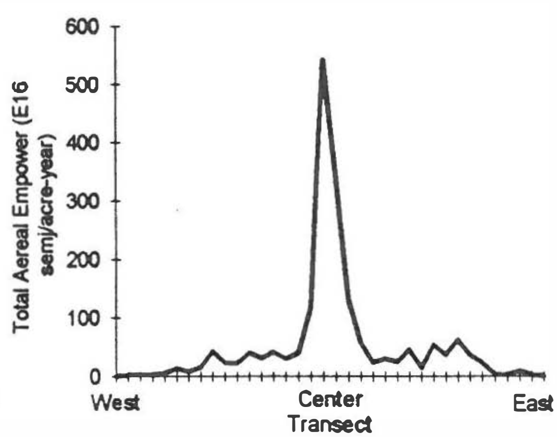

Figure 11.0 Distribution of aereal empower across a mean cross section of the city. Transect starts from the western boundary and extends through the city center ending at the eastern boundary.

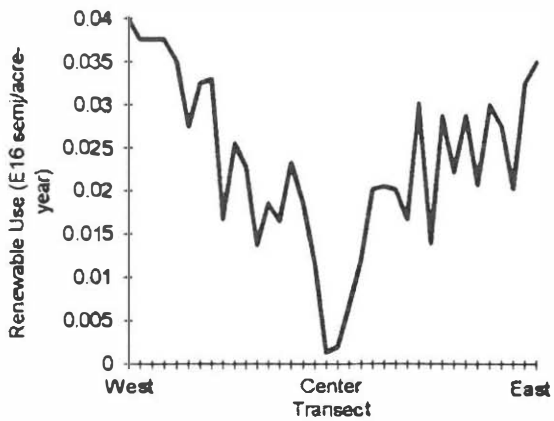

Figure 12.0 Distribution of renewable use intensity across a mean cross section of the city. Transect starts from the western boundary and extends through the city center ending at the eastern boundary.

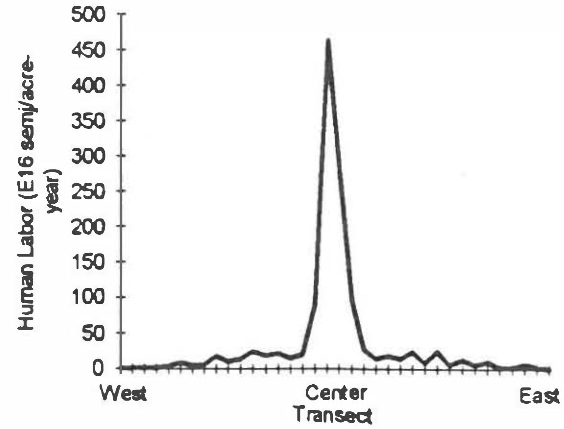

Figure 13.0 Distribution of human labor use per acre across a mean cross section of the city. Transect starts from the western boundary and extends through the city center ending at the eastern boundary.

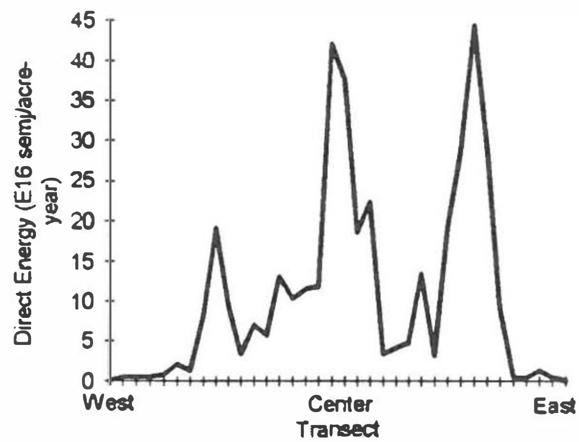

Figure 14.0 Distribution of nonrenewable energy per acre across a mean cross section of the city. Transect starts from the western boundary and extends through the city center ending at the eastern boundary.

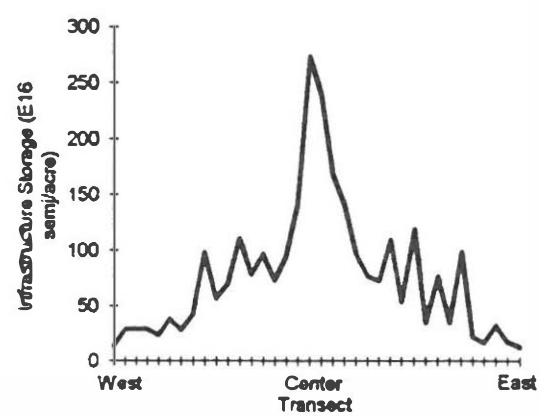

Figure 15.0 Distribution of infrastructure storage across a mean cross section of the city. Transect starts from the western boundary and extends through the city center ending at the eastern boundary.

Discussion

County Resource Use

Cities consume resources to support a dizzying array of functions. However, there are a relatively small set of functions that drive and form the organization of a city. Figure 1-1 was an attempt to simplify the complexity and examine the forces that truly shape an urban system. Fossil fuel, a nonrenewable resource, was the largest flow into the system. Energy made up 62% of the total resources consumed in 1992. Of this energy, electricity was 40% and gasoline 22%.

The dependence on fossil fuel resources has left American cities susceptible to changes in energy prices. Crude oil prices have experienced sharp changes over the last twenty years. Several times between 1973 and the early eighties crude oil prices have increased dramatically over a short period of time. For example, between 1979 and 1981, the official price of crude oil from foreign countries rose 260% (Energy Information Administration, 1991). As fossil fuel reserves are used up, alternative energy resources will inevitably be needed. Under existing conditions, cities that rely most heavily on the automobile would appear to be adversely affected by higher transportation costs.

Renewable contributions from the environment supplement purchased resource use. Currently, renewable resources contribute 4.35% of the total resources used within Jacksonville. It is important to realize that cities could not be sustainable in the true sense of the word. As centers for converging and transforming primary materials into products, cities concentrate resources from a large territory. Using exclusively renewable resources, the land area of Jacksonville could only support 30,159 people at the present standard of living. Currently, Jacksonville supports a population of 650,000. Planning a truly sustainable city may be impossible and irrelevant. However, planning a city that maximizes environmental contributions is a better goal. As fossil fuel reserves decline, cities able to supplement or replace purchased resources with renewable resources will have a competitive advantage.

A city relates to the environment with its land use pattern. Natural system productivity is tied closely to area. For a city to enhance its environment, the area of impact necessary to support urban functions needs to be minimized for renewable contributions to be maximized. The following discussion relates four land use patterns to their impact on renewable contributions and total resource use.

Growth in Jacksonville's Suburbs

The City of Jacksonville predicts continued population growth increasing the demand for housing. Between 1974 and 1992, residential land area grew 85.79% while the population grew at a slower rate, 21.59%. According to the Jacksonville Planning Department (J.P.D.), between the years 1985 and 2010, eighty-eight percent of new housing will be developed at an average gross density of less than four dwelling units per acre. Another 11.5 percent of residential growth will be medium density; seven to twenty dwelling units per acre. Residential growth also necessitates new road construction. Currently 17.9% of the urban land is used for streets and highways. This low density of development forces a large investment in transportation in both operating costs and construction.

Urban Infrastructure

The streets, buildings, sewer and water lines represent a large infrastructure investment for a city. These assets are the "hardware" that make human enterprises function. This study evaluated building and transportation resources. Building assets measured were the materials in building shells and interiors, and the service used to build the structure. For roads, materials and the service to build and maintain roads were evaluated. The following discussion identifies infrastructure use for residential and commercial land uses.

Residential Infrastructure

Per capita residential infrastructure to support a low density residential land use at 2.73 dwelling units per acre was 2.40 times larger than the high density residential land use at 30 dwelling units per acre. When this large investment is amplified by the larger area of low density residential, this infrastructure becomes a significant part of a city's total resources.

Low density residential uses a per capita 5.34E15 semj/acre compared to 3.05E15 semj/acre for high density land uses. In other words, 43% more resources are used in buildings and roads for the low density land use than in the high density land use.

Commercial Infrastructure

Downtown Jacksonville had the largest proportion of building and transportation infrastructure per acre in the city at 2.46E18 semj/acre. Downtown uses 28.5% more infrastructure than the next closest land use, strip commercial, at 1.76E18 semj/acre. Several forms of transportation are available downtown, a bus system, rail system, and an extensive street grid. The road network and expanded rail system referred to as the Automated Skyway are reported to be under-utilized by the Jacksonville Chamber of Commerce (J. C. C., 1992). The Automated Skyway suffers from low ridership and the road system is under-utilized in some vacant city blocks. These regional transportation resources appear to represent a large investment that is being wasted.

The CBD competes with suburban business parks for office development. On a per worker basis, the infrastructure use is similar for these two land uses. However, business parks require an extensive suburban freeway system and lack mass transit facilities such as the Automated Skyway. The complete impact of suburban office parks can only be evaluated by including the personal transportation costs associated with suburban land uses, discussed later in this section.

Total Infrastructure Resource Use

Higher infrastructure costs can be expected from a land use pattern dominated by land uses requiring a large amount of infrastructure per person to support urban functions. The proposed high density land use pattern concentrated development by placing 11.9% of the population in city neighborhoods. This resulted in a 7.2% reduction of annual infrastructure use by this alternative pattern. Similarly, the pedestrian pocket land use pattern concentrated development by placing 15.2% of the residential population into pedestrian pockets. This resulted in an estimated reduction of 10.8% in annual infrastructure use.

The assets in buildings and roads were estimated to represent 13.5% of the total resource use for the 1985 existing land use pattern. Under the alternative patterns a 1%-1.5% savings in total resource use appears possible.

Environmental Contributions

The environment contributes many life support functions to a city. Vegetation converts dilute energy from the sun along with carbon dioxide into biomass and oxygen. Some of the other functions natural systems perform include microclimate modification and flood attenuation. This study measured the work performed by ecosystems from the transpiration rates of plant communities. The work performed by natural systems comes from renewable resources at a limited cost to human society. Replacement of these functions represents a loss of renewable resource processing for society.

Natural systems have a large amount of evolutionary resources invested in them, not evaluated by this study. Biodiversity requires hundreds of years of trial and error to select species that maximize an ecosystems resource use. The cumulative energy in this process can be measured with emergy and related to other resources. However, the question of biodiversity was deemed beyond the scope of this study. In many development conflicts, the value of the natural system is in its biological diversity. Natural systems that are endangered represent a permanent loss of evolutionary resources. In Jacksonville, the predominant ecosystem of pine flat woods was not considered endangered.

The pattern of urban development has a large influence on environmental contributions. Low density land use patterns tend to remove natural systems and replace them with energy intensive urban landscapes, highways, and parking lots. Low density residential land uses have the largest impact, by representing almost 50% of the developed area. On a per capita basis, low density residential land uses have a large contribution of renewable resource use. Low density residential also has a larger renewable contribution than the proposed pedestrian pocket and city neighborhood land uses. However, low density land uses also require more per capita road structure as mentioned earlier. To correctly judge the impact of low density residential land uses, the total renewable resources contributed by the resultant land use pattern has to be evaluated

A useful index for measuring the renewable contributions in the context of total resource use is the emergy investment ratio. The emergy investment ratio relates purchased resources to renewable resources. The larger the renewable contribution the lower the emergy investment ratio. A lower emergy investment ratio indicates that a city is using less purchased resources to support its population. The emergy investment ratio can also be thought of as a index of sprawl since most renewable contributions are area based. The less natural area, the lower the renewable contributions to the system. With a lower emergy investment ratio, the city of Jacksonville would produce products with more renewable resources and less purchased resources. This would suggest that products could be produced for a lower price and as a result be more competitive.

The future land use plan estimated from the 2010 Comprehensive plan shows the long term implications of the existing low density development. Natural contributions begin to drop considerably as Jacksonville builds out the county. Renewable contributions are reduced 14.2% from the 1985 land use plan. The emergy investment ratio climbs to 633.80, a 62% increase from the 1985 land use plan. Many of the qualities attracting economic development may be effected by a large loss of natural resources.

The two alternative land use patterns suggest that a mixed use concept implemented on a large scale may reduce infrastructure costs and lower natural resource loss. The dependence on nonrenewable resources can also be reduced with a larger portion of the population using pedestrian and mass transit alternatives. Walking to urban functions is only possible in a land use that combines several urban functions in close proximity to a residential community. The result would be higher density land uses. With higher densities, mass transit then becomes a real option.

Spatial Patterns

As discussed in the preceding sections, the spatial relationships between urban functions have a major impact on infrastructure and energy costs. As urban functions are separated from one another and single use land uses become dominant, resource use increases. The relationship between downtown Jacksonville and the suburbs provides a clue to the increased resource consumption associated with urban sprawl.

The energy use of the city suggests an even distribution of use. From downtown to the rural fringe, electricity, and gasoline was used at a fairly constant aereal intensity. Downtown Jacksonville still remained the largest consumer of goods and services. However, past the CBD, resource use appeared flat. If high density mixed use land uses were used to center resource use in the suburbs along radial freeways, the resource signature of Jacksonville would show larger peaks of resource use in the suburbs. A resource signature of a section through southeast Jacksonville was used to illustrate this point. The 1986 existing land use pattern was compared with an alternative using a pedestrian pocket. The alternative signature shows a sharp increase in resource use where a pedestrian pocket is centered. In contrast, the existing pattern is centered by a freeway flanked by a medium density residential land use.

The suburbs do have centers of resource use, shopping centers and business parks, that are similar in aereal resource use to pedestrian pockets. However, most of these suburban centers are removed from residential areas, separated by major arterials. The potential for integrating these regional centers with high density residential to create a pedestrian friendly environment is great.

The annual resource use when mapped suggested a strong relationship between commercial and transportation land uses. The need to provide automobile access along narrow strips to maximize street frontage probably adds to the distance between urban functions. The pedestrian pocket and city neighborhood concepts attempt to diversify transportation modes. Walking and mass transit are added to the mix. Both walking and mass transit are enhanced by concentrated development. Land use patterns that use mixed use centers would have centers of resource use primarily at intersections of transportation corridors, not along narrow strips.

Conclusions and Recommendations

This study evaluated three major components of urban systems: urban infrastructure, transportation resource consumption, and environmental contributions. In each of these areas, the existing low density land use pattern appeared to consume more resources than alternative patterns concentrating development. For individual land uses, strip commercial and low density residential land uses required more infrastructure per person and caused more natural system loss. Results suggest that resources can be saved with the concepts implemented by the alternative land use patterns.

Mixed use land uses that combine commercial and residential functions enhance pedestrian activity. Walking requires considerably less resources than existing resource intensive transportation modes that depend on nonrenewable resources. This dependence threatens the long term economic stability of American cities.

If flows from fuels and goods and services decrease (Figure 1.0) cities will have to utilize more renewable resources and conserve the remaining purchased resources. This will mean transportation systems will have to rely less on fossil fuels and more on human effort. The impact on individual land uses will mean patterns that require cars to complete most functions will be uncompetitive.

The following are some process and policy suggestions related to land use planning.

1. Natural resource indices should be identified for Jacksonville and tracked over time. The existing comprehensive plan catalogues natural resources, but does not provide summary statistics and indices.

2. Suburban development plans should allow for future high density uses. If as

nonrenewable resources decline, and high density living becomes prevalent, formerly suburban areas will need to be converted into higher density systems.

3. Comprehensive plans should directly address energy consumption. The transportation and concurrency elements have perhaps the largest impact on energy consumption, but the importance of energy consumption as a unifying theme needs to be a larger component of the planning process.

4. Comprehensive plans should integrate planning elements with general systems principals. Comprehensive plans must try to quantify relationships between major flows and storages of resources. Today, most comprehensive plans use future land use maps as an end product integrating elements. However, the step from written policy to zoning boundaries is still more political than objective.

5. The method of projecting urban change should include several alternatives. Jacksonville's comprehensive plan appeared to rely on one projection of population growth for its planning needs. Perhaps several alternatives should be investigated and incorporated into the planning process. A no growth, recession or high growth alternatives should all be part of the planning process.

6. Finally, comprehensive plans should employ several analytical methods for public policy decisions. A good compliment to data collection and statistical analysis may be emergy and economic analysis. Both techniques provide unique and important information. The contrasts between these methods present many issues that we as a society face.

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4. ORGANIZATION & DISTRIBUTION OF URBAN STRUCTURE IN METROPOLITAN MIAMI, FLORIDA.

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INTRODUCTION

One theory of landscape organization is that landscapes are organized by their driving energies. The convergence, storage, and divergence of energies shape the landscape and in turn are organized by it. In natural landscapes, dilute forms of energy such as sunlight, wind, tide, rain, etc. are concentrated into forms of higher quality such as rivers, plants, and animals. With increased presence of humans in the landscape, these energies and processes have been superseded in importance by the flows of energy under direct control of human populations. As a result, where human development has occurred, fossil fuels are the primary driving energy, shaping and altering landscape processes, structure and form. In landscapes dominated by humanity, energies converge in central places and then diverge again. Understanding the spatial relationships between driving energies and structure and the patterns of energy convergence and divergence, may help in the planning, operation, and management of landscapes dominated by humans. Evaluating urban organization and zonation, may help in predicting environmental impacts of urbanization, and ultimately in redirecting energies to minimize impacts.

Plan of Study

Most studies of urban systems focus on either the landscape scale, in which theories of central place and clusters of urban centers have relevance, or at a smaller scale, in which the internal organization of the city is analyzed. The second approach is the scale applied here, without ignoring the position that the city studied plays in the larger context; and the particular characteristics that derive from it.

Spatial data of the Metropolitan Miami Area were analyzed to determine the distribution of urban structure, empower density, economic values, age of structure, and measures of information based on light reflectance of satellite imagery. Data were gathered along transects originating in the center of Miami and radiating outward to the surrounding lands dominated by natural and agricultural uses. Graphs of the various data sets were generated along the axis of each transect and summarized for the entire Metropolitan Miami Area.

Description of the Study Area

Figure 1 is a satellite image of metropolitan Miami, a city on the southeastern coast of Florida, located on Biscayne Bay. The metropolitan area of Miami is the largest urban area in Florida and one of the largest in the Southern United States. The population is over 1 million people within the metropolitan area that stretches along the Atlantic coast.

The climate is subtropical, with an annual rainfall average of about 1,525 mm (60 in). The metropolitan area stretches along the coast extending north and south on a slightly elevated coastal ridge. To the west is the Everglades, a large wetland area that is the primary source of potable water recharge for the urban system. The topography is such that groundwater tables are at or very near the surface for about half the year. As a result there is an extensive system of canals and structures used for water management throughout the metropolitan area.

Miami's early history was dominated by the Spanish who first established a Jesuit mission for the Tequesta Indians in the Miami area in the 1560s. The city of Miami was founded in 1870. An East Coast railroad was built in the 1870's that connected Miami with the northern east coast of the United States, but the metropolitan area did not grow significantly until the early 1920s and again in the 1950s. In its early years of development, Miami was a tourist destination with some agricultural crops, especially winter vegetables and citrus. Beginning in the 1950's extensive areas to the south of the city were placed in agricultural uses. Miami has an international airport and a major seaport and is considered the "gateway" to South America and the Caribbean. During the 1960s, Miami became a major center of finance and business with Latin America.

As Miami has grown in size, its urban area extended, first, along the coastal ridge in a north- south axis and then began to move westward. Figure 2 shows the growth pattern of metropolitan Miami for 1920 to the present. The metropolitan area now extends over an area measuring about 905 km^2 (350 mi^2). There is continued growth in a southerly direction that is beginning to threaten agricultural lands.

Review of the Literature

A city is a large and complex human settlement which by definition is dependent on people outside the urban system for at least part of its provisions (Douglas, 1983). Two aspects can be distinguished when studying urban systems: the physical structure of the city, and the functional

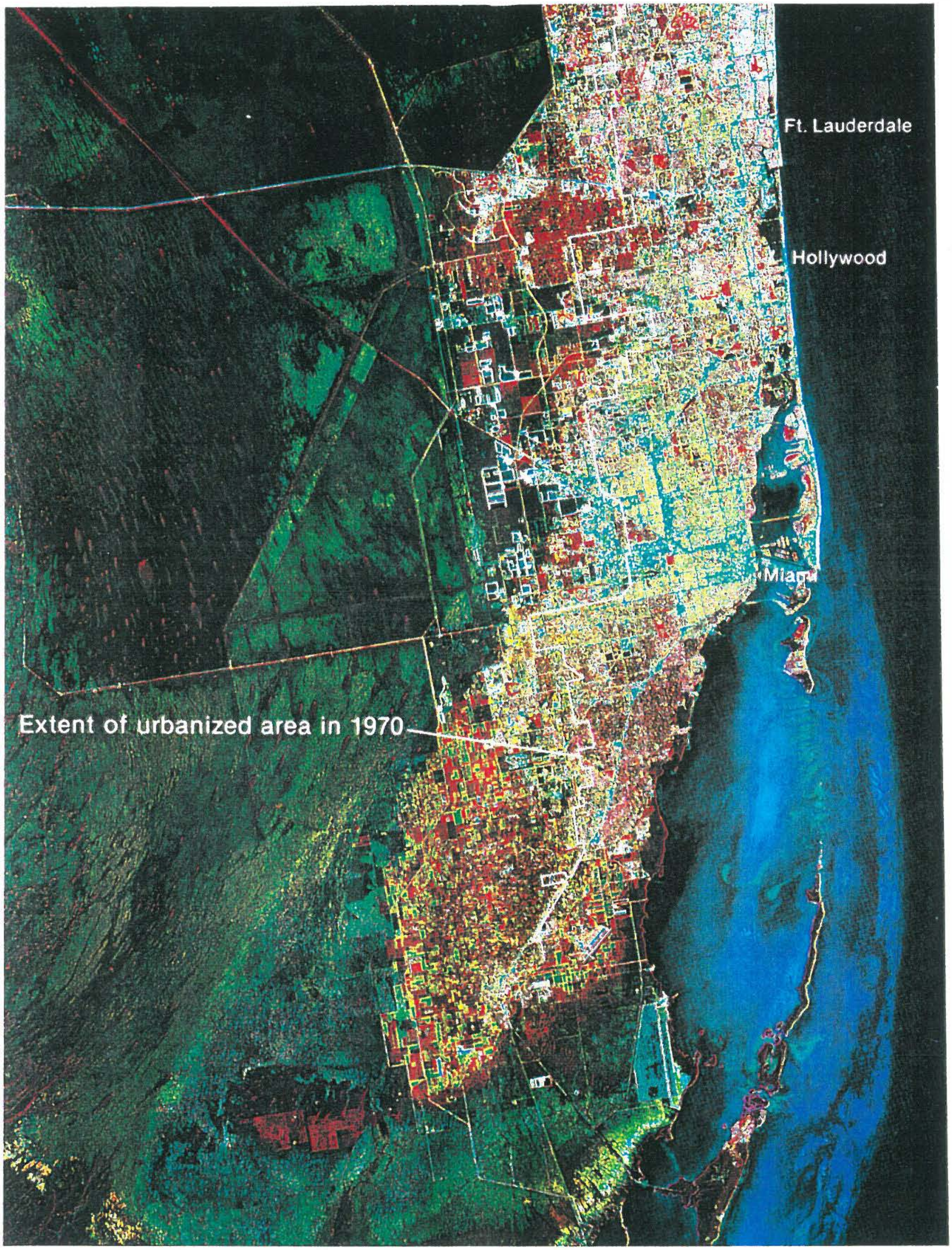

Figure 1. Satellite image of South Florida showing metropolitan Miami and surrounding area. To the west of Miami is the wetland system known as the Everglades, to the east is Biscayne Bay and the Atlantic Ocean. To the southwest are mixed urban and agricultural lands. From Fernald et al. (1994).

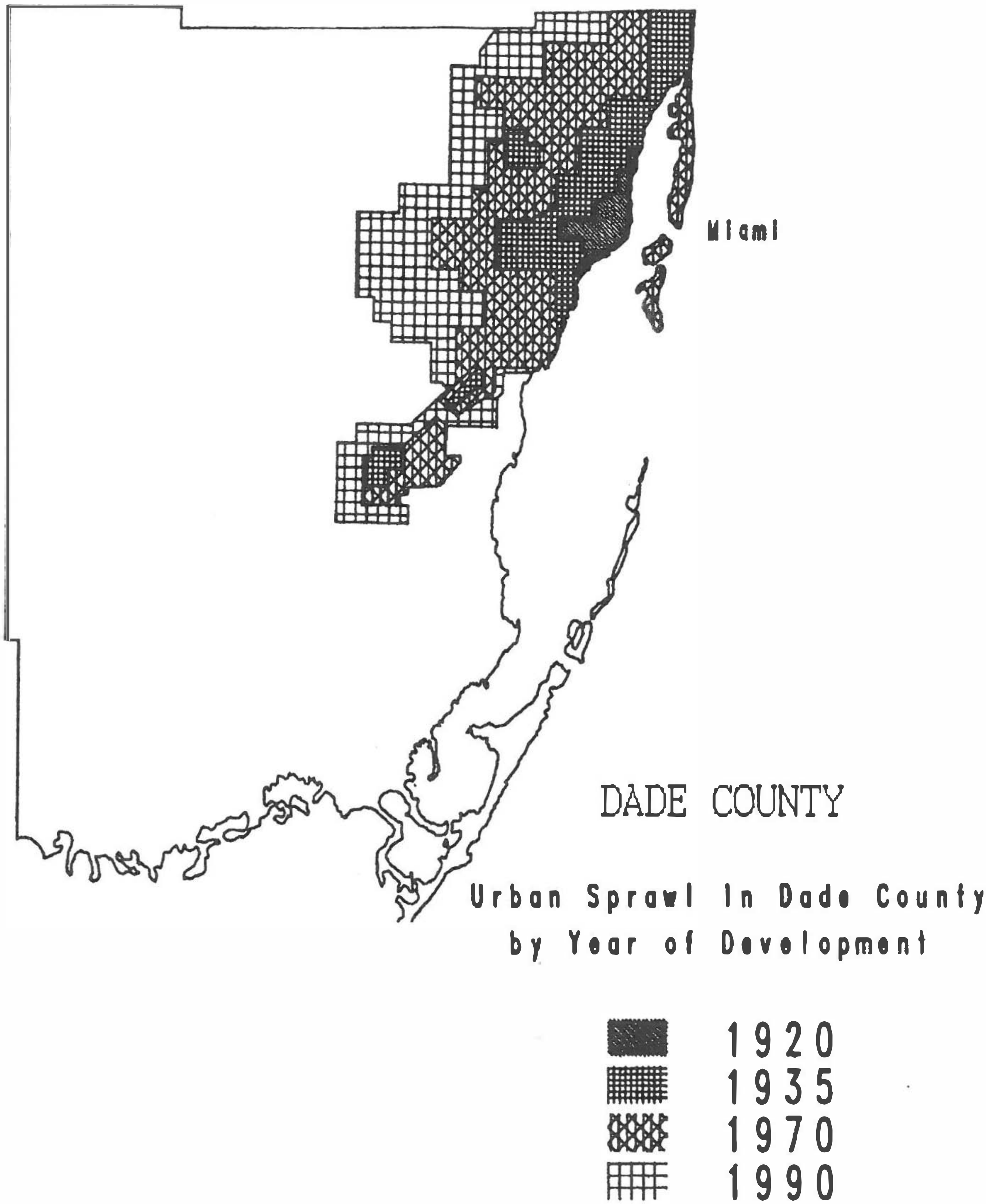

Figure 2. Growth of metropolitan Miami from 1920 to 1990. Miami has grown westward and northward and has now connected with urban centers to the north in a continuous urbanized area extending along the coast. Recent growth has been toward the west and southwest.

processes occurring in it. The city is the regional site where economic and administrative activities take place, and contains the cultural, educational, and religious centers. The organization of these activities, interacting with physical constraints, gives shape to the urban structure. In fact, as Deevey (1963) stated, "city" is a derivation of "civitas", which stands for a way of living, rather than a physical place. The "urb" part, that is, the physical structure reflects the organization of the function, and feeds back allowing the later to develop. Douglas (1983), points out that the main emphasis in studies of cities has been typically been explaining the city in terms of economic forces, without making explicit distinction between function and structure.

Organization of Cities

The relation between structure and function has caused some research to focus on the similarities between cities and an ecosystems. Many homologies have been noted, such as a succession: cities are found to have periods of growth, homeostasis, retrogression, renewal and oscillation (Odum, 1984); and metabolism: the city takes up resources from areas surrounding it, uses and transforms them to maintain or build more structure, and releases wastes that have to be dispersed. Havlick (1974), showed how the transfers and loss of energy through food chains can be found among systems of cities of increasing size, and related the construction of new urban structure to the organism creating new cells. Davis (1973), referred to the physiology and anatomy of cities, and described the circulatory system essential for the existence of cities.

However, beyond the biological-like characteristics, deeper and more general principles can be found to dominate the behavior of systems in general. Prigogine (1978) described a town as an open system far from equilibrium which organization and evolution towards more order depends on a continuous supply of energy; and Odum (1971) proposed that the maximization of energy flows is the general principle dominating the organization, function, and structure of human, ecological and general systems. The maximum power principle was originally proposed by Lotka (1922), with corollaries by Odum (1971).

Applying the maximum power principle yields many predictions which have proved useful for understanding the energetic processes that originate and maintain cities. Among the main ideas are those of a hierarchical organization of systems, and the progression of energy through the hierarchies towards higher quality levels, with increasing its capabilities, complexity and information. The city as the educational, administrative, and commercial center, as well as the internal distribution of these functions is predicted by this approach.

Odum (1984) considers regional systems as integrated wholes in which ". . . Geologic and meteorologic processes, wild ecosystems, human dominated ecosystems, human economy, and hierarchical urban centers. . ." interact following patterns dictated, through natural selection acting on different scales of time, by the maximum power principle (Odum, 1984). In natural landscapes dilute forms of energy such as sunlight, wind, tide, rain, etc., are concentrated into forms of higher quality energy, such as rivers, plants, and animals. In landscapes dominated by humanity not only do humans locate themselves in the zones of convergence, but they actively concentrate resources in central areas, such as market places and factories. There are always several kinds of dispersed sources available; usually the higher quality forms are used to concentrate, amplify and upgrade the lower quality forms.

Areas of convergence develop in hierarchical patterns even when energy inflows are spatially uniform, as with the distribution of land surface, rainfall, and sunlight. The energy sources are of defined forms, frequencies, and intensities; together these are known as the energy signature of a system. Systems will develop in temporal and spatial patterns so that the utilization of the signature is maximized. In this fashion cities follow sources of energy developing along coastlines, surrounding point sources like water springs, or along major roads over which resources are being transported.

Centers of convergence occupy small spatial area, requiring large support area, have high emergy flows per unit area, and exert control over the system around them. The quality and intensity of the centers develop in relation to the energy flows in the system: the higher the energy flows, the more total activity there is, and the higher quality is developed at the center. Brown (1980) determined the support area of cities by matching the EMERGY productivity of the area with the EMERGY concentration of the urban center. These areas represent the range of influence of the hierarchical centers; and are not only the source of dilute energy to be concentrated, but also the recipients of the dispersion of goods and services from the center, which can be described by diffusion equations.

Quality of energies is a measure of the relative value of components. Brown (1980), using the amount of chemical potential energy associated with different construction materials, calculated the value of the structure per unit area, and obtained the transformity for materials. He obtained a correlation of volume of structure and power density, to the complexity of land uses; and demonstrated that high turnover time occurs in low hierarchical units, and low turnover time in high hierarchical units.

The greater the density of development, the more an urbanized area relies on external areas for sources of primary goods and energies. As density of human activity increases, the total exports to other regions increases and it can be assumed that imports increased as well, since a balance of payments must be achieved (Brown, 1980). An increase in the percentage of land devoted to industrial and commercial uses indicates the extent to which a city is a central place.

Consumption of EMERGY is a predictor of development of structure that have been used to provide guidance for development. Whitfield (1994), using Jacksonville, Florida, as the study area, related the urban infrastructure to the consumption and availability of resources, costs of transportation, and patterns of land use. Using EMERGY units, he concluded that the amount of resources being consumed have a large impact on the patterns of land use and distribution of structure, and proposed that concentrating urban development and using mixed land use schemes can reduce resource consumption and impact on natural systems.

Zonation in Urban Systems

Cities with concentric distributions and clusters of development are expected to be the norm. Previous works using different methodologies have given descriptions similar to those predicted by ecological systems theory. Hurd in 1911, and Ratcliff in 1949, recognized that ". . . location patterns of land use in urban areas result from basic economic forces, and the arrangements of activities at strategic points on the web of transportation is a part of the economic mechanism of society. . . ." (Garner, 1967). Concentric models of internal structure were proposed, based on the assumption that accessibility declines equally in all directions from the central sector of the city.

Burguess in 1925 proposed a perfect concentric shape, based on studies of Chicago. He recognized five main zones: (1) inner central zone with the bulk of commercial, social, cultural and industrial life; (2) a transitional zone of mixed land uses in which deteriorating residential property dominates; (3) a working class residential zone, with a heavy component of immigrants; (4) a zone of better single-family dwellings interspersed with exclusive residences; and (5) the suburbs and fringe satellite communities. The pattern proposed was confirmed by several studies, although distortions are always expected to arise from natural barriers and not perfect radial transport system (Garner, 1967).

Land value was also seen to show definite patterns. Brigham (1964) showed how land value reached a high peak at the center of the city, and decreased toward the outskirts. Higher values were also found along major traffic roads, and local peaks of high value, away from the center, occurred at the intersection of major roads. Garner (1967) defined specific revenue or utility for types of land use. The highest use that can be obtained from a parcel of land determines how much the user is willing to pay for it. For Garner, competition in the urban land market determines that the highest and best uses are located in the most preferred places. In his view a pattern develops in which rents throughout the systems are maximized and all activities are optimally located.

Prescott and Lewis (1975) observed that through the rural-urban continuum the ratio of land to labor decreases as one moves from rural areas to the central cities, as does the dependence on primary resources, and therefore the degree of self-sufficiency. The costs of transportation from home to work place increases from rural areas to cities, as does the specialization and diversity of land uses. Based on a trade-off between the costs of site-rental and product distribution, Prescott and Lewis proposed functions predicting the distribution of land use dedicated to services, manufacturing, and agriculture.

Miami and Dade County have been the subject of previous studies using ecological and general systems theory. Browder et al. (1976) emphasized the role that imported fuels played in the development of human ecosystems. They described the region of South Florida as composed of three large subsystems: natural, agricultural, and urban; and analyzed the sources for the structure in each: plants, animals, land, water, people, information, buildings, machinery, roads, money, etc. In their analysis the sources of energy maintaining the structure of the region were largely of external origin, being purchased from income from tourism, transfer payments from the federal government, investment activities, and retirement benefits. Natural resources were important to the economy in two ways: they were "sold" as image to retirees, tourist, and land buyers, and they entered the local economy as free services and as direct exploited commodities such as fishing.

Zucchetto (1975) studied Miami and Dade County relating energy flows to the organization and growth of the urban system. Economic indicators were compared to energy flows and growth of populations, structure, and consumption of resources. Time series data and the rates of change for many parameters of urban systems correlated well with fossil fuel energy use. Simulation models of the urban system related economics with energy availability and predicted declines in growth rates of Metropolitan Miami based on lowered availability of fossil fuels.

METHODS

The organization and zonation of metropolitan Miami were analyzed using digital property tax data, GIS coverages of land use/land cover, and satellite images. These spatial data were sampled along seven transects that were established radiating outward from central Miami and reaching beyond the limits of developed land. The seven transects were 1 mile across (1.6 Km.) and from 14 to 30 miles (22 to 48 Km.) long. The location of the transects is shown in Figure 3. Much of the spatial data used in this analysis were derived from sources that use the english system

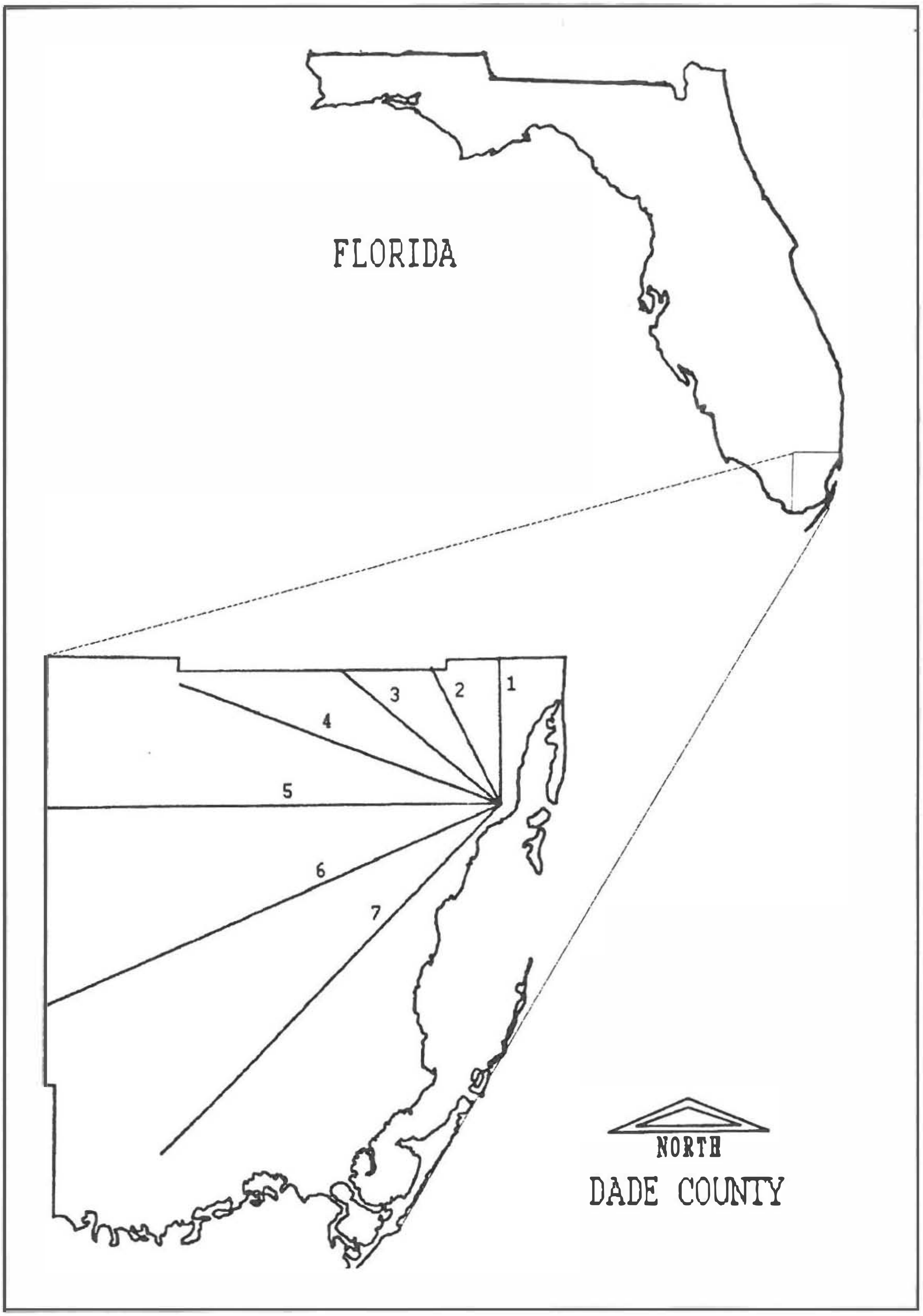

Figure 3. Map of metropolitan Miami showing location of seven transects used to collect data for analysis of spatial organization. Transects were 1 mile (1.6 km) wide and 14 to 30 miles (22 to 48 km.) long.

of measure and as a result some measures are given in miles instead of metric units, although metric units are given with each english expression. For instance, all tax data that are maintained by the government in metropolitan Miami are recorded using the english survey system of township, range and sections. These data were converted to metric equivalents in the presentation of results.

Spatial analysis of economic value, age, and area of structure.

Using property tax records of Metropolitan Miami, data for each single parcel of land were extracted along each transect. The parameters extracted from the property tax records were: (1) total taxable value, (2) year of construction, and (3) total area of structure. Data were summarized on a transect width of one mile (1.6 Km.), and sampling length of 16 miles (25 km.).

Total taxable value is the assessed value of buildings and any other improvement as well as the value of land. Total value was obtained by summing the value of each parcel at each square mile along the transects. The year of construction is the year in which the principle structure on a parcel was built. Year built for every principle structure within the transect was extracted from the data set and the mean taken at each square mile along the transect. Area of structure is the total enclosed and/or conditioned floor area of all structures on each parcel. Data were summed for all parcels and then summarized for each square mile of the transects.

Spatial Analysis of Empower Density and Emergy in Structure.

Using GIS coverages of Land Use/Land cover for 1990, empower density and Emergy in structure were calculated for transects shown in Figure 3. Land use/Land cover maps were prepared by the South Florida Water Management District. A reduced version of the land use/land cover map is given as Figure 4. Empower density was calculated for each mile segment of each transect by multiplying area of land use types by typical empower density for that land use type, and summed for the square mile (2.56 square kilometers). The emergy density and emergy in structure values were obtained from previous studies of empower and urban structure by Brown (1980), and Whitfield (1994) (see Table 1). In like manner, the emergy of urban structure was calculated by multiplying area of each land use type by emergy value of structure and then summed for each square mile (2.56 square kilometers).

Spatial Analysis of Reflectance and Information

Using satellite imagery data (similar to that shown in Figure 1), produced by the French System for the Observation of the Earth (SPOT) satellite, reflectance in the Infra-red band and a

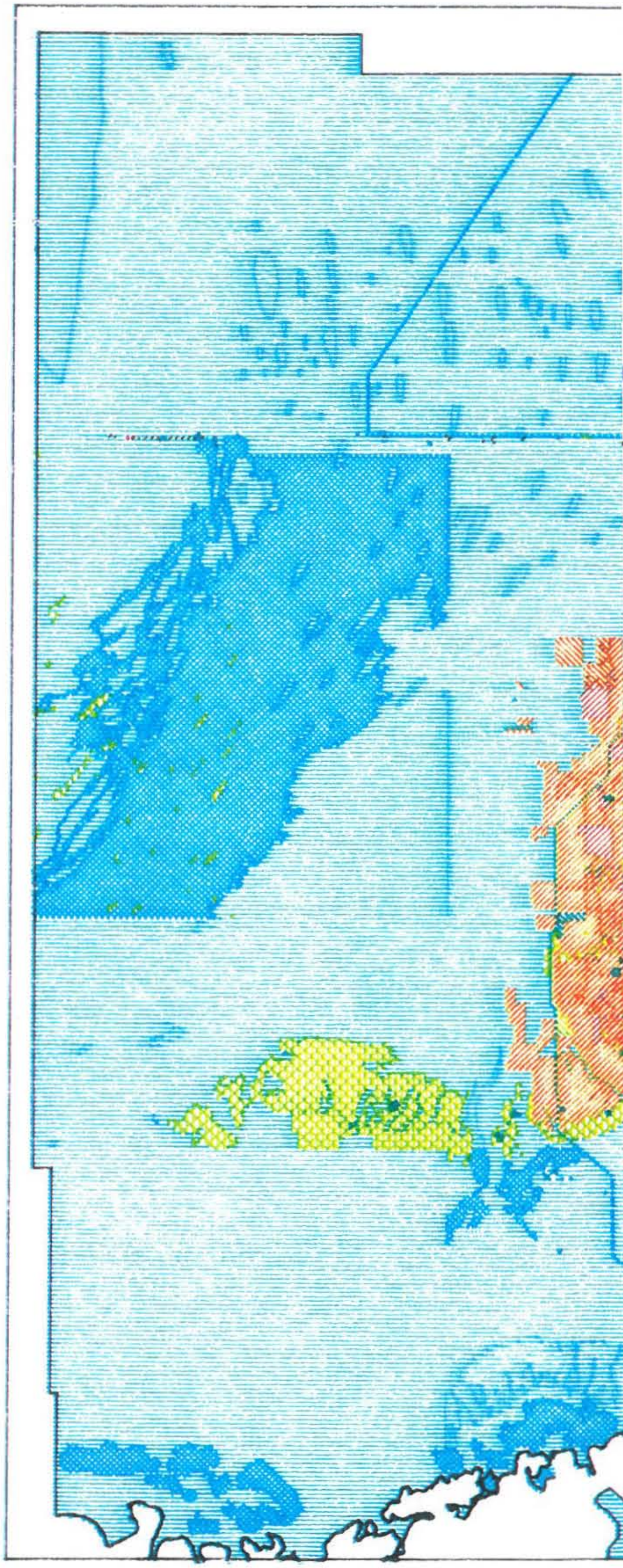

Figure 4. A map of land use and land cover for the south western portion of metropolitan Miami.

Table 1.- Typical values of empower density and emergy content of structure.

Land use	Empower Density '(E+13 sej/ha-y)	Structure (E+13sej/ha)
Open Land	8.3	1.1
Protected area	11.2	8.3
Agriculture	41.4	207
Institutional	210	2068
Transportation	1034	4137
Low/med residential	517	1552
Med/high residential	1076	2586
Business/industrial	3310	12413

measure of information (standard deviation of pixels per unit area) were measured along the seven transects shown in Figure 3. The SPOT Multispectral images have a resolution of 20 x 20 meters.

Images were sampled along the seven transects. Thirty line strips, one pixel in width were sampled along each of the seven transects. Reflectance of each pixel was graphed as a transect profile. Higher reflectance in the infra-red band is associated with urbanized areas because of the percent of impervious surfaces, while reflectance of vegetation is lower. In addition to pixel by pixel reflectance, a measure of information (i.e. the variance of reflectance from one pixel to the next) was graphed as transect profiles. The measure of variance used was standard deviation of the 30 pixels at each of the pixel locations. For instance, on each of the transects, an area 30 pixels wide and 1 pixel in length was sampled and standard deviation calculated, then the next 30 pixel by 1 pixel sample was calculated and so forth to the end of the transect. Standard deviation at each pixel location was graphed as a transect profile.

RESULTS

Evaluation of the zonation in energy flows, structure, economic values and information are given as graphs of variables verses distance from the city center. Figure 3 shows seven transects which were used as the basis for data collection. For the most part, mean values for the seven transects are presented, although where there are interesting aspects on individual transects, they are presented separately.

Spatial analysis of economic value, age, and area of structure.

Mean taxable value graphed against distance from the central city is shown in Figure 5. Mean taxable value exhibited an increase to a maximum of about \$65 million per km^2 at a distance of about 10 kilometers and declined to a minimum of about \$10 million per km^2 at a distance of about 20 km from the central city. The decrease in taxable value was more than 85% from the central city to the urban fringe. Of interest is the fact that taxable value in the central city is lower (mean equal to about \$35 million per km^2) than values at a distance of about 10 km. Central Miami is dominated by government buildings that are not taxed, thus values in this core area are lower than the intermediate zones of commercial and residential activity.

Year of construction of structures on individual parcels was extracted from the property tax records and averaged for each section, then plotted versus distance as shown in Figure 6. Values

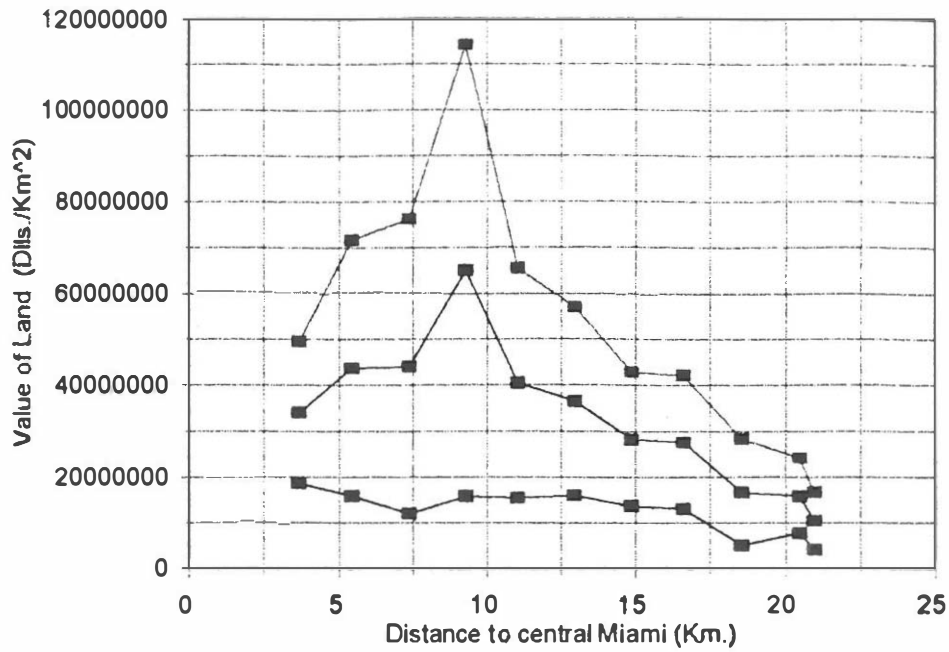

Figure 5. Graph of taxable value of land and structure versus distance from the city center. The middle line is the mean of seven transects, and the top and bottom lines are maximum and minimum values.

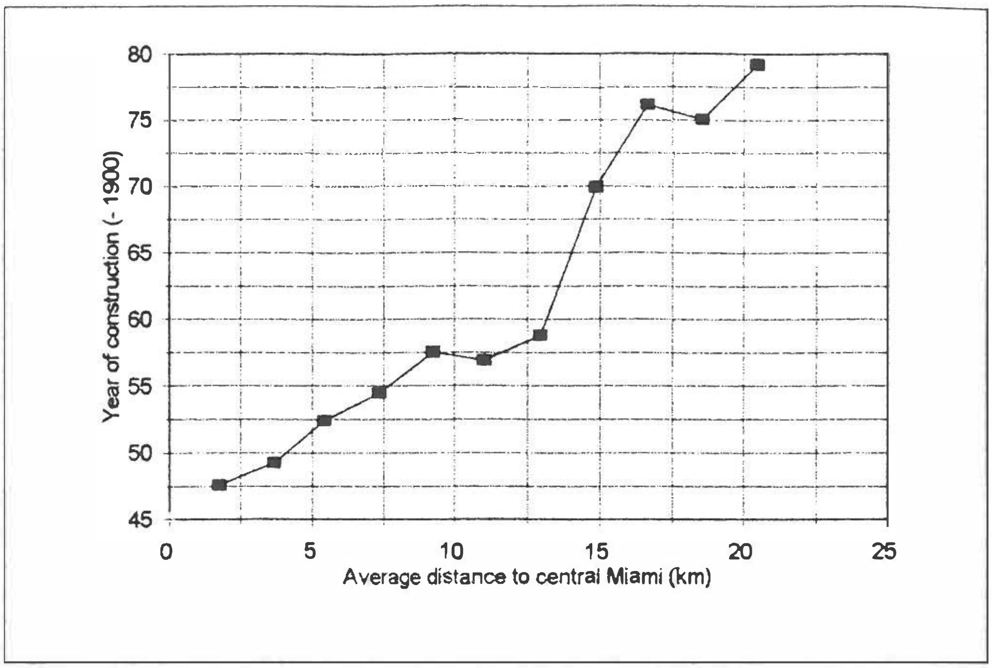

Figure 6. Graph of average year of construction versus distance from the city center. Line represents the average year of construction for all structures within seven transects.

shown are the mean of the seven transects. The mean age of structure at the city center is about 48 years (built in 1947). Age decreases with distance from the city center reaching a minimum of about 15 years of age (built in 1980) at a distance of 20 km. .

Figure 7 shows the mean constructed floor area per square mile. Total floor area decreased from about 220,000 m^2 per km^2 in central Miami, to about 100,000 m^2 per km^2 at a distance of about 20 km. Again there is a slight increase in area as one moves away from the central city, but this is probably due to the large area of government buildings in the central city.

In all, total taxable value and area of structure increase as one moves from the outskirts of the city toward the central metropolitan area. Age of structure increases the closer one is to the central city, suggesting that the city has grown in zones outward from the early settlement location. Figure 2 shows the growth of metropolitan Miami beginning in 1920 taken from aerial photographs and early maps of the region.

Spatial Analysis of Empower Density and Emergy in Structure.

A portion of the land use/land cover map of metropolitan Miami is given in Figure 3. Land uses were organized into twelve main categories. Agricultural areas are concentrated in the southwest portions of the developed area. To the west, all development is restricted by the large expanse of wetlands known as the "Everglades." The bulk of development is concentrated in central Miami and the northeast section of the county, and diminishes in intensity to the south and southwest.

Land use data were extracted from the GIS coverage of metropolitan Miami along each of the transects and from these data, empower density and emergy of urban structure were calculated. Figure 8 shows the mean emergy flow per unit time per unit area (empower density) for all seven transects. Mean empower density was about 1.2 E19 sej/ha in the central city, declining to about 0.5 E 19 sej/ha at the urban fringe. Empower is be related to the total amount of structure. With higher volume of structure, empower should be higher. Figure 9 is a graph of the mean emergy of structure per unit area along the seven transects. The highest mean emergy in structure was found in central Miami (5.0 E+19 Sej/ha.) , corresponding to the heavily developed commercial and business district. Mean emergy in structure decreased with distance from the city center to about 1E+16 sej/ha., corresponding to parks and natural areas at the urban fringe. Emergy of structure is plotted against empower density in Figure 10. The graph is for data from seven transects as shown in Figures 8 and 9. As the emergy content in structure increases there is a corresponding increase in empower density.

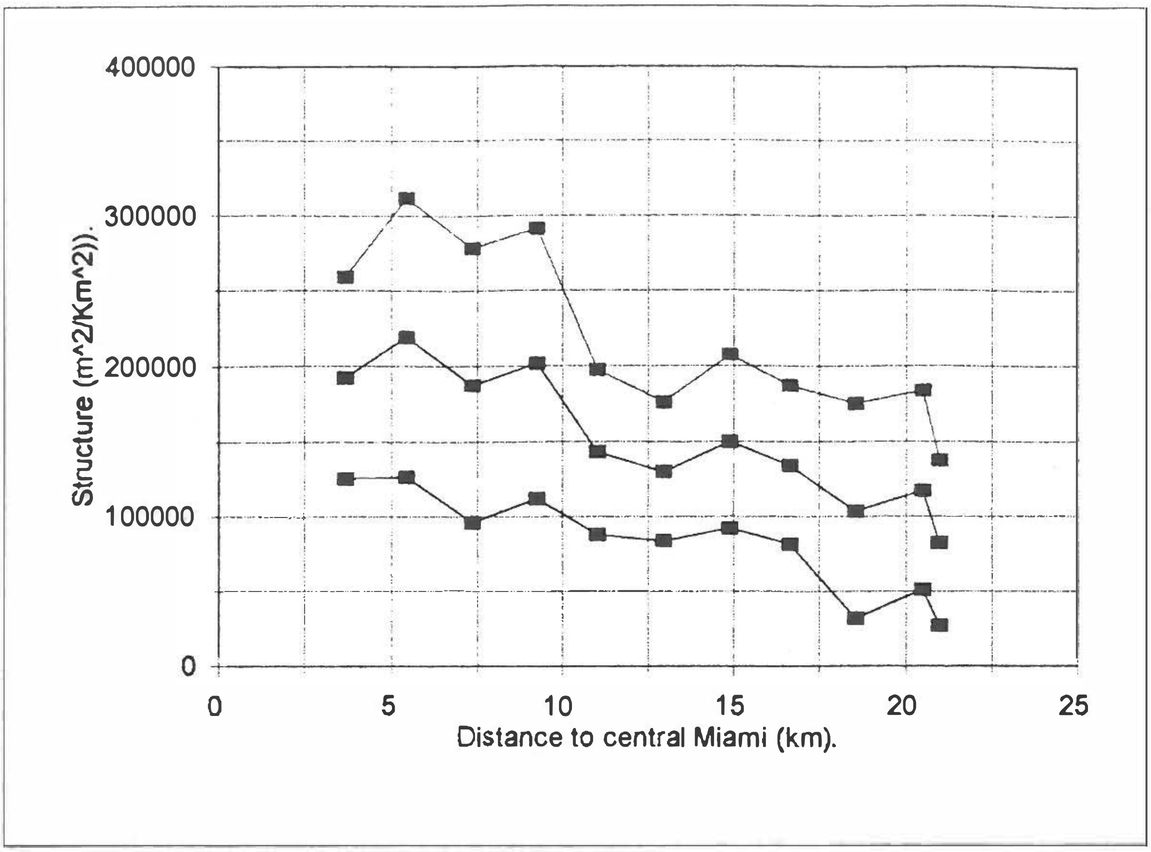

Figure 7. Graph of area of structure versus distance from the city center. The middle line is the mean of seven transects, and the top and bottom lines are maximum and minimum values.

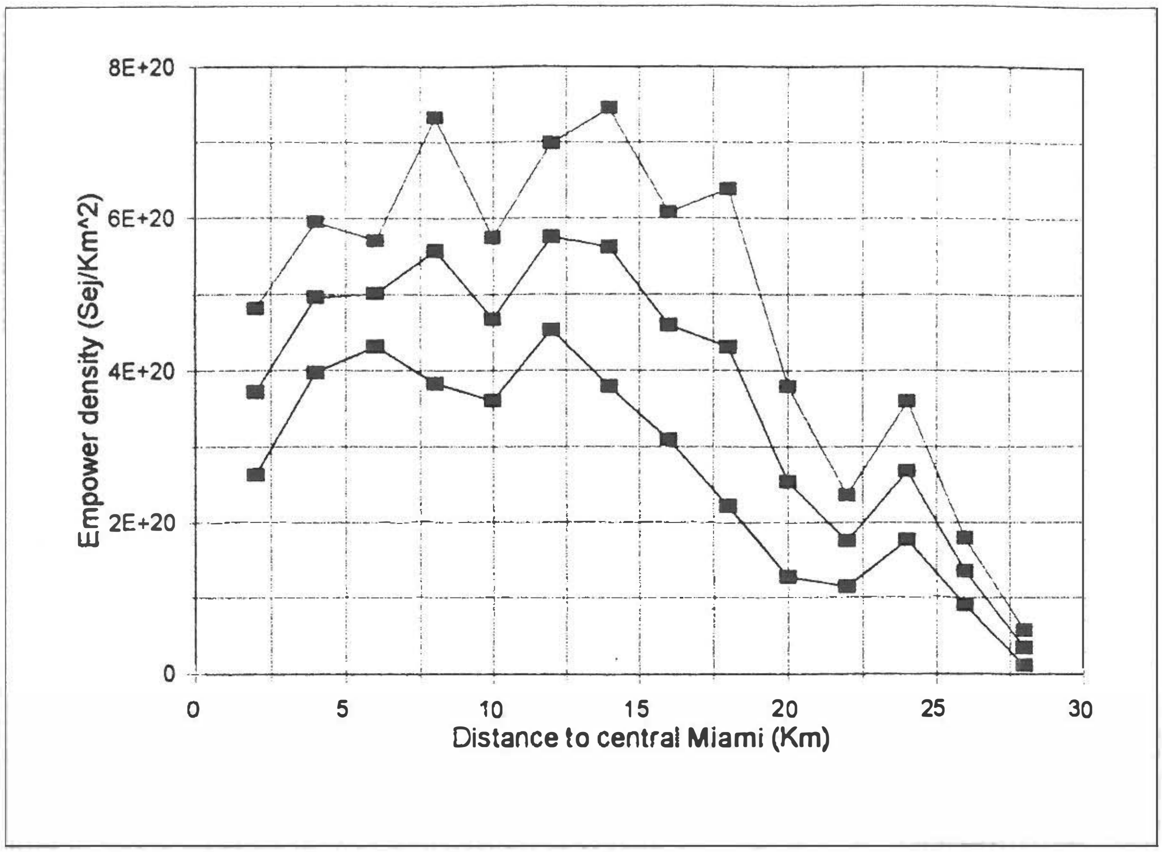

Figure 8. Graph of emergy flow per unit time per unit area (empower density) versus distance from the city center. The middle line is the mean of seven transects, and the top and bottom lines are maximum and minimum values.

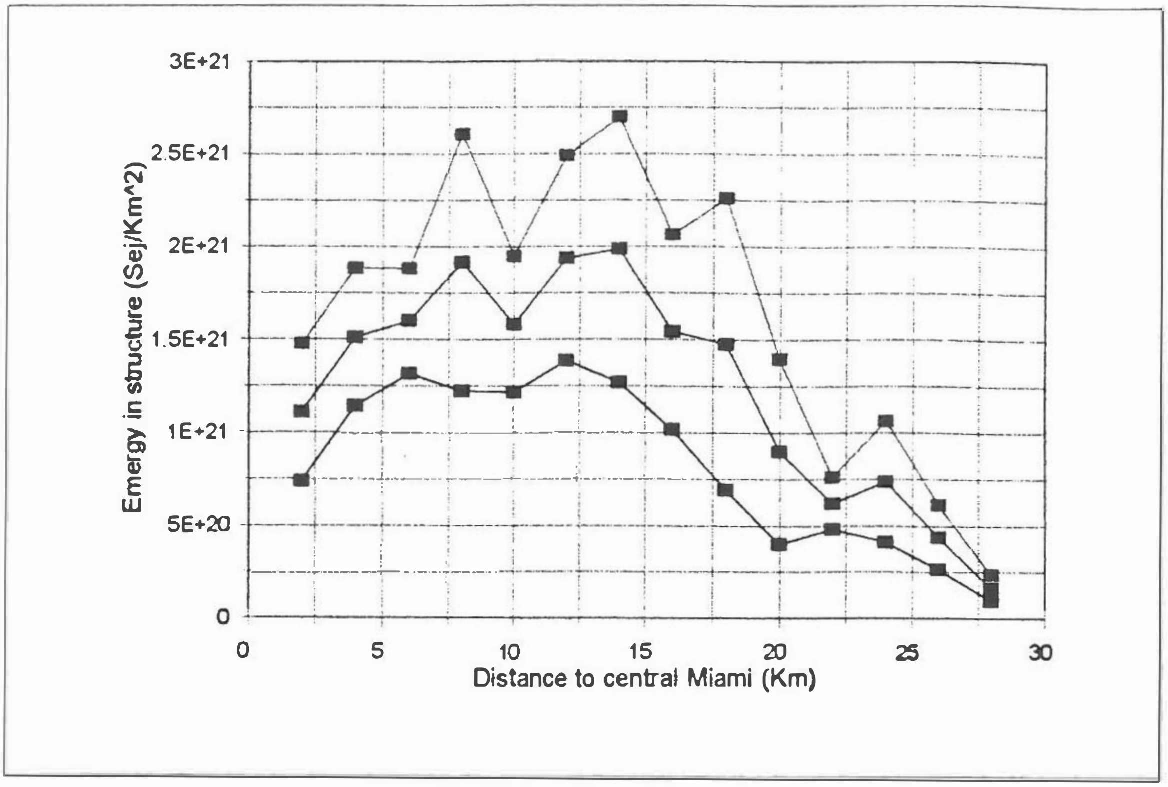

Figure 9. Graph of emergy content of urban structure versus distance from the city center. The middle line is the mean of seven transects, and the top and bottom lines are maximum and minimum values.

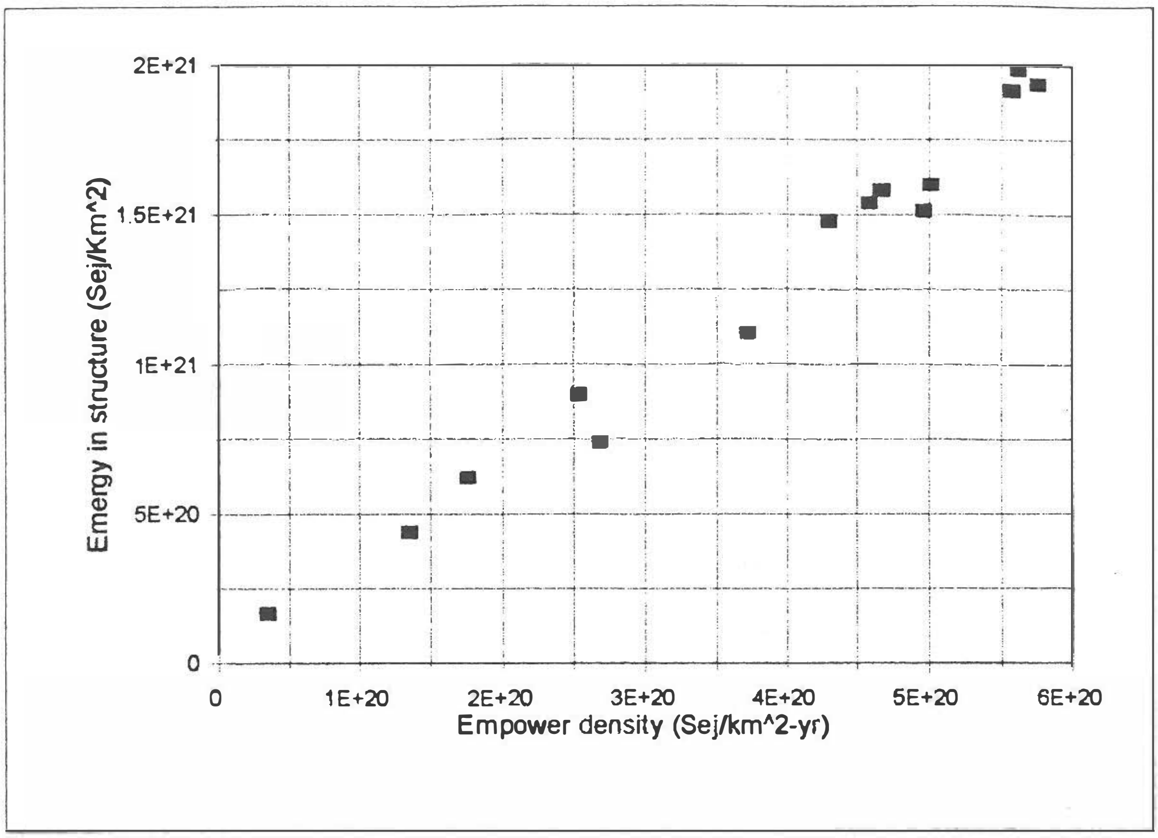

Figure 10. Graph of empower density versus emergy content of urban structure using data derived from seven transects originating in central Miami and radiating outward to the urban fringe.

Total area of structures is graphed against emergy content of structure of different land use classes in Figure 11. Area of each category of land use identified was summed for all seven transects and graphed against the average emergy in structure for each land use type. Agriculture and open areas, with emergy values of about 1E+15 solar em-joules per hectare, occupy an area of more than 400E+6 m^2; followed by low density residential with 1E+18 sej/ha., with 370 E+6 m^2; high density residential of 5 E+18 sej/ha., with 230E+6 m^2; and business and industrial areas, with 7 E+18 sej/ha., and 150 E+6 m^2. Because Dade County has a significant portion of its western area dominated by the Everglades that are protected and remain in conservation, urban development ends at the edge great wetland and relatively large areas of the county remain undeveloped.

Spatial Analysis of Reflectance and Information

Figure 12 shows the mean reflectance in the infra-red band as a percent of total infra-red radiation graphed against distance in kilometers for the seven transects shown in Figure 3. The three lines in the graph represent maximum, minimum, and average reflectance values. Transects 1 and 2 extend northward along the coast and therefore do not end in an undeveloped landscape, thus the reflectance does not decline along the length of the transect. Transects 3 through 6 all end in undeveloped lands to the west and southwest of the central city so reflectance decreases significantly as the transects reach undeveloped lands. The seventh transect transverses southwest along the coast and does not enter undeveloped lands, but does transverse large expanses of alternating urban and agricultural uses. The general trend is for initial reflectance of around 35% for central Miami, followed by an increase to 40% at mid distance (from 7 to 20 kilometers) and then a step decline where the profile enters the undeveloped areas of the Everglades. Vegetation and water of the Everglades absorb most of the infra-red radiation.

Reflectance values on each transect are the average of 30 linear profiles, one pixel wide. When the variance of reflectance is plotted against distance a measure of the information content of the landscape is given. Figure 13 variance in reflectance plotted against distance for each of the seven transects. Variance is highest in urban transects and lowest in those portions of transects that cross undeveloped regions of the Everglades. Largest variance is found on transects 2 and 7, both of which cross areas where lands alternate between agricultural and urban uses. Of interest is the fact that central Miami and natural areas, in general, appear to have lower variance than the areas in between.

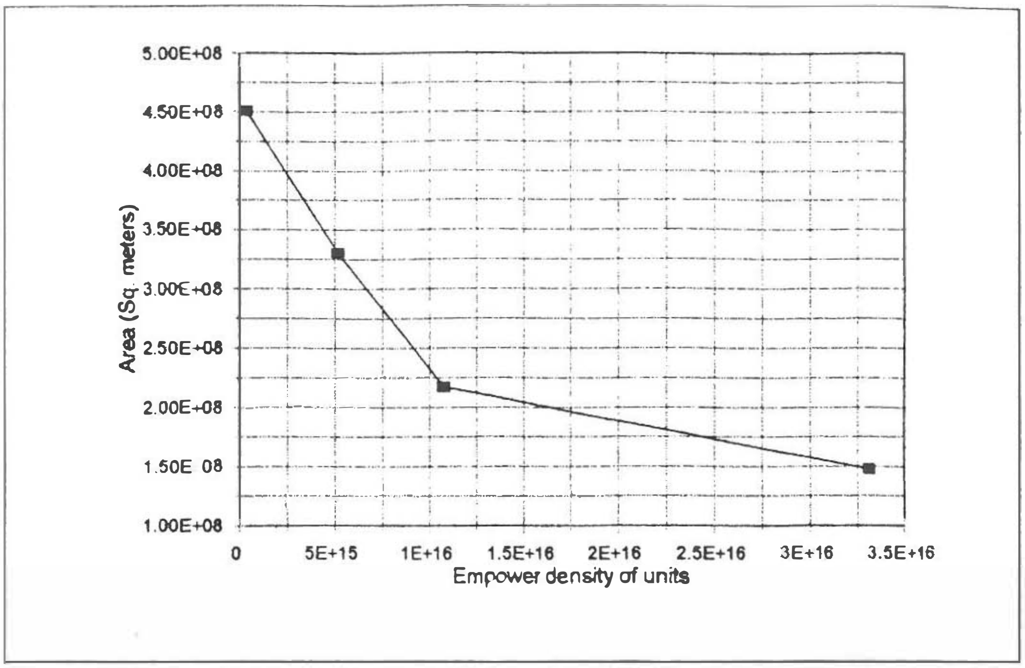

Figure 11. Graph of area of various land use types versus empower density. Area data are from seven transects originating in central Miami and radiating outward to the urban fringe.

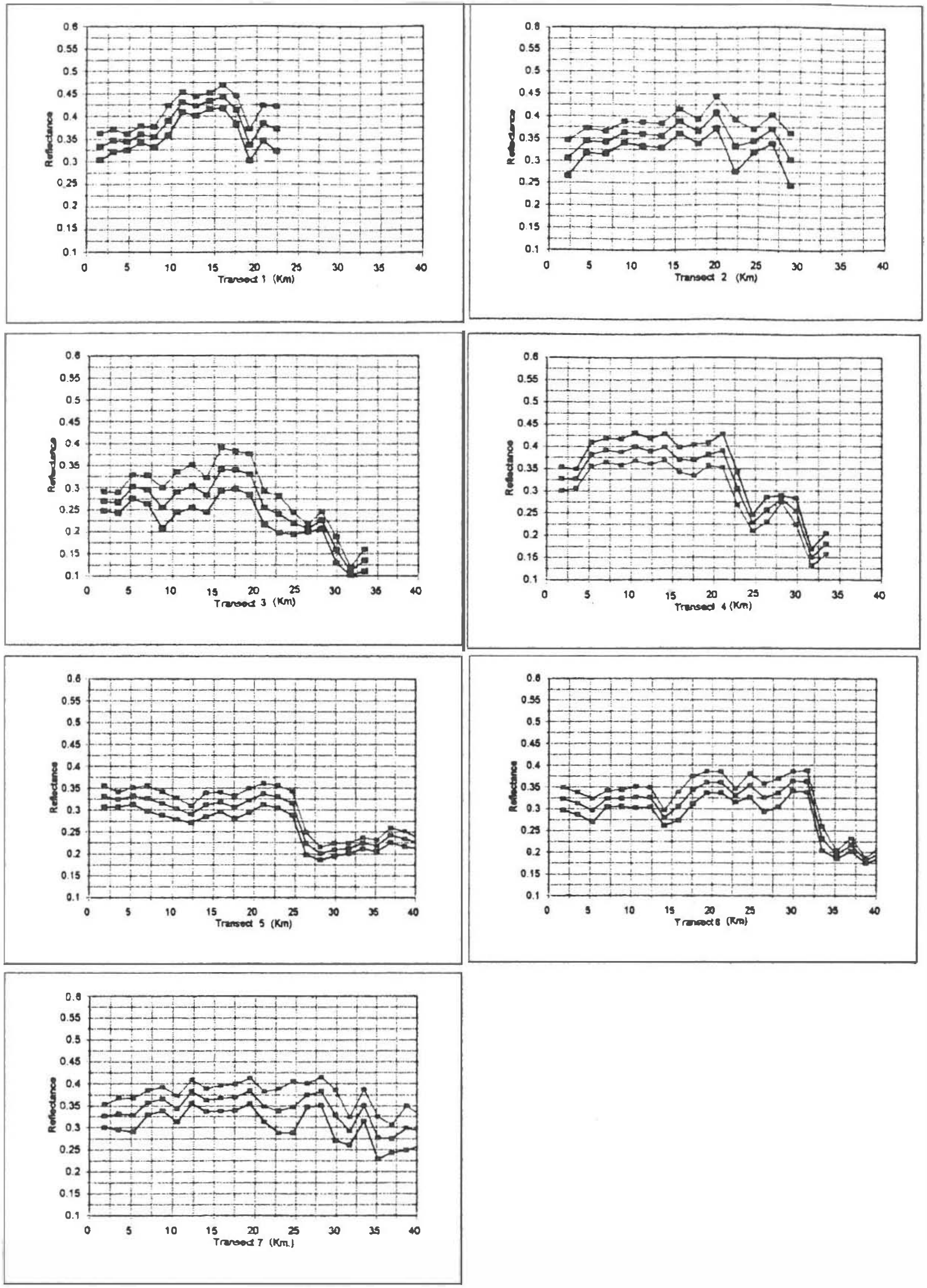

Figure 12. Graph of mean reflectance in the infra-red band as a percent of total infra-red radiation versus distance from the city center for the seven transects shown in Figure 3.

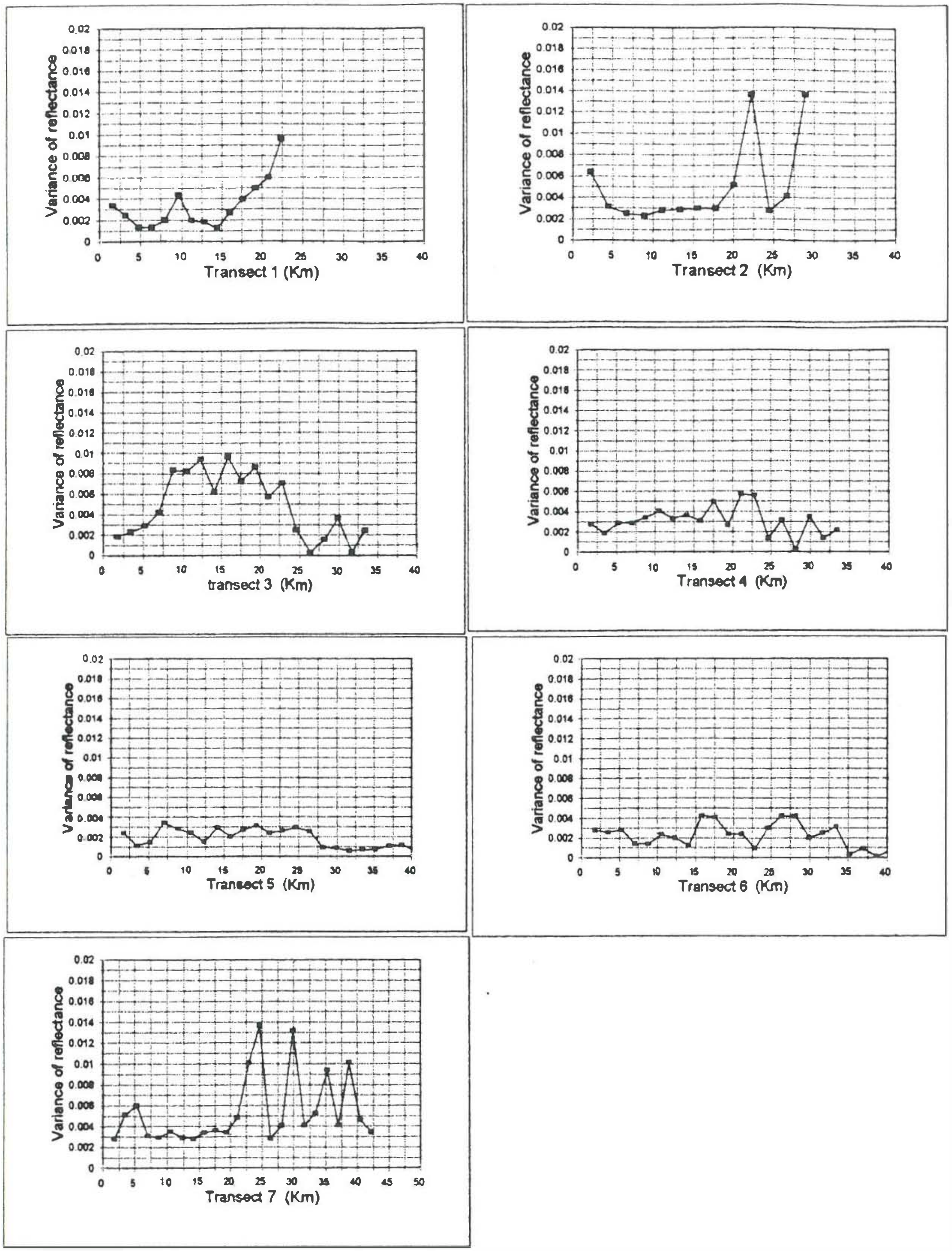

Figure 13. Graph of the variance in mean reflectance in the infra-red band as a percent of total infra-red radiation versus distance from the city center for the seven transects shown in Figure 3.

DISCUSSION

Metropolitan Miami is located between ocean on one side and a major wetlands system on the other. As a result Miami has grown along a north south axis. With relatively little developable land in the coastal zone, settlements that were once separate and distinct, have grown together in a massive urban system stretching over 200 km along the coast of south Florida. Although the area south of metropolitan Miami has a well developed agricultural zone between the urban development and natural areas, the rest of the metropolitan area is constricted between the ocean and the Everglades, that limits the natural tendency of urban development. This characteristic was identified by Brown (1980): ". . .the South Florida region represents a unique situation from a physical standpoint, which inhibits the development of a complete array of city sizes. . ."

Figure 4 shows a map of the main land uses in metropolitan Miami. Total volume of structure and intensity of uses are higher in the central city and radiate outward in decreasing zones of intensity toward the urban fringes. Larger empower density are found at the central zone (Figure 8) as is the emergy stored in structure (Figure 9). Central Miami is not only the original center from which development radiated, but it is also the convergence center of the Miami river, the Tamiami trail (a major high connecting the east and west coasts of south Florida), major north/south roads, and a maritime port. The zone is dominated by business and commercial uses, as well as institutional functions. Toward the southwest, urban development follows the pattern of zones of decreasing intensity, with agricultural uses ending in rural lands dominated by natural cover. These lands are the only remaining agricultural lands in south Florida, as metropolitan Miami has over grown farm lands to the west and northwest, converting them to urban uses over the past several decades.

Odum (1984) said that when energy flows occur in high densities, less area is required to support the urban centers, and more centers can develop with small territories. Furthermore, during periods of heavy reliance on abundant high yielding fuels, the central cities have the advantage and grow more vigorously than smaller peripheral places, which draw more on renewable, more dispersed energies. Brown (1980) found an inverse relation between the area occupied and the empower density of units. Figure 11 shows the total area of four categories of land use graphed against their mean empower density . The general pattern is decreasing area of higher intensity uses, conforming to the theory of hierarchical organization. However, as it is noticeable from the map in Figure 4 and the satellite image in Figure 1, there are no agricultural areas and almost no low density residential zones between the wetlands of the Everglades and the high intensity developments of the metropolitan Miami area. Overall, throughout the Miami area the amount of land devoted to agriculture appears to be low on the average, compared to the higher density uses. Brown (1980) pointed out that ". . .the extent that a city serves as a central place is indicated...as the percent of industrial and commercial land use increases." In Brown's work, agriculture occupied an area at least one order of magnitude larger than the area occupied by residential uses. With lower total area in agricultural uses than the average, it is obvious that metropolitan Miami serves as central place for commerce and services for a much lager area than its immediate support region.

Zonation in Metropolitan Miami

Zonation in the metropolitan Miami area is truncated in the westward direction by the Everglades. Urban land uses extend from the Atlantic Coast to the edge of the Everglades, leaving little space for agriculture uses. Zonation in the northward direction, does not exhibit the expected decrease in intensity and changes in land uses from commerce to low density residential to agricultural since Miami has “overgrown” neighboring cities to the north resulting in a continuous expanse of relatively high intensity urban uses. To the south, the last areas of undeveloped lands and agricultural uses, Miami exhibits more typical zonation. Yet as Miami may continue to increase in size and intensity, these areas to the south may well become more urbanized, at the expense of the remaining open and agricultural lands.

It has been suggested that landscape development undergoes a process similar to that of ecological succession, in which periods of growth, homeostasis, retrogression, renewal and oscillation can be identified (Odum, 1984). Dansereau (1973) (cited by Odum, 1984), suggested that as more and more energy is converged, the land passes through stages of natural land, to open land, to agriculture, to industrial, and to housing. Data from transects that ran southwest from central Miami show zonal patterns similar to those described by Brown, Dansereau and others. The first 5 miles were dominated by commercial and high density residential areas, turning to areas dominated by low density residential and finally to mostly agricultural lands. In agreement with the idea of succession in the rural-urban continuum, Whitehand (1987) recognized that residential development typically colonized new areas faster and created new space by subdividing plots, while commercial development was adaptive as it was more constrained by existing morphology.

Typical zonation from Central Business District (CBD) to high density residential, to lower density residential, to agricultural, and finally to rural natural lands appears to exist in the southwest portions of Metropolitan Miami. Zonation in the intensity of urban land use was shown in all transects and data that were analyzed. Land values declined at a rate of about $25 million per kilometer distance from the central city, and there appeared to be a zone of highest land value that was about 9 kilometers outward from the central city (Figure 5). Area of structure appeared to be maximum at about 8 to 12 kilometers from the urban center and declined to the urban fringe at a rate of about 23,000 m^2 per kilometer (Figure 7). Empower density declined at a rate of about 5.0 E 17 sej/ha per kilometer of distance from the urban center (Figure 8). There appeared to be a zone of maximum empower density at about 7 to 8 kilometers from the urban center and another zone where intensity increased higher than expected at about 20 kilometers distance from the center. When urban structure was expressed in emergy (Figure 9), total emergy content of structure declined at the rate of about 0.25 E19 sej per kilometer of distance from a high of 5 E19 sej/ha at the city center to a low of about 1.0 E16 sej/ha. A zone of highest emergy content in structure appeared to occupy a central zone about 5 to 8 kilometers from the central city.

Infra-red Reflectance as a Measure of Urban Intensity

Urban areas are highly reflective zones in the landscape. They have been referred to as heat islands when compared with adjacent rural areas. In the reflectance patterns registered in Miami (Figure 12) three distinct zones of reflectance could be detected: (1) a central city zone that exhibited average reflectance of from 30 to 35%, (2) a zone of higher reflectance that had values up to 45%, and an urban fringe zone that had reflectance values 20% and below Spatially, the three zones were located with highest reflectance at intermediate distances from the urban center. This is somewhat counter to expected high reflectance in the city center followed by decreasing reflectance as one moves away from the city center. The center, having highest structure, should have highest reflectance, yet reflectance from Miami's urban center is lower than the reflectance in mid-range zones. The large volume of structure may account for the lower infra-red reflectance. Douglas (1982), suggested that the volume of structure in the central district acts as a heat storage, that absorbs short-wave radiation during the insolation time, and emits long-wave during the entire 24 hours. Douglas points out that infra-red reflectance in urban areas can be affected by various factors like, volume of structure and high heat capacities and conductivities of buildings and roadways. The buildings of a city can absorb up to six times more heat than the surrounding countryside, and release it during the night. Vertical walls tend to reflect solar radiation towards the ground rather than the sky. Radiation reflected by the ground bounces back on to the walls of adjacent buildings. Areas of dispersed suburban housing would absorb only slightly more than the rural plain (Douglas, 1982).

Infra-red reflectance is highest in the mid- zones that are dominated by transportation and commercial activity (Figure 12). That these areas exhibit higher reflectance may be a function of the lower overall building mass. Buildings in this zone are characteristically single story (or at most two story) in height, and impervious surfaces approach 100%. In these areas the effects of reflection and reabsorption by adjacent building may be absent, thus resulting in higher infra-red reflectance skyward. These mid-zones correspond to areas that had high empower density and emergy content in structure (Figures 8 and 9).

Variance of Infra-Red Reflectance as a Measure of Urban Activity

Variance is an expression of diversity; and in a land cover diversity can be understood as a manifestation of the overlying covers being partially replaced by others. In this sense diversity is a stored manifestation of previous energy flows "... indices of diversity can be used as an indicator of the state of a system in the balance between energy flows that develop diversity and those negative actions that may decrease it..." (Odum, 1984). The variance of infra-red reflectance may be a measure of the landscape information content. Higher variance areas are those areas where there are numerous activities that affect the land cover. In urban landscapes, variance is highest in zones at the urban fringe urban fringe (Figure 13), especially on those transects that had significant mixing of urban/sub-urban development with agricultural land uses. The central city had lower overall variance in reflectance than mid-points between the center and urban fringe. Central areas may show less variance because of the dominance of hard surfaces. Whitfield described a steady decrease of renewable energies use toward the city center. In areas mid-way between the urban fringe and central Miami, a dominant land use type often has not been established, and large green areas alternate with residential neighborhoods and open limestone quarries. Variance is lowest in undeveloped areas where cover type is little changed. In these areas both reflectance and variance are low.

Summary

The organization and distribution of urban structure in Miami, Florida was evaluated using emergy and economic indicators and reflectance in the infra-red spectrum. Indicators such as area of structures and economic value as measured by property tax value show marked decreases as distance from the CBD increases. The highest values and area of structure per unit area are within 5 kilometers of the CBD. When measured using emergy flow (empower density) and the emergy content of structures, again there is strong evidence of zonation as they decrease with increasing distance from the CBD. Age of structures decreases as well, with the oldest average age structure per unit area in the city center, and newest structures along the fringes of the urban area.

Because of land constraints zonation is somewhat truncated in the east, west, directions. In the northern direction, Miami has grown to fill in the space between it and the next city to the north so that developed lands form a continuous band paralleling the Atlantic Coast. Only in the southern quadrant, does metropolitan Miami exhibit a zonation that includes agricultural lands and natural rural areas. Growth of the Miami urban system is in this direction, and some predictions are that it will over grow these agricultural lands within the next decade.

Reflectance of infra-red radiation show zonation that more or less follows the zonation found in the emergy analysis. Areas of low structure area, have lower reflectance, but often have higher variance in reflectance (a measure of diversity of activity). There appears to by a zone of highest reflectance that corresponds to a middle zone between the city center and the urban fringe. This zone also has relatively high empower density, high economic value, and highest total area of structure.

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5. ZONES OF EMPOWER DENSITY IN AMERICAN CITIES

Robert Woithe

INTRODUCTION

Three spatial patterns of empower use in 3 major U.S. cities (Chicago in 1966, San Francisco in 1971, and Miami, in 1985) were evaluated and compared in order to study empower gradients (Figure 1). Miami is also evaluated in more detail in Chapter 6.

Chicago

Chicago is situated on the southwestern shore of Lake Michigan at what was historically an important point on the water route linking the Great Lakes with the Mississippi River. The original european settlement was established in 1803. Chicago began development as an important western city after the 1825 opening of the Erie Canal from the U.S. east coast to the Great Lakes. This development was reinforced by the construction of railroads in the 1850's. Steel production, lumbering, and meat-packing were important early industries. A major fire in 1871 destroyed much of developing Chicago.

Chicago experienced a second major growth period around 1900 with the arrival of thousands of European immigrants in the city. Around this time, many of Chicago's citizens began emigrating to the suburbs, and the city's population growth slowed through the 20th century. The city has long been the center of a heavily industrialized area of the United States. Chicago has the largest harbor in the Great Lakes region, shipping primarily grain and iron ore.

San Francisco

San Francisco is located on the Pacific coast on a peninsula that forms the western shore of San Francisco Bay. A Spanish fort was established on the peninsula in 1776, followed by a settlement in 1835. San Francisco was an entry an supply point for the California Gold Rush in 1849 and a Nevada silver strike in 1859. An earth quake and resultant fire in 1906 destroyed much of San Francisco , but the city was quickly rebuilt. It was a major military port in World War II. San Francisco has increasingly evolved an economy based on technological and service industries.

METHODS

The patterns of empower use in three United States cities were evaluated based on land use in the cities. The land use patterns of Chicago, Illinois (circa 1966), San Francisco, California (circa 1971), and Miami, Florida (circa 1985) were sampled using transects radiating out from their central business districts. For Chicago, randomly chosen transects with compass headings of 169°, 191°, 224°, 237°, 254°, and 309° from the mouth of the Chicago River were used (Figure 2). Transects with compass headings of 177°, 191°, 205°, 225°, 263°, and 276° from the Market Street water front were used to sample San Francisco (Figure 3); and 172°, 203°, 239°, 260°, 305°, and 328° compass headings from the mouth of the Miami River were used to sample Miami. A more detailed analysis of Miami is given elsewhere in this report. Annual empower flows for land uses

Figure. 1. The U.S. cities evaluated in this study.

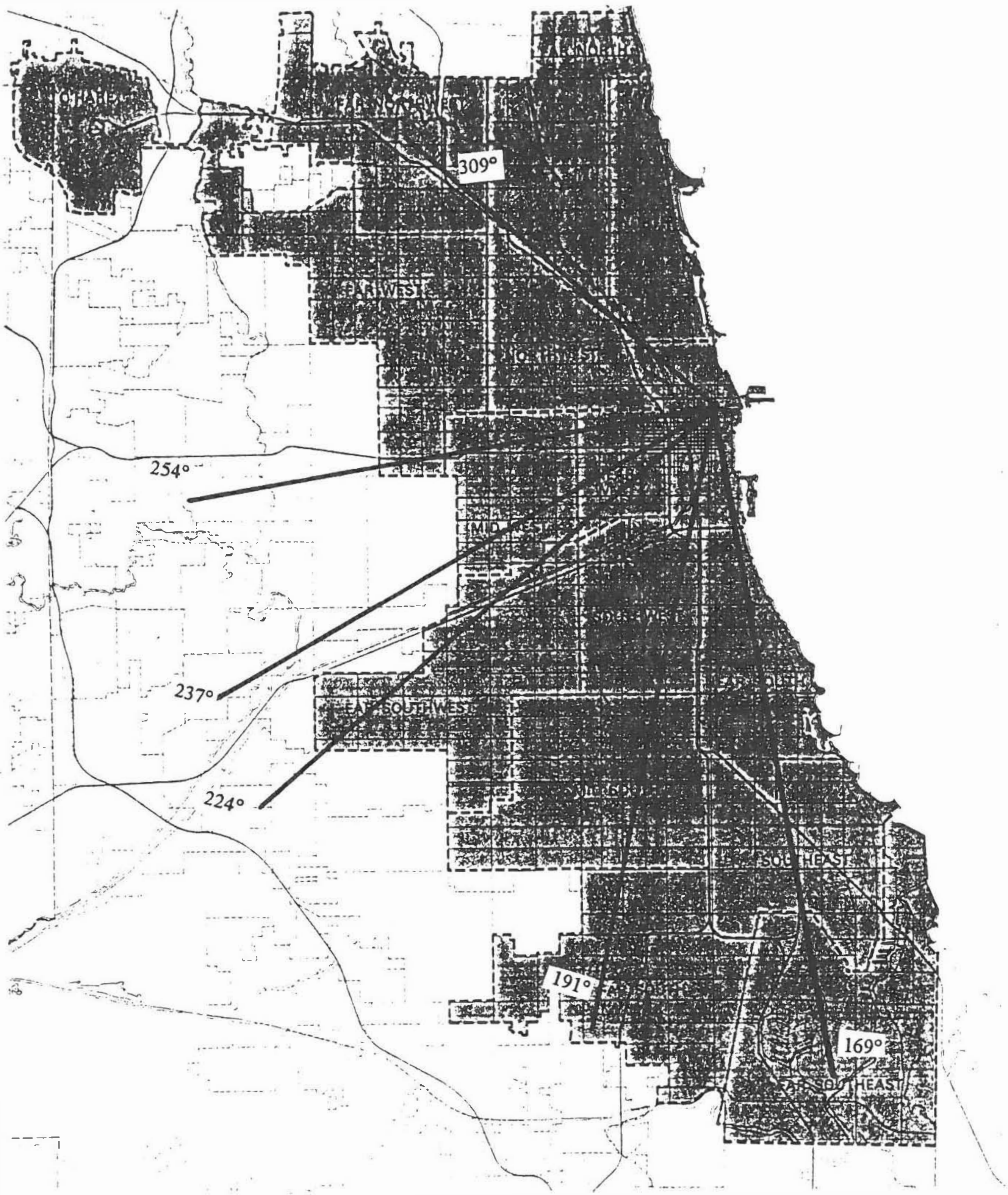

Figure 2. Chicago, Illinois circa 1966 and the transects used in this study (map from Chicago Department of Development and Planning (1966)).

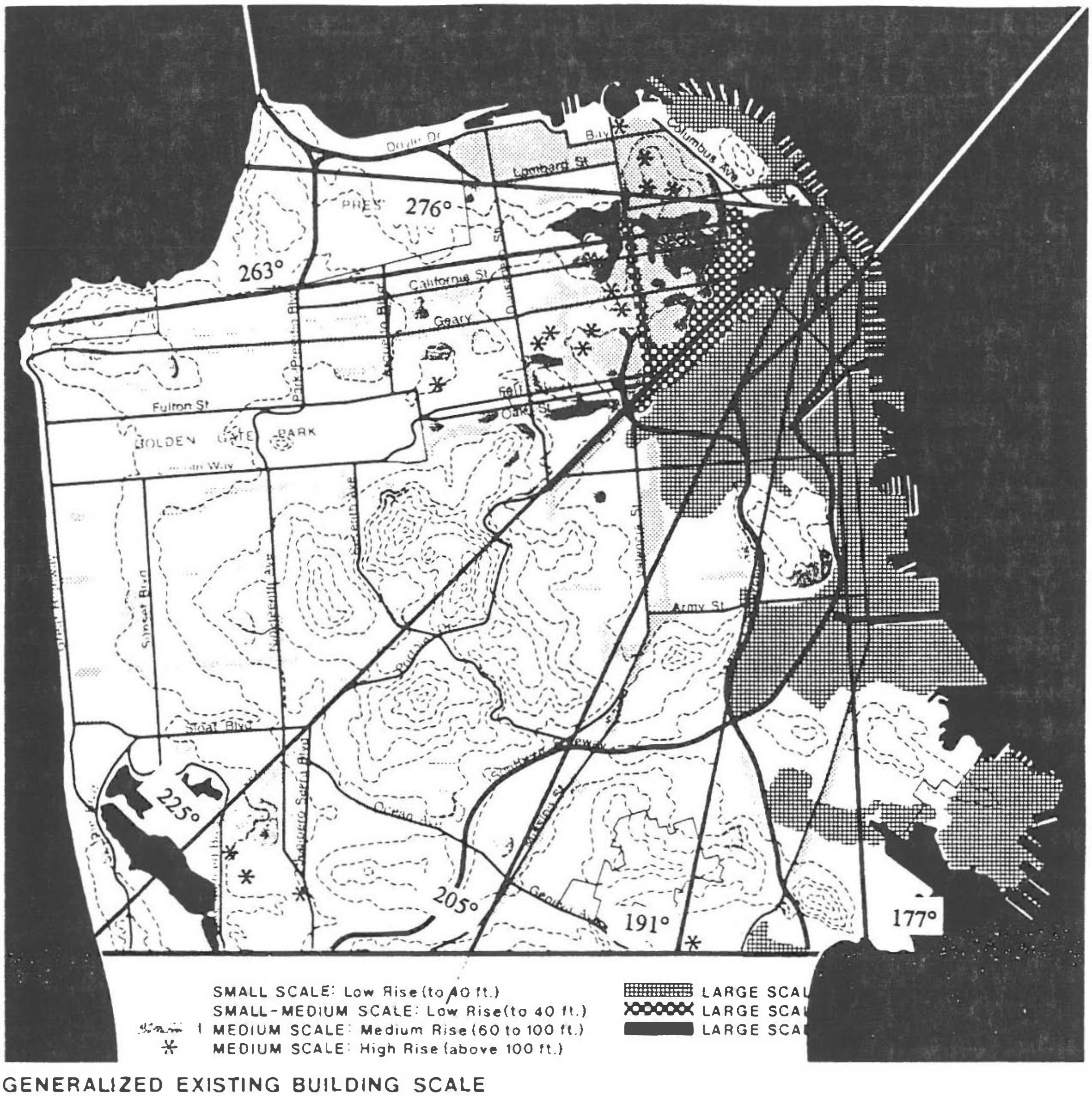

Figure 3. San Francisco, California circa 1971 and the transects used in this study (map from San Francisco Department of City Planning (1971)).

in the three cities were estimated from flows calculated by Whitfield (1994) for land uses in Jacksonville, Florida (Table 1).

RESULTS and DISCUSSION

The mean empower was calculated for 5 kilometer segments of each transect and these were averaged to develop an general empower profile for each city. These profiles are given in Figures 4, 5, and 6. The 169° Chicago transect and the 172° Miami transect were not included in these general profiles. These two transects were located along the waterfronts and appeared to be indicative of the water front development of the cities rather than their general organization.

Miami showed a unique feature in that there was a significantly lower empower at 12.5 km than at 17.5 km (paired t-test, $p=0.0483$). This zone of lower empower included Miami International Airport and other areas with heavy transportation. The data for Chicago and San Francisco may not have been at a scale small enough to detect similar zones of lower empower if they existed. The fact that the original land use data for the three cities were given in different units hampers the empower comparisons of the cities to a small extent, but not irreparably.

All three cities show distinct gradients of decreasing empower from the center of the city (0 km) to 12.5 km or 17.5 km. These gradients tended to level off between 12.5 km and 22.5 km, and then decrease again. This leveling effect is most pronounced in Miami, the latest analysis (1985), and least pronounced in Chicago, the earliest analysis (1966). It is difficult to determine if this leveling effect is increasing with time in U.S. cities. If the effect is increasing, it would suggest a less distinct gradient in U.S. cities.

Table 1. The annual empowers for different land uses in the evaluations of Chicago and San Francisco. All empowers are estimated from Whitfield (1994).

Chicago: land use types are from Chicago Department of Development and Planning (1966).

Land Use Type:	**Annual Empower** **(sej/m^2-y)**
Central Business District	5.4E+15
Industrial	9.8E+14
High Access Corridor	7.9E+14
Port	6.2E+14
High Density Residential	5.6E+14
Medium Density Residential	2.7E+14
Low Density Residential	6.7E+13
Park land and Other	3.0E+11

San Francisco: land use types are from San Francisco Department of City Planning (1971).

Land Use Type:	**Annual Empower** **(sej/m^2-y)**
Large Scale-High Rise	5.4E+15
Large Scale-Medium Rise	9.7E+14
Large Scale-Low Rise	8.4E+14
Medium Scale	5.6E+14
Medium-Small Scale	3.7E+14
Small Scale	1.9E+14
Other	3.0E+11

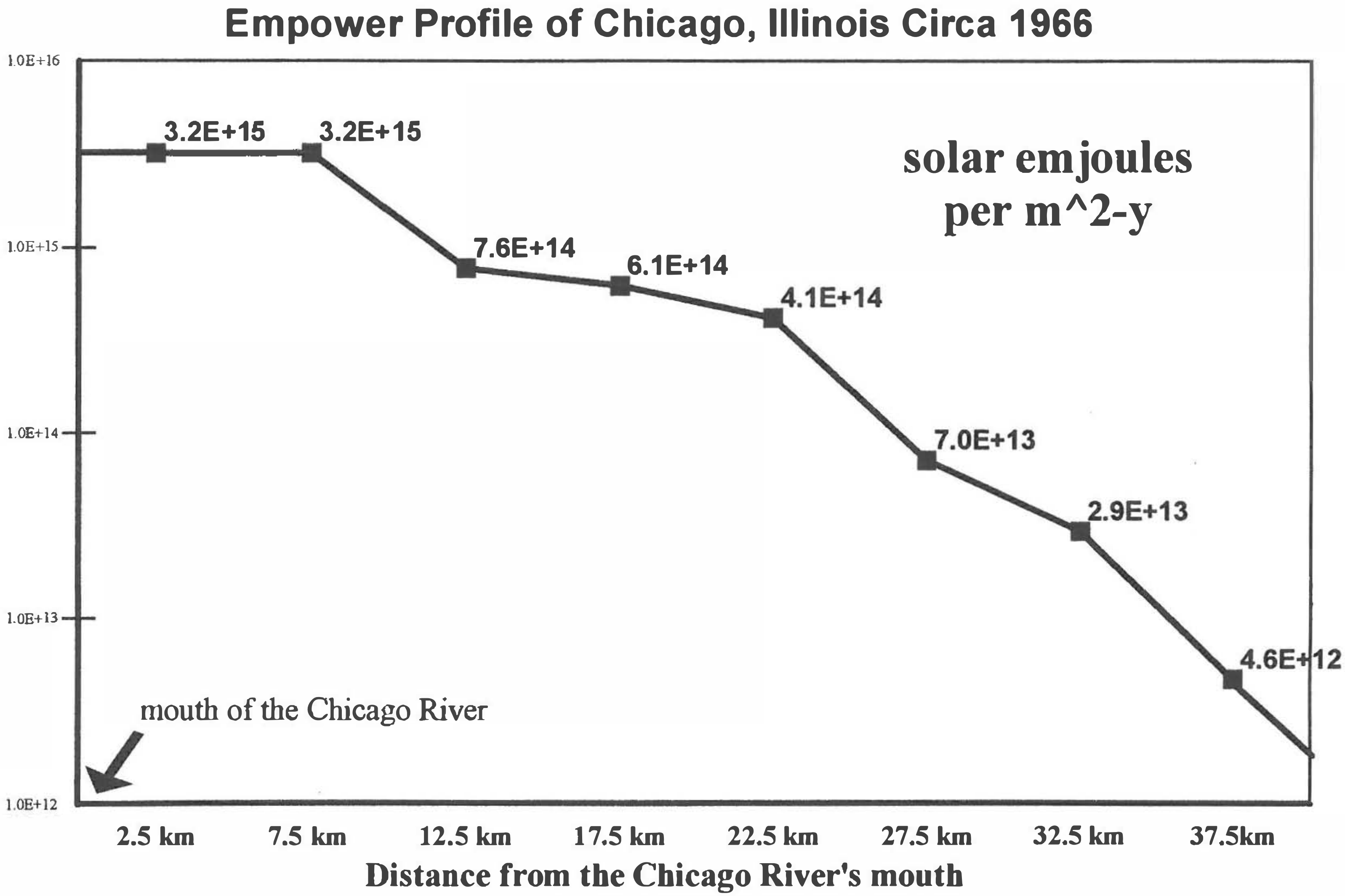

Figure 4. **An averaged empower profile of Chicago, Illinois circa 1966. Profile is an average of transects originating at the Chicago River's mouth.**

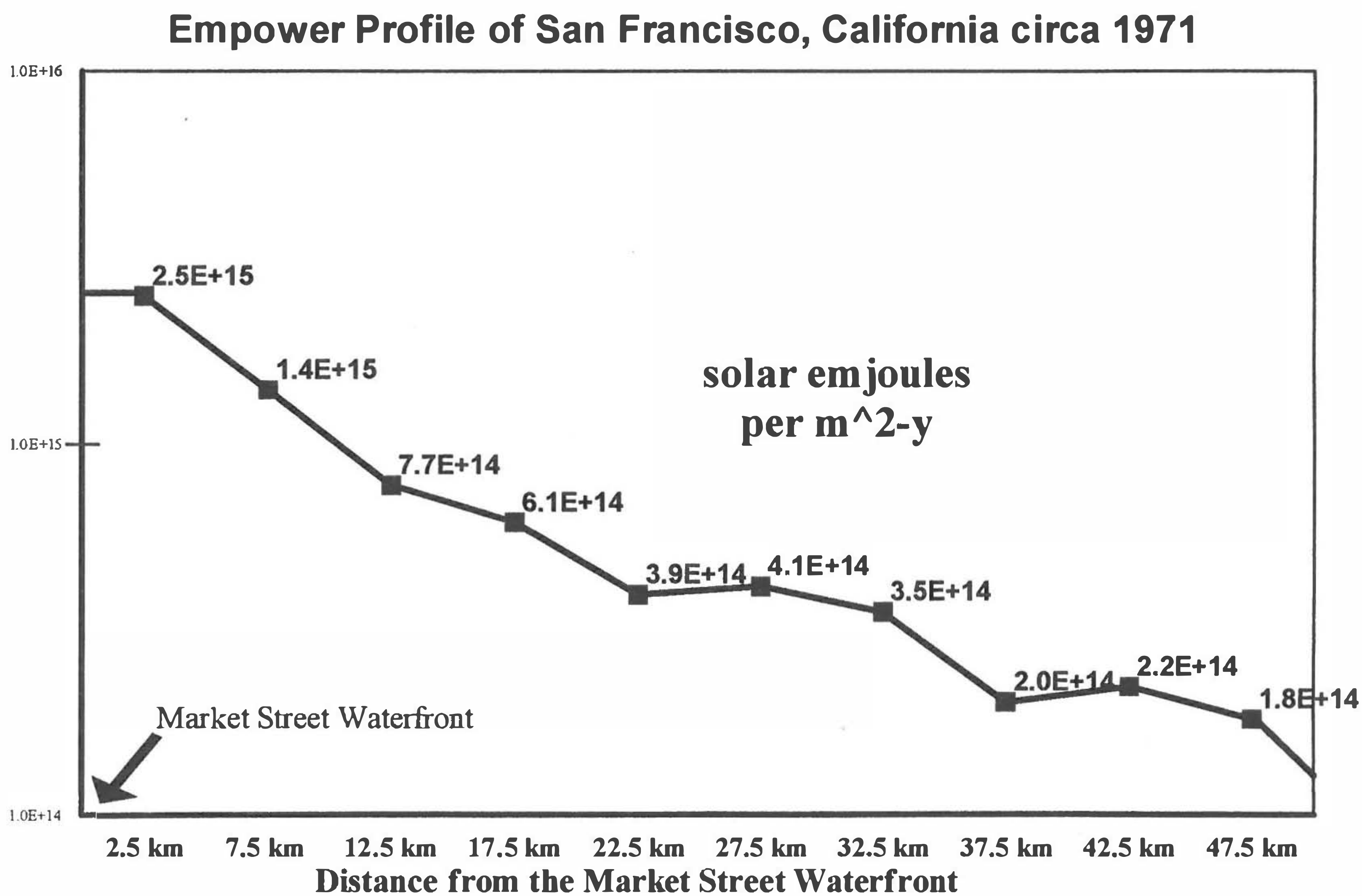

Figure 5. An averaged empower profile of San Francisco, California circa 1966. Profile is an average of transects originating at the Chicago River's mouth.

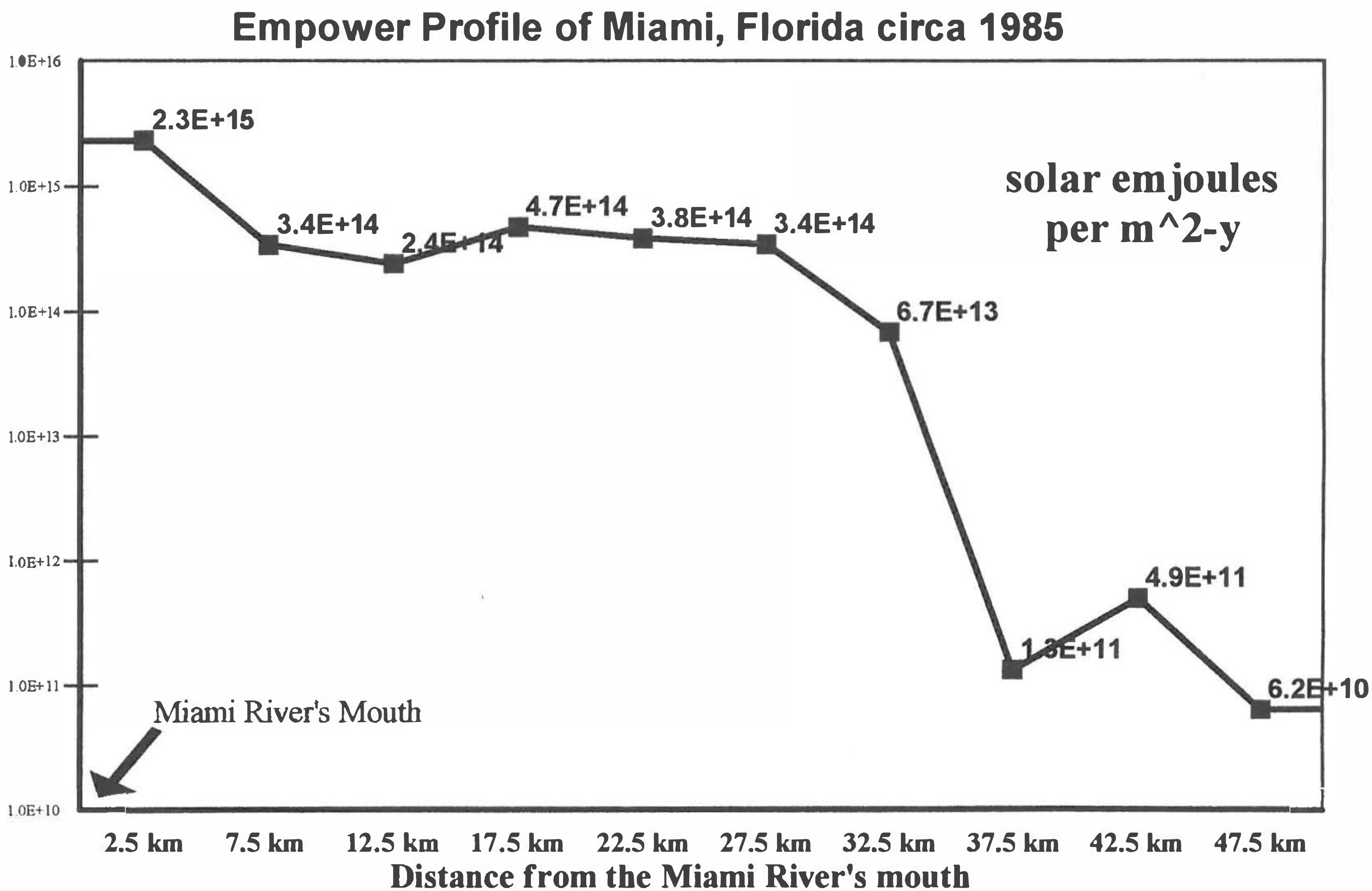

Figure 6. An averaged empower profile of Miami, Florida circa 1985. Profile is an average of transects originating at the Miami River's mouth.

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6. Emergy Indices of Dade County (Miami), Florida

Robert Woithe

Using the procedures for evaluating nations, EMERGY indices were estimated for Dade County, Florida. Figure 1 shows Dade county at the tip of peninsular Florida and the pathway of Hurricane Andrew which destroyed much of Homestead and southern suburbs of Miami in 199 . Main inputs to the county are given in Table 1 summarized in Table 2. These main flows are combined in indices in Table 3.

Similar data are assembled in Table 4-6 for the hurricane impact area (Figure 1). Table 7 has EMERGY and emdollar values of the land use areas.

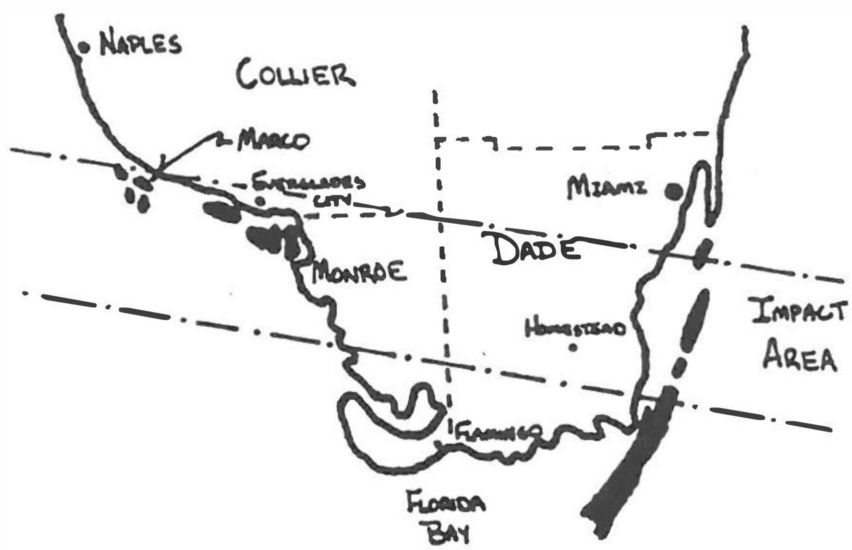

Figure 1 Map of south Florida showing Dade County, Miami, and the path of destruction created by Hurricane Andrew.

Table 1. Annual emergy support for Dade County, Florida in 1990,

Note	Item	Raw Units (J,$ or g)		Trans-formity (sej/unit)	Solar Emergy (E19 sej)	Emdollars (1990 US em$) (E8 em$)
RENEWABLE RESOURCES:						
1	Sunlight	3.56E+19	J	1	3.56	0.22
2	Wind, kinetic	6.00E+17	J	620	37.20	2.33
3	Rain, geopotential	6.25E+13	J	8900	0.06	0.00
4	Rain, chemical	9.19E+16	J	15000	137.90	8.62
5	Tide	3.89E+16	J	24000	93.43	5.84
6	Waves	8.07E+15	J	26000	20.99	1.31
INDIGENOUS RENEWABLE ENERGY:						
7	Agriculture product	5.50E+12	J	2.00E+05	0.11	0.01
8	Shellfish	2.00E+12	J	8.00E+05	0.16	0.01
9	Finfish	1.90E+12	J	2.00E+06	0.38	0.02
NONRENEWABLE SOURCES FROM WITHIN SYSTEM:						
10	Groundwater	1.22E+13	J	41000	0.05	0.00
11	Limestone	4.70E+11	g	6.70E+06	0.31	0.02
IMPORTS AND OUTSIDE SOURCES:						
12	Fuel	1.60E+17	J	5.30E+04	848.00	53.00
13	Electicity	2.20E+17	J	1.59E+05	3498.00	218.63
14	Net migration	5.12E+13	J	4.06E+07	207.87	12.99
15	Services in Import	1.27E+10	$	1.60E+12	2032.00	127.00
EXPORTS:						
16	Agriculture prods.	1.05E+14	J	2.00E+05	2.09	0.13
17	Limestone	4.70E+11	g	6.70E+06	0.31	0.02
18	Services in Export	3.12E+08	$	1.60E+12	49.92	3.12

Notes to Table 1.

NOTE:

1 SUNLIGHT ABSORBED AT SURFACE:

Annual Energy =	((shelf area) m^2 + (land area) m^2 * (insolation) J/m^2-y* (1-albedo)	
Continental shelf=	9.30E+08	m^2 (estimated)
Land Area =	5.06E+09	m^2 (UFBEBR, 1991)
Insolation =	6.90E+09	J/m^2-y (Visher, 1954)
Albedo =	0.14	(% given as decimal) (Odum et al., 1987)

Land Area =	3.40E+09	m^2 (UFBEBR, 1991)
Insolation =	6.90E+09	J/m^2-y (Vishner, 1954)
Albedo =	0.14	(% given as decimal) (Odum et al., 1987)
Annual Energy =	3.12E+19	J/y

2 WIND ABSORBED AT SURFACE:

Surface Wind = 4.00E+17 J/y (estimated from Odum et al. (In Preparation))

3 RAIN, GEOPOTENTIAL:

Annual Energy = (area) m^2 * (mean elevation) m * (runoff) m/y * (water density) kg/m^3 * (gravitational constant) m/s^2

Area =	3.40E+09	m^2
Runoff =	0.25	m (Odum et al., 1987)
Avg elev. =	2	m
Grav. constant =	9.80	m/s^2
Water density =	1.00E+03	kg/m^3
Annual Energy =	1.68E+13	J/y

4 RAIN, CHEMICAL POTENTIAL:

Annual Energy = ((land area) m^2 * (land rainfall) m/y * (fraction evapotranspired) + (shelf area) m^2 * (shelf rainfall) m/y)) * (moles water * univ. gas constant * temp.) kcal/oK-g * (ln((fresh water conc.)/(sea water conc.)) * (rain water density) Kg/m^3

Land area =	3.40E+09	m^2 (UFBEBR, 1991)
Continental shelf =	1.86E+09	m^2 (estimated)
Rainfall =	1.46	m/yr (UFBEBR,1991)
Rain over shelf =	1.46	m/yr
Evapotrans rate =	0.50	(percent given as decimal)
Fresh water conc. =	1.00E+06	ppm (assumed)
Sea water conc. =	9.65E+05	ppm (assumed)
Moles * R * temp. =	5.00E+03	J/Kg
Water density =	1.00E+03	kg/m^3
Annual Energy =	9.45E+16	J/y

5 WAVES BREAKING ON SHORELINES:

Annual Energy = (exposed shore length) cm * 1/8 * (sea water density) g/cm^3 * (gravitational constant) cm/s^2 * ((mean wave height)^2 cm^2 * (water depth @ wave gage) m)^1 1.0E-07 J/erg * 3.2e+07 ??????

Shore length =	6.00E+06	cm (estimated)
Sea water density =	1.03	g/cm^3
Grav. constant =	980.00	cm/s^2
mean wave ht. =	65.00	cm
depth @ gage =	300.00	cm
Annual Energy =	5.44E+15	J/y ???????

6 TIDES:

Annual Energy = (shelf area) m^2 * 1/2 * (# tides/y) * (mean tidal range)^2 m^2 * (fraction of tide absorbed) * (sea water density) kg/m^3 * gravitational constant) m/s^2 * 1.0E-07 J/erg * 3.15+07 s/y * 100 cm/m

Continental Shelf=	1.86E+13	cm^2 (estimated)
Mean Tidal Range =	70.00	cm (Odum et al., 1987)
Number tides/yr =	730.00	
Tide absorbed =	0.13	fraction (estimated)
Sea water density =	1.03	g/cm^3
Grav. constant =	980.00	cm/s^2
Annual Energy =	7.79E+16	J/y

INDIGENOUS RENEWABLES

7 AGRICULTURAL PRODUCTION:

1990 total crops =	4.95E+13	J/y (estimated from UFBEBR (1991), SFGO (1992), & Planka (198
Used within area =	2.48E+12	J/y (assumed 5% of total used within area)

At < 1% of state's total (UFBEBR, 1991), livestock production assumed to be negligible

FISHERIES:

8	1990 Shellfish =	5.62E+12	J/y (estimated from UFBEBER (1991))
	used in area =	5.62E+11	J/y (assumes 10% used within area)
9	1990 Finfish =	2.07E+12	J/y (estimated from UFBEBER (1991))
	used in area =	2.07E+11	J/y (assumes 10% used within area)

NONRENEWABLE SOURCES FROM WITHIN THE SYSTEM

10 GROUNDWATER WITHDRAWLS:

Annual Energy = (water withdrawn) m^3/y * (moles water * univ. gas constant * temp.) * kcal/oK-g * (ln((fresh water conc.)/(sea water conc.)) * (fresh water density) Kg/m^3

1990 withdrawl =	1.27E+08	m^3/yr (estimated from UFBEBR (1991) and MDCPD (1988))
Moles * R * temp. =	5.00E+03	J/Kg
Fresh water conc. =	1.00E+06	ppm (assumed)
Sea water conc. =	9.65E+05	ppm (assumed)
Water density =	1.00E+03	kg/m^3
Annual Energy =	2.31E+12	J/y

11 LIMESTONE:

1990 extraction =	2.35E+11	g/y (estimated from FDC (1991))
% used in area =	50.00	% (assumed)
Used in area =	1.18E+11	g/y (assumes 50% used in Dade County)

IMPORTS AND OUTSIDE SOURCES:

12 FUEL:

1990 gasoline use =	3.04E+16	J/y (estimated from UFBEBR (1991))

13 ELECTICITY:

1990 total use =	4.18E+16	J/y (estimated from UFBEBR (1991))

14 NET IMMIGRATION:

Immigration =	4000	people/y (estimated from FDC (1991))
Average Age =	???	years
J/ind =	3.20E+09	J/indiv
Energy in immigrants =	1.28E+13	J/y

15 GOODS & SERVICES IN IMPORTS:

1990 total tourism input=	5.89E+08	$/y (Estimated from FLDEDR (March, 1990 - February, 1991)
1990 net Federal input=	1.03E+09	$/y (Estimated from UFBEBR (1991)) Net Federal Government Input = (Funding, Spending, & Payments - Taxes)
1990 transfer payments=	7.98E+08	$/y (UFBEBR (1991))
Total =	2.41E+09	$/y

EXPORTS

16 AGRICULTUAL PRODUCTS:

1990 exports =	4.70E+13	J/y (assumes 95% of total production exported (from note 7 above))

FISHERIES:

17 1990 Shellfish = 5.62E+12 J/y (estimated from UFBEBER (1991))

exported from area = 5.06E+12 J/y (assumes 90% exported area)

18 1990 Finfish = 2.07E+12 J/y (estimated from UFBEBER (1991))

exported from area = 1.86E+12 J/y (assumes 90% exported area)

19 LIMESTONE:

1990 extraction = 1.18E+11 g/y (assumes 50.00 % export (see note 11))

20 SERVICES IN EXPORTS

Services in other exports = (Ag Exports + Mineral Exports)

= 2.70E+08 $/y (estimated from FDC (1991))

Table 2. Summary of annual empower and money flows in Dade County, Florida in 1990

Summary Flow		Solar Empower (E19 sej/y)	U.S. emdollars 1E+08 em$	
R	Renewable sources (rain, tide)	231.3	14.46	
N	Nonrenewable sources	0.7	0.04	
N1	Nonrenewable sources used w/i County	0.4	0.02	
N2	Nonrenewable sources exported w/o use	0.3	0.02	
F	Imported Fuels and Minerals	4346.0	271.63	
H	Net Human Immigration	207.87	12.99	
P2I	Emergy Value of Service in Imports	2032.0		
P1E	Emergy Value of Service in Exports	49.9		
x	Florida Gross State Product (1990)		$/y	0.00E+00
P2	U.S. emergy/$ ratio, used in imports		sej/U.S.$	1.80E+12
P1	Dade County's emergy/$ ratio		sej/Dade$	ERR
EL	Emergy in Electric Use	3498.000		
FF	Emergy in Fossil Fuel Use	848.000		
U	Emergy in total Dade energy use	6817.57		

Table 3. Dade County, Florida 1990 emergy indicies derived from Tables A and B.

Index	Name of Index	Expression	Value	Units
I1	Flow of imported emergy	F+P2I	6378.0	E+19 sej/y
I2	Total emergy inflows	R+N+F+H+P2I	6610.0	E+19 sej/y
I3	Economic component	U-R	6586.2	E+19 sej/y
I4	Total exported emergy	N2+P1E	50.23	E+19 sej/y
I5	% Locally renewable	R/U	3.4	%
I6	Economic/environment ratio	(U-R)/R	28.47	
I7	Ratio of imports to exports	(F+P2I)/(N2+P1E)	126.96	
I8	Ratio of Export to Imports	(N2+P1E)/(F+P2I)	0.01	
I9	Imports minus exports	(F+P2I)-(N2+P1E)	6327.77	E+19 sej/y
I10	% of emergy use purchased	(F+P2I)/U * 100%	93.55	%
I11	Fraction imported service	P2I/U	0.30	
I12	% of emergy use derived from home sources	(R+N1)/U * 100%	3.40	%
I13	% of use that is free	(R)/U * 100%	3.39	%
I14	Use per unit area	U/(area) a	1.35	E+13 sej/m^2-y
I15	Use per person	U/population b	3.52	E+16 sej/person-y
I16	Renewable carrying capacity at present living standard	(R/U) (population) b	65728.25	people
I17	Ratio of use to GDP,	P1=U/GDP	ERR	sej/$
I18	Fraction Electric	(EL)/U	0.513	
I19	Fraction Fossil Fuels	(FF)/U	0.124	
I20	Fuel use per person	FF/population	4.38	E+15 sej/person-y

a Area of Dade County = 5.06E+09 m^2 (UFBEBR, 1991)
b Population of Dade County = 1.94E+06 people (UFBEBR, 1991)

Table 4. Annual emergy support for the Hurricane Andrew impact area.

Note	Item	Raw Units (J,$ or g)		Trans-formity (sej/unit)	Solar Emergy (E19 sej)	Emdollars (1990 US em$) (E8 em$)
RENEWABLE RESOURCES:						
1	Sunlight	3.12E+19	J	1	3.12	0.20
2	Wind, kinetic	4.00E+17	J	620	24.80	1.55
3	Rain, geopotential	1.68E+13	J	8900	0.01	0.00
4	Rain, chemical	9.45E+16	J	15000	141.80	8.86
5	Tide	7.79E+16	J	24000	186.87	11.68
6	Waves	5.44E+15	J	26000	14.15	0.88
INDIGENOUS RENEWABLE ENERGY:						
7	Agriculture product	2.48E+12	J	2.00E+05	0.05	0.00
8	Shellfish	5.62E+12	J	8.00E+05	0.45	0.03
9	Finfish	2.07E+12	J	2.00E+06	0.41	0.03
NONRENEWABLE SOURCES FROM WITHIN SYSTEM:						
10	Groundwater	2.31E+12	J	41000	0.01	0.00
11	Limestone	1.18E+11	g	6.70E+06	0.08	0.00
IMPORTS AND OUTSIDE SOURCES:						
12	Fuel	3.04E+16	J	5.30E+04	161.12	10.07
13	Electicity	4.18E+16	J	1.59E+05	664.62	41.54
14	Net migration	1.28E+13	J	4.06E+07	51.97	3.25
15	Services in Import	2.41E+09	$	1.60E+12	386.08	24.13
EXPORTS:						
18	Agriculture prods.	4.70E+13	J	2.00E+05	0.94	0.06
17	Shellfish	5.06E+12	J	8.00E+05	0.40	0.03
18	Finfish	1.86E+12	J	2.00E+06	0.37	0.02
19	Limestone	1.18E+11	g	6.70E+06	0.08	0.00
20	Services In Export	2.70E+08	$	1.60E+12	43.18	2.70

Notes to Table 4.

NOTE:

1 SUNLIGHT ABSORBED AT SURFACE:

Annual Energy = ((shelf area) m^2 + (land area) m^2 * (insolation) J/m^2-y * (1-albedo)

Continental shelf= 1.86E+09 m^2 (estimated)

Annual Energy = 3.56E+19 J/y

2 WIND ABSORBED AT SURFACE:

Surface Wind = 6.00E+17 J/y (estimated from Odum et al. (In Preparation))

3 RAIN, GEOPOTENTIAL:

Annual Energy = (area) m^2 * (mean elevation) m * (runoff) m/y * (water density) kg/m^3 * (gravitational constant) m/s^2

Area =	5.06E+09	m^2
Runoff =	0.25	m (Odum et al., 1987)
Avg elev. =	5	m
Grav. constant =	9.80	m/s^2
Water density =	1.00E+03	kg/m^3
Annual Energy =	6.25E+13	J/y

4 RAIN, CHEMICAL POTENTIAL:

Annual Energy = ((land area) m^2 * (land rainfall) m/y * (fraction evapotranspired) + (shelf area) m^2 * (shelf rainfall) m/y)) * (moles water * univ. gas constant * temp.) kcal/oK-g * (ln((fresh water conc.)/(sea water conc.)) * (rain water density) Kg/m^3

Land area =	5.06E+09	m^2 (UFBEBR, 1991)
Continental shelf =	9.30E+08	m^2 (estimated)
Rainfall =	1.46	m/yr (UFBEBR, 1991)
Rain over shelf =	1.46	m/yr
Evapotrans rate =	0.50	(percent given as decimal)
Fresh water conc. =	1.00E+06	ppm (assumed)
Sea water conc. =	9.65E+05	ppm (assumed)
Moles * R * temp. =	5.00E+03	J/Kg
Water density =	1.00E+03	kg/m^3
Annual Energy =	9.19E+16	J/y

5 WAVES BREAKING ON SHORELINES:

Annual Energy = (exposed shore length) cm * 1/8 * (sea water density) g/cm^3 * (gravitational constant) cm/s^2 * ((mean wave height)^2 cm^2 * (water depth @ wave gage) m)^1 1.0E-07 J/erg * 3.2e+07 ??????

Shore length =	8.90E+06	cm (estimated)
Sea water density =	1.03	g/cm^3
Grav. constant =	980.00	cm/s^2
mean wave ht. =	65.00	cm
depth @ gage =	300.00	cm
Annual Energy =	8.07E+15	J/y ???????

6 TIDES:

Annual Energy = (shelf area) m^2 * 1/2 * (# tides/y) * (mean tidal range)^2 m^2 * (fraction of tide absorbed) * (sea water density) kg/m^3 * gravitational constant) m/s^2 * 1.0E-07 J/erg * 3.15+07 s/y * 100 cm/m

Continental Shelf=	9.30E+12	cm^2 (estimated)
Mean Tidal Range =	70.00	cm (Odum et al., 1987)
Number tides/yr =	730.00	
Tide absorbed =	0.13	fraction (estimated)
Sea water density =	1.03	g/cm^3
Grav. constant =	980.00	cm/s^2
Annual Energy =	3.69E+16	J/y

INDIGENOUS RENEWABLES

7 AGRICULTURAL PRODUCTION:

1990 total crops =	1.10E+14	J/y (estimated from UFBEBR (1991), SFGO (1992), & Pianka (198
Used within area =	5.50E+12	J/y (assumed 5% of total used within Dade)

At < 1% of state's total (UFBEBR, 1991), livestock production assumed to be negligible

FISHERIES:

8 1990 Shellfish =	2.00E+12	J/y (from UFBEBER (1991)) (assumes all used within Dade)
9 1990 Finfish =	1.90E+12	J/y (from UFBEBER (1991)) (assumes all used within Dade)

NONRENEWABLE SOURCES FROM WITHIN THE SYSTEM

10 GROUNDWATER WITHDRAWLS:

Annual Energy = (water withdrawn) m^3/y * (moles water * univ. gas constant * temp.) * kcal/oK-g * (ln((fresh water conc.)/(sea water conc.)) * (fresh water density) Kg/m^3

1990 withdrawl =	6.70E+06	m^3/yr (UFBEBR, 1991)
Moles * R * temp. =	5.00E+03	J/Kg
Fresh water conc. =	1.00E+06	ppm (assumed)
Sea water conc. =	9.65E+05	ppm (assumed)
Water density =	1.00E+03	kg/m^3
Annual Energy =	1.22E+13	J/y

11 LIMESTONE:

1990 extraction =	9.40E+11	g/y (estimated from FDC (1991))
% used in Dade =	50.00	% (assumed)
Used in Dade =	4.70E+11	g/y (assumes 50% used in Dade County)

IMPORTS AND OUTSIDE SOURCES:

12 FUEL:

1990 gasoline use =	1.60E+17	J/y (estimated from UFBEBR (1991))

13 ELECTICITY:

1990 total use =	2.20E+17	J/y (estimated from UFBEBR (1991))

14 NET IMMIGRATION:

Immigration =	16000	people/y (from FDC (1991))
Average Age =	???	years
j/Ind =	3.20E+09	j/indiv
Energy in immigrants =	5.12E+13	J/y

15 GOODS & SERVICES IN IMPORTS:

1990 total tourism input=	3.10E+09	$/y (Estimated from FLDEDR (March, 1990 - February, 1991)
1990 net Federal input=	5.40E+09	$/y (Estimated from UFBEBR (1991))
		Net Federal Government Input = (Funding, Spending, & Payments - Taxes)
1990 transfer paymnts=	4.20E+09	$/y (UFBEBR (1991))
Total =	1.27E+10	$/y

EXPORTS

16 AGRICULTUAL PRODUCTS:

1990 exports =	1.05E+14	J/y (assumes 95% of total production exported (from note 7 above))

19 LIMESTONE:

1990 extraction =	4.70E+11	g/y (assumes 50.00 % export)

20 SERVICES IN EXPORTS

Services in other exports = (Ag Exports + Mineral Exports)

= 3.12E+08 $/y (estimated from FDC (1991))

ABBREVIATIONS USED IN THIS REPORT

FDC	Florida Department of Commerce
FLDEDR	Florida Legislature Division of Economic & Demographic Research
MDCPD	Metro-Dade County Planning Department
UFBEBR	University of Florida, Bureau of Economic & Business Research
USFWS	United States Fish and Wildlife Service

Table 5. Summary of annual empower and money flows of the Hurricane Andrew impact are

Summary Flow		Solar Empower (E19 sej/y)	U.S. emdollars 1E+08 em$	
R	Renewable sources (rain, tide)	328.7	20.54	
R1	Renewable used within	327.9	20.49	
R2	Renewable exported without use	0.8	0.05	
N	Nonrenewable sources	0.2	0.01	
N1	Nonrenewable sources used w/i Area	0.1	0.01	
N2	Nonrenewable sources exported w/o use	0.1	0.00	
F	Imported Fuels and Minerals	825.7	51.61	
H	Net Human Immigration	51.97	3.25	
P2I	Emergy Value of Service in Imports	386.1		
P1E	Emergy Value of Service in Exports	43.2		
x	Area Gross Domestic Product (1990)		$/y	0.00E+00
P2	U.S. emergy/$ ratio, used in imports		sej/U.S.$	1.60E+12
P1	Area's emergy/$ ratio		sej/Area$	ERR
EL	Emergy in Electric Use	664.620		
FF	Emergy in Fossil Fuel Use	161.120		
U	Emergy in total Area energy use	1591.76		

Table 6. Hurricane Andrew impact area emergy indicies derived from Tables D and E.

Index	Name of Index	Expression	Value	Units
I1	Flow of imported emergy	F+P2I	1211.8	E+19 sej/y
I2	Total emergy inflows	R+N+F+H+P2I	1540.7	E+19 sej/y
I3	Economic component	U-R	1263.1	E+19 sej/y
I4	Total exported emergy	N2+P1E	43.26	E+19 sej/y
I5	% Locally renewable	R/U	20.6	%
I6	Economic/environment ratio	(U-R)/R	3.84	
I7	Ratio of imports to exports	(F+P2I)/(N2+P1E)	28.01	
I8	Ratio of Export to Imports	(N2+P1E)/(F+P2I)	0.04	
I9	Imports minus exports	(F+P2I)-(N2+P1E)	1168.56	E+19 sej/y
I10	% of emergy use purchased	(F+P2I)/U * 100%	76.13	%
I11	Fraction imported service	P2I/U	0.24	
I12	% of emergy use derived from home sources	(R+N1)/U * 100%	20.65	%
I13	% of use that is free	(R)/U * 100%	20.65	%
I14	Use per unit area	U/(area) a	0.47	E+13 sej/m^2-y
I15	Use per person	U/population b	4.13	E+16 sej/person-y
I16	Renewable carrying capacity at present living standard	(R/U) (population) b	79494.20	people
I17	Ratio of use to GDP,	P1=U/GDP	ERR	sej/$
I18	Fraction Electric	(EL)/U	0.418	
I19	Fraction Fossil Fuels	(FF)/U	0.101	
I20	Fuel use per person	FF/population	4.18	E+15 sej/person-y

a Area of Impact Region = 3.40E+09 m^2 (estimated from UFBEBR, 1991)

b Population of Impact Region 3.85E+05 people (estimated from UFBEBR, 1991)

Table 7. Emergy value of storages of the Hurricane Andrew impact area by land use cat

Note	Item	Raw Units (hectares)		Trans-formity (sej/unit)	Solar Emergy (E14 sej)	Emdollars (1990 US (E10 em
1	Beaches, dunes & salt flats	1.4E+02	ha	2.0E+10	0.0	0.2
2	Emerging systems	3.6E+02	ha	2.5E+10	0.1	0.6
3	Scrub mangroves	5.4E+03	ha	3.5E+10	1.9	11.7
4	Lakes and ponds	9.7E+02	ha	3.7E+10	0.4	2.2
5	Urban parks	1.5E+03	ha	1.2E+11	1.8	11.4
6	Wet prairie	4.4E+04	ha	2.5E+11	108.7	679.5
7	Scrub cypress	5.2E+03	ha	3.0E+11	15.4	96.4
8	Pine uplands	1.1E+03	ha	4.0E+11	4.3	27.2
10	Agriculture	1.6E+04	ha	8.9E+11	142.3	889.6
11	Mangroves and salt marshes	6.0E+04	ha	1.0E+12	607.9	3799.2
12	Cypress domes & strands	2.5E+04	ha	1.1E+12	265.6	1660.2
13	Hardwood hammocks	4.1E+03	ha	1.2E+12	47.8	297.6
14	Sawgrass marsh	1.1E+05	ha	1.4E+12	1495.0	9343.5
15	Single-family residential	5.3E+04	ha	3.7E+12	1964.4	12277.8
16	Transportation	6.8E+03	ha	9.9E+12	672.1	4200.7
17	Multi-family residential	4.0E+03	ha	1.1E+13	444.8	2779.9
18	Commercial & industrial	4.2E+03	ha	5.4E+13	2283.2	14270.0
		ha			E14 sej	(E10em$
	Sum:	3.4E+05			8056	50347

Notes to Table 7.

NOTE:

1 Beaches, dunes & salt flats

1.4E+02 ha (estimated from Brown ??)

2 Emerging systems

3.6E+02 ha (estimated from Brown ??)

3 Scrub mangroves

5.4E+03 ha (estimated from Brown ??)

4 Lakes and ponds

9.7E+02 ha (estimated from Brown ??)

5 Urban parks

1.5E+03 ha (estimated from MDCDP (1988))

6 Wet prairie

4.4E+04 ha (estimated from USFWS (1985) and Stephens (198

7 Scrub cypress

5.2E+03 ha (estimated from Brown (19??) and USFWS (1985))

8 Pine uplands

1.1E+03 ha (estimated from Brown (1977) and MDCDP (1988))

10 Agriculture

1.6E+04 ha (estimated from MDCDP (1988))

11 Mangroves and salt marshes

6.0E+04 ha (estimated from Brown (1977) and USFWS (1985))

12 Cypress domes & strands

2.5E+04 ha (estimated from Brown (1977) and USFWS (1985))

13 Hardwood hammocks

4.1E+03 ha (estimated from Brown 77)

14 Sawgrass marsh

1.1E+05 ha (estimated from USFWS (1985) and Stephens (198

15 Single-family residential

5.3E+04 ha (estimated from MDCDP (1988))

16 Transportation

6.8E+03 ha (estimated from MDCDP (1988))

17 Multi-family residential

4.0E+03 ha (estimated from MDCDP (1988))

18 Commercial & industrial

4.2E+03 ha (estimated from MDCDP (1988))

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7. Emergy Evaluation of San Juan, Puerto Rico

Steven Doherty

An analysis of San Juan, the capital city of Puerto Rico, its resource base, economy and population was undertaken to better understand the underpinnings of a major metropolitan area and its role in Puerto Rico's combined ecologic-economic system. Puerto Rico is a part of the Greater Antilles island chain in the northeastern Caribbean (Figure 1). Puerto Rico has developed from a largely rural economy in the early part of the century to an urban industrialized economy today. U.S. interests and commonwealth initiatives such as Operation Bootstrap in the early 1950's developed urban infrastructure and housing that along with industry incentives spurred unprecedented growth. The island economy became centered on manufacturing businesses based on imported fuels and high quality goods and services. A declining market for farm products has resulted in an immigration of people to city centers. Abandoned agricultural lands are now reforesting. Puerto Rico's population in 1992 was 3.6 million people or 400 persons per square kilometer. Its gross economic product, including revenues earned overseas for on-island production, in 1992 was 39.8 billion US$. Between 1985 and 1992, the cumulative growth of Puerto Rico's economy was 21% (GDB 1992). This analysis contrasts economic indicators of growth with emergy-based indicators.

Available statistics for San Juan were combined with a completed analysis of Puerto Rico between 1987 and 1992 (Doherty et al 1994). Data from 1987, the most current year with tabulated statistics, were used to evaluate external trade commodities (Junta de Planificacion 1989). The emergy-basis for 1992 was estimated based on actual data for fuel imports (the major import to Puerto Rico), and trade costs and revenues for that year (Junta de Planificacion 1992). The environmental sources were considered unchanged from year to year. Unknown values for San Juan were estimated in relative proportion to related statistics from the Puerto Rico analysis adjusted for known differences in resource use. All computations are given as footnotes. A systems diagram of Puerto Rico, its resource base, major economic sectors and urban centers is given in Figure 2 for overview.

Issues of trade are also considered here, with the assumption that all imports and exports move through San Juan, Puerto Rico's major port city. Puerto Rico's total emergy-use increased 24% from 1987 to 1992 while its gross economic product increased 58% from 25.2 billion $ to 39.8 billion $ over the same period (Doherty et al 1994). This resulted in a decrease in emergy/dollar index from 2.10E+12 sej/$ in 1987 to 1.64E+12 sej/$ in 1992. This latter figure was used to estimate human services emergy supporting human services in production activities and exports, in proportion to the money paid. Imports were evaluated using the index of emergy/GNP for the U.S. in 1992 (1.60E+12 sej/$; Odum 1988, updated 1994).

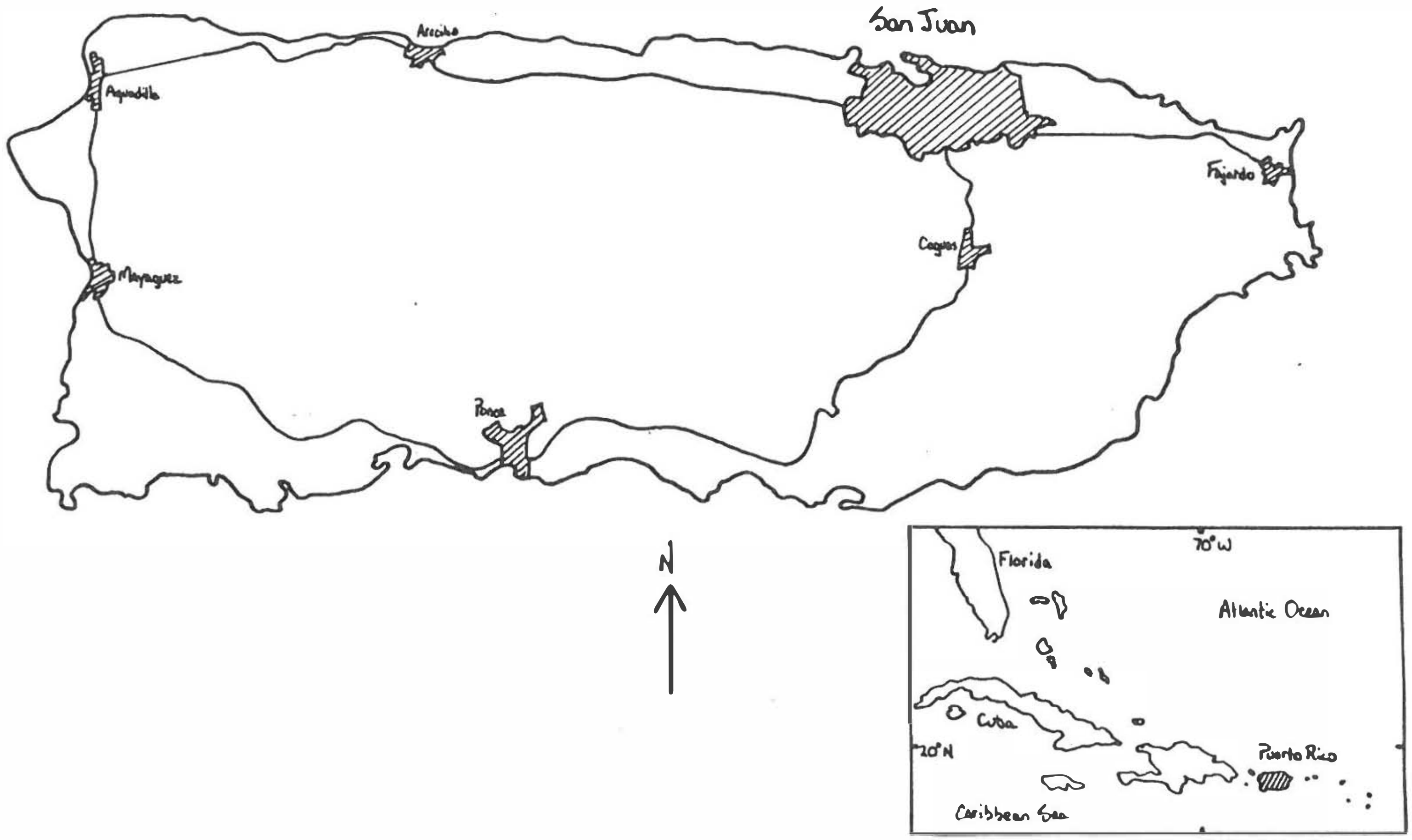

Figure 1. Map of Puerto Rico, its capital city San Juan, other major urban and industrial centers, and main highway system.

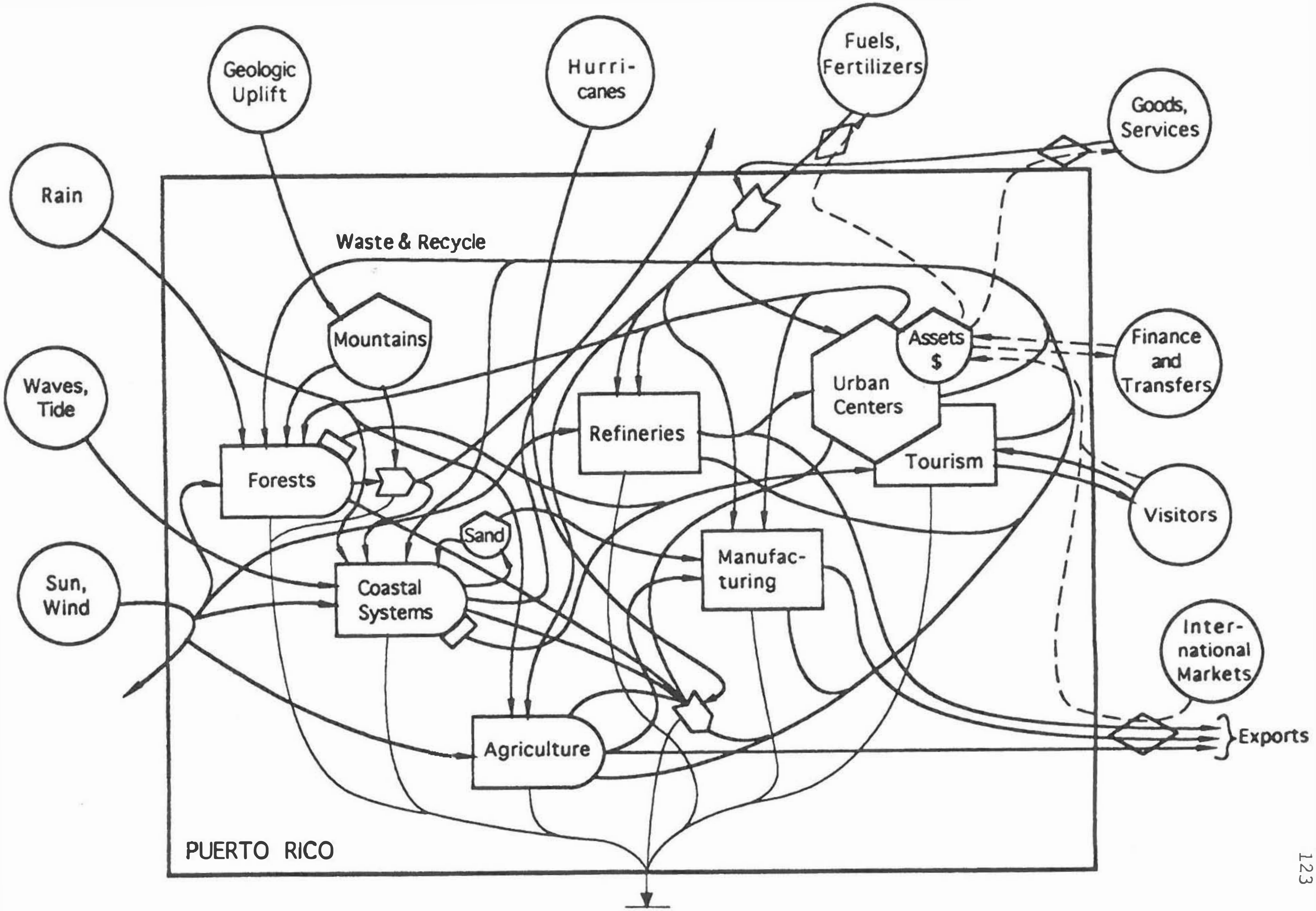

Figure 2. Overview systems diagram of Puerto Rico, its resource base, ecological life zones, major economic sectors, interactive flows and circulation of money.

San Juan's Emergy Basis

Resource-use and population for Puerto Rico and the city of San Juan in 1992 are given in Table 1. Like the island commonwealth of Puerto Rico, its capital city San Juan is largely dependent upon external, purchased fuels, goods and service. While Puerto Rico receives about 2% of its emergy used annually from environmental sources, less than 1% of San Juan's emergy basis is derived from environmental sources. San Juan receives about 1.8 m of rain annually, with an estimated 58% runoff (San Juan lies in the subtropical moist forest lifezone which evapotranspires as much as 84% of incident rainfall but is here considered half that potential due to paved and impermeable city surfaces). This results in chemical and geopotential emergy contributions from precipitation of 3.9E+19 sej/yr (item 1), about half of the average environmental empower density of Puerto Rico (0.73E+11 sej/m^2/yr compared to 1.57E+11 sej/m^2/yr).

Almost ten times the amount of imports are used within San Juan than for Puerto Rico (7.0E+13 sej/m^2/yr compared to 7.2E+12 sej/m^2/yr) (items 2 and 5). About 35% of all emergy used in San Juan is direct consumption of imported fossil fuels. Other import commodities comprise about 27% of all emergy used, with associated human services, U.S. loans and revenue derived from tourism totalling 38% of the city's annual emergy-use. Together, environmental and economic emergy totals 2.76E+22 sej/yr for San Juan (item 3).

Almost 50% of Puerto Rico's population lived in San Juan in 1992 (1.71 million people of the island total of 3.56 million) in an area 1/16th the size of the island (items 8-9). This results in a population eight times more dense than the island average (3179 people/km^2 compared to 401 people/km^2) (item 10). Emergy-use and fuel-use per capita are both about 1.3 times greater for San Juan residents than for others living in Puerto Rico (items 12-13). The ratio of economic to environmental emergy is high for both the island (45 to 1) and the capital city (964 to 1) making San Juan more than 20 times more dependent upon economically derived imports and fuels than Puerto Rico (item 7).

An estimated 5775 kWh of electricity were used per capita annually in San Juan. This resulted in an estimated annual emergy use of 6.7E+21 sej/yr of electricity for the city, about 11.8% of the total emergy used (item 6). Average revenue per kilowatt hour of electricity in Puerto Rico was 1.37 times greater than the U.S. average (0.10 $/kWh; San Juan Star, Sept. 2, 1993). With this estimate, electricity prices account for only about a third of the total em$ value that electric energy contributes to the economy. This suggests that as much as 2.7 billion em$ in macro-economic value is from geologic-environmental emergy in fossil fuels used in electric power generation and is unaccounted for in consumer prices, contributing directly to surplus emergy supporting San Juan's economy.

Per capita water demand was 146 gallons per person per day in San Juan and 116 gal/p/d on average throughout Puerto Rico in 1992 (item 14). By calculating the environmental emergy of water production and the economically derived emergy of water treatment and transport, an estimated 2.77E+20 solar emjoules were used per year for consumer water in San Juan. On a per capita basis, San Juan uses 1.62E+14 sej/p/yr compared with 1.28E+14 sej/p/yr for other

Table 1. Resource-use and population for Puerto Rico and its capital city, San Juan, 1992.

	Item/index	Puerto Rico	San Juan		magnitude difference
1.	Environmental contribution	1.41E+21	3.90E+19	sej/yr	--
2.	Economic contribution:	6.41E+22	3.76E+22	sej/yr	--
	Imported goods	1.67E+22	1.01E+22	sej/yr	--
	Imported fossil fuels	2.12E+22	1.32E+22	sej/yr	--
	Services, U.S. loans, tourism	2.54E+22	1.43E+22	sej/yr	--
3.	Total solar emergy-use	6.55E+22	3.76E+22	sej/yr	--
4.	% environmental	1.6	0.10	%	--
5.	% external, economic:	97.8	99.9	%	--
	% imported goods	26.1	26.8	%	--
	% imported fossil fuels	33.0	35.2	%	--
	% import services, loans, tourism	38.7	37.9	%	--
6.	% electricity	9.4	11.8	%	--
7.	Economic/environment ratio	45	964		21.3
8.	Population	3.56E+06	1.71E+06	people	--
9.	Area	8897	537	km2	--
10.	Population density	401	3179	person/km2	7.9
11.	Solar emergy-use/area	7.36E+12	7.01E+13	sej/m2/yr	9.5
12.	Solar emergy-use/capita	1.84E+16	2.20E+16	sej/p/yr	1.2
13.	Fuel-use/capita	6.07E+15	7.75E+15	sej/p/yr	1.3
14.	Water demand/capita	116	146	gal/p/day	1.3

footnotes to Table 1.

Values for Puerto Rico are from Doherty et al. (1994); Emergy Evaluation of the Luquillo Experimental Forest and Puerto Rico.

I = environment, R = renewables, N = non-renewable; F = fuels; G = goods; S = human services; P = population; W = per capita water demand; E = electricity; U = total annual emergy-use

1. Environmental contribution (I):
   Puerto Rico: I = R+N = 1.02E21 sej/yr + 0.395E21 sej/yr = 1.41E21 sej/yr
   San Juan: Rainfall = 70 in/yr; 84% evapotranspired in subtropical moist forest life zone (Ewel and Whitmore 1973).
   Chemical potential emergy = potential ET reduced by 1/2 from paved surface;
   (70 in /y) (25.4 mm/in) (0.84) (1/2) (537 km2) (1000 kg/m3) (4940 J/kg) = 1.98E15 J/y (18200 sej/J) = 3.61E19 sej/y
   Gravitational potential emergy = (70 in/y) (25.4 mm/in) (1 - 0.42) (537 km2) (50 m avg. elev.) (1000 kg/m3) (9.8 m/s2) = 2.71E14 J/y (10500 sej/J) = 2.5E18 sej/y
   Total environmental emergy (I_{SJ}) = 3.61E19 sej/y + 2.5E18 sej/y = 3.90E19 sej/y

2. Economic contribution estimated in proportion to population and per capita water demand for San Juan relative to Puerto Rico:
   Fuel use = (F_{PR}) (P_{SJ}/P_{PR}) (W_{SJ}/W_{PR}) = (2.12E22 sej/y) (1.71E6 p/3.56E6 p) (146 g/p/d) / (116 g/p/d)
   Imported goods = (1.67E22 sej/y) (1.71E6 p/3.56E6 p) (146 g/p/d) / (116 g/p/d)
   Human services, loans, tourism = U.S. Loans + tourism (80%) + (S_{PR}) (P_{SJ}/P_{PR}) (W_{SJ}/W_{PR})
   = (2.93E21 sej/y) + (2.56E21 sej/y) (0.80) + (1.99E22 sej/y) (1.71E6 p/3.56E6 p) (146 g/p/d) / (116 g/p/d)

3. Total emergy-use (U) = I + F + G + S
4. % environmental emergy = I / U
5. % external, economic = (F+G+S) / U

6. % electricity = electricity consumption / U;
   Puerto Rico annual electric-use (1992) = 1.10E10 kWh = 4.96E21 sej/yr; $\%E_{PR}$ = 9.4%;
   San Juan = ($\%E_{PR}$) (W_{SJ}/W_{PR}) = (9.4) (146 g/p/d) / (116 g/p/d) = 11.8%;
   (0.118) (U_{SJ} = 3.76E22 sej/yr) / (125000 sej/J) / (3.6E6 J/kWh) = 9.86E9 kWh/yr;
   per capita electricity consumption = (9.86E9 kWh/yr) / (1.71E6 people) = 5775 kWh/p/yr
   total reveunues from electric production = (9.86E9 kWh/yr) (0.10 \$/kWh; avg. U.S. price) (1.37; % above U.S. avg.; San Juan Star, 2 Sept. 1993) = 1.35E9 \$/yr.
   environment = (3.76E22 sej/yr) (0.118) = 4.44E21 sej/yr
   economic = (1.35E9 \$/yr) (1.64E12 sej/\$) = 2.22E21 sej/yr
   total = 4.44E21 sej + 2.22E21 sej = 6.66E21 sej/yr
   fraction paid for = (2.22E21 sej) / (6.66E21 sej) = 0.3
   emergy/\$ cost ratio = (kWh/0.10 \$) (3.6E6 J/kWh) (125000 sej/J) = 4.5E12 sej/\$ + 1.64E12 sej/\$ (human services est.) = 6.14E12 sej/\$; (6.14E12 sej/\$; E-price) / (1.64E12 sej/\$; PR avg.) = 3.7

7. Economic/environment ratio = (F+G+S) / I
8. General Population Characteristics of Puerto Rico (1990 CP-1-53) U.S. Dept. Commerce (1992)
9. Area estimated from digitized incorporated area of San Juan = 537 km2
10. Population density = P / area
11. Solar empower density = U / area
12. Per capita emergy-use = U / P
13. Per capita fuel-use = F / P

Table 1 footnotes, continued.

14. Per capita water demand from PRASA (1992).
    San Juan water demand:
        environment = (146 gal/p/d) (3.785E-3 m3/gal) (1000 kg/m3) (4920 J/kg) (1.71E6 people) (365 d/yr) (48450 sej/J) = 8.22E19 sej/yr;
        economic = (146 g/p/d) (0.0013 $/gal) (1.71E6 p) (365 d/yr) = 118.5E6 $/yr (1.64E12 sej/$) = 1.94E20 sej/yr;
        total emergy in water supplied = 8.22E19 sej + 1.94E20 sej = 2.77E20 sej/yr
        per capita water demand = (2.77E20 sej/yr) / (1.71E6 p) = 1.62E14 sej/p/yr
        em$ value of water = (2.77E20 sej/yr) / (1.64E12 sej/$) = 1.69E8 em$/yr
        fraction paid for = (119E6 $) / (169E6 em$) = 0.7
        emergy/$ cost ratio = (gal/0.0013 $) (3.75E-3 m3/gal) (1000 kg/m3) (4920 J/kg) (48450 sej/J) = 6.94E11 sej/$ + 1.64E12 sej/$ (human services est.) = 2.34E12 sej/$; (2.34E12 sej/$; W-price) / (1.64E12 sej/$; PR avg.) = 1.42
    Puerto Rico water demand:
        environment = (116 gal/p/d) (3.785E-3 m3/gal) (1000 kg/m3) (4920 J/kg) (3.56E6 people) (365 d/yr) (48450 sej/J) = 1.36E20 sej/yr;
        economic = (116 g/p/d) (0.0013 $/gal) (3.56E6 p) (365 d/yr) = 196E6 $/yr (1.64E12 sej/$) = 3.21E20 sej/yr;
        total emergy in water supplied = 1.36E20 sej + 3.21E20 sej = 4.57E20 sej/yr
        per capita water demand = (4.57E20 sej/yr) / (3.56E6 p) = 1.28E14 sej/p/yr

island residents -- 1.3 times more emergy used. If current market value of water is 1.3 $/1000 gal (1990 U.S. consumer price average; Nieswiadomy 1992), the em$ value of water calculated here is 1.4 times the consumer price, representing 50 million dollars of unpaid services supporting San Juan's economy. This is because the consumer value only includes the cost of treatment and distribution and does not include the work of the forest in providing this water.

By calculating the emergy/dollar index for water and electricity, relative worth of these purchased resources can be assessed by comparing these values with the average emergy/dollar index for Puerto Rico (1.64E+12 sej/$, 1992; Doherty et al 1994). Consumer water prices (1.3 $/1000 gal) yield 2.34E+12 sej/$. Electric prices (averaged for residential, commercial and industrial sectors; 0.10 $/kWh) yield 6.14E+12 sej/$. These emergy/$ cost ratios suggest that water delivers 1.4 times more, and purchased electricity 3.7 times more emergy than would be gained by purchasing general goods and services. These calculations indicate the importance of water and electricity to the urban infrastructure and functioning of San Juan.

Changes in emergy-use and population in San Juan between 1987 and 1992 are given in Table 2. Values for 1987 were estimated in direct proportion to island wide changes documented in the emergy analysis of Puerto Rico (Doherty et al 1994). Total emergy-use increased by 25% from 3.02E+22 sej/yr in 1987 to 3.76E+22 sej/yr five years later in 1992 (item 3). This change was due to increased use of economic goods, fuels and related services (item 2). Use of imported fossil fuels rose 32% from 1987-92. Goods similarly increased 31% and emergy derived from services, U.S. loans and tourism rose 15%. Environmental contributions were considered unchanged over the period (item 1). This resulted in a 25% rise in the ratio of economic to environmental emergy from 773 to 964 over 5 years (item 7).

San Juan's population increased from 1.58 million people in 1987 to 1.71 million in 1992 -- an 8% change (item 7). While per capita emergy-use increased 15% during this period, per capita fossil fuel-use increased by 22% (items 10-11). Empower density increased 25% over 5 years, reflecting the heightened use of imported emergy in San Juan (item 9).

Table 2. Changes in resource-use for the city of San Juan, Puerto Rico from 1987 to 1992.

	Item/index	1987	1992		% change
1.	Environmental contribution	3.90E+19	3.90E+19	sej/yr	0
2.	Economic contribution:	3.02E+22	3.76E+22	sej/yr	25
	Imported goods	7.69E+21	1.01E+22	sej/yr	31
	Imported fossil fuels	1.00E+22	1.32E+22	sej/yr	32
	Services, U.S. loans, tourism	1.24E+22	1.43E+22	sej/yr	15
3.	Total solar emergy-use	3.02E+22	3.76E+22	sej/yr	25
4.	% environmental, renewable	0.13	0.10	%	-20
5.	% external, economic:	99.9	99.9	%	0
	% imported goods	25.5	26.8	%	5
	% imported fossil fuels	33.2	35.2	%	6
	% import services, loans, tourism	41.2	37.9	%	-8
6.	% electricity	11.1	11.8	%	6
7.	Economic/environment ratio	773	964		25
8.	Population	1.58E+06	1.71E+06	people	8
9.	Solar emergy-use/area	5.62E+13	7.01E+13	sej/m2/yr	25
10.	Solar emergy-use/capita	1.91E+16	2.20E+16	sej/p/yr	15
11.	Fuel-use/capita	6.35E+15	7.75E+15	sej/p/yr	22
12.	Water demand/capita	145	146	gal/p/day	1

1987 emergy-use estimates based on 1987-92 % change for Puerto Rico (Doherty et al 1994):
(1992 San Juan emergy-use; Table 1) (1992-87 % change in emergy-use for Puerto Rico)
San Juan population from U.S. Department of Commerce (1992).
San Juan per capita water demand from PRASA (1992)

Emergy Basis for Trade

San Juan, Puerto Rico imported 1.3 times as much emergy as it exported in 1992, although this was down 16% from 1987 when it was 1.6. The net benefit from trade was 70E+20 sej. Expressed as a percentage of the island's annual emergy-use, this trade surplus represents over 10% of the total, down from 20% in 1987 (Doherty et al 1992).

These numbers contrast traditional accounts of trade advantage (Table 3). In 1992, comparing the dollar revenues received from exports (21.2 E+6 $) to the dollars paid for imports (15.2 E+6 $), a ratio of 1.4 is obtained. This is considered by economists as the net benefit San Juan and Puerto Rico receive due to external trade. When all resources are considered on common basis, however, Puerto Rico is shown to benefit only 1.2 times, less than is indicated by traditional accounts. More illustrative is the percent change in trade benefits from 1987 to 1992 according to both emergy and dollars. In economic terms, Puerto Rico's trade surplus has increased by 23% over 5 years. In emergy terms, however, the trade surplus is shown to have decreased by 24% over the same period.

But the net dollar revenues from trade (1.4 billion US$ in 1987 and 5.9 billion US$ in 1992) can be used to purchase additional products from abroad and the emergy value can be estimated with the emergy/GNP for the U.S., its major trading partner. Thus, an additional 2.8 E+21 sej and 9.4 E+21 sej were contributed annually through a positive net trade balance for 1987 and 1992, respectfully. Adding these amounts to the net emergy trade advantage of 11.1 E+21sej/yr and 7.0 E+21 sej/yr in 1987 and 1992, the actual trade advantage, in emergy terms, measures 13.9 E+21 sej/yr and 16.4 E+21 sej/yr for 1987 and 1992, representing an decline of only 14% in net emergy trade benefit over 5 years.

These analyses measure resource flows, which move in opposite direction of monetary flows. Therefore a trade advantage is measured by subtracting exported emergy from that received as imports, the opposite of economic accounts which measure benefits from trade by subtracting import costs from revenues received. Both of these measurements are useful and insightful.

Comparing emergy received per unit cost for imports (3.5E+12 sej/$) and emergy sent out per unit revenue received (2.27E+12 sej/$), an import/export price index of 1.7 is obtained. Puerto Rico receives more emergy per dollar spent than it exports per dollar received. If thought of as a measure of production efficiency, Puerto Rico and its manufacturing sectors in San Juan are shown to generate revenue at a lower emergy cost of production than its trading partners. In an exchange with trading partners, Puerto Rico receives, on average, more emergy per dollar.

Although Puerto Rico currently enjoys a net advantage due to external trade, this analysis suggests that the advantage has declined between 1987-92. Further, most of the island's production is supported by imported fuels and goods. Whether these commodities are available into the future and the climate of international trade are important considerations for San Juan, Puerto Rico whose economy is so dependent on external trade.

Table 3. Comparison of traditional economic and emergy accounts of external trade in San Juan, Puerto Rico between 1987 and 1992 (from Doherty et al 1994).

Market dollars (billion US$):

	Export revenues	Import costs	Net trade advantage	Export/import ratio
1987	12.1	10.7	1.4	1.13
1992	21.1	15.2	5.9	1.39

Solar emergy (10^{21} sej):

	Imported emergy	Exported emergy	Net trade advantage	Import/export ratio
1987	29.3	18.2	11.1	1.61
1992	38.7	31.7	7.0	1.22

Percent change in trade ratio from 1987-92:

market $	+ 23 %
solar emergy	- 24 %

Additional resources potentially purchased with net revenues received in external trade:
(market dollar value of net trade advantage) (U.S. emergy / $);
for 1987: (1.4E+9 US$) (2.0E+12 sej/$) = 2.8 x 10^{21} sej
for 1992: (5.9E+9 US$) (1.6E+12 sej/$) = 9.4 x 10^{21} sej

Adjusted incoming emergy = (import emergy) + (additional resources purchased with net market revenues):
in 1987: 29.3E+21 sej + 2.8E+21 sej = 32.1
in 1992: 38.7E+21 sej + 9.4E+21 sej = 48.1

Adjusted emergy import/export ratio = (adjusted incoming emergy) / (exported emergy):
for 1987: 32.1 / 18.2 = 1.76
for 1992: 48.1 / 31.7 = 1.52

Adjusted net trade advantage including resources purchased with net revenues:
(emergy value of net trade advantage) + (additional resources obtained with net market revenues):
for 1987: 11.1E+21 sej + 2.8E+21 sej = 13.9 x 10^{21} sej
for 1992: 7.0E+21 sej + 9.4E+21 sej = 16.4 x 10^{21} sej

Adjusted percent change in exchange ratio from 1987 to 1992:
(1992 ratio - 1987 ratio) / (1987 ratio) * 100% = (1.52 / 1.76) / 1.52 * 100 = -14%

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8. A Zonal Energy Simulation Model for Cities and Environment

Howard T. Odum

The zones of a city may be represented as a cross section from the supporting rural areas on the left to the concentrated center on the right. Energy and EMERGY for each zone of the a city may be presented in this one dimension and related to the concepts and hypotheses (Figure 1). One hypothesis is that the activities and functions of the city are organized according to the transformity, ranging from low, rural values on the left to high values for concentrated information on the right (Chapter 2).

In order to explore the consequences of the theory of Zonal City organization, the complexities of two dimensional landscapes were reduced for computer simulation to a chain of hierarchical blocks, each representing an aggregated concentric zone as measured from the dispersed rural areas to the center of the city (Figure 1). Then a simulation model was prepared based on the hierarchical principle that each block maximizes its function by interacting with the zones on either side, pumping land back and forth in proportion to the assets developed in that zone. In this chapter, the properties of a unit model of one block representing one zone are given. Preliminary simulations were made of 5 zonal blocks together (not included in this chapter).

The sketch in Figure 1 summarizes the base model and the way the zones are connected. In each unit, the production function generates zonal assets and population in proportion to the product of local environmental input (times its area), times flow from assets from the outer zone, times feedback from the next higher zone. In later versions a population stock was added to each of the 5 zonal units.

Figure 2 contains the unit model for one zone in more detail including a population storage. Although the letters in the diagram are for the agricultural zone, the results would be similar for other sectors. Equations are given as derived from the energy systems model. Numbers for calibration are written on the pathways. These numbers were entered into the calibration work sheet in Table 1 so that coefficients for the equations could be calculated. These equations were included in a program in BASIC that simulates the model. The program is listed as Table 2.

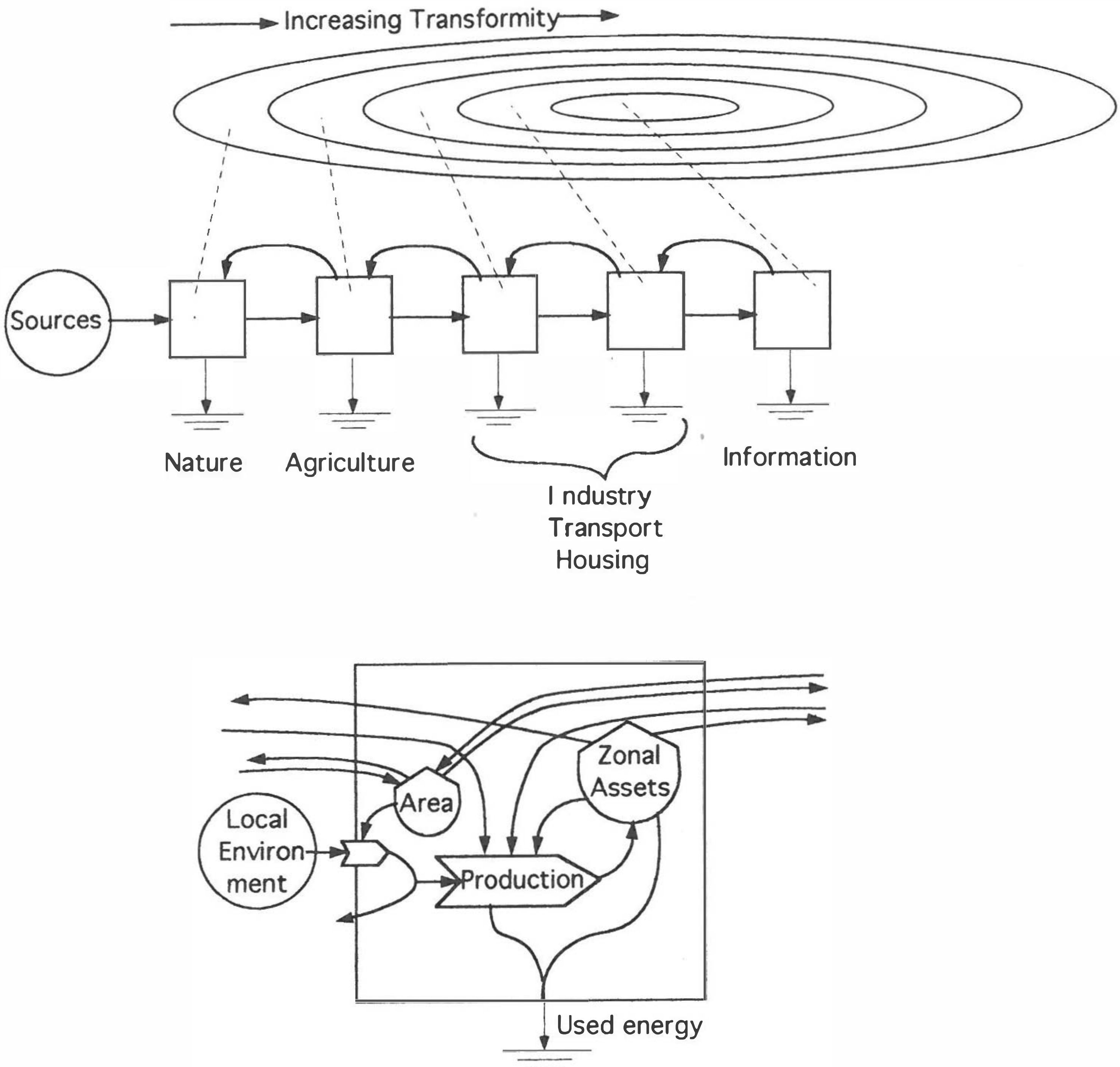
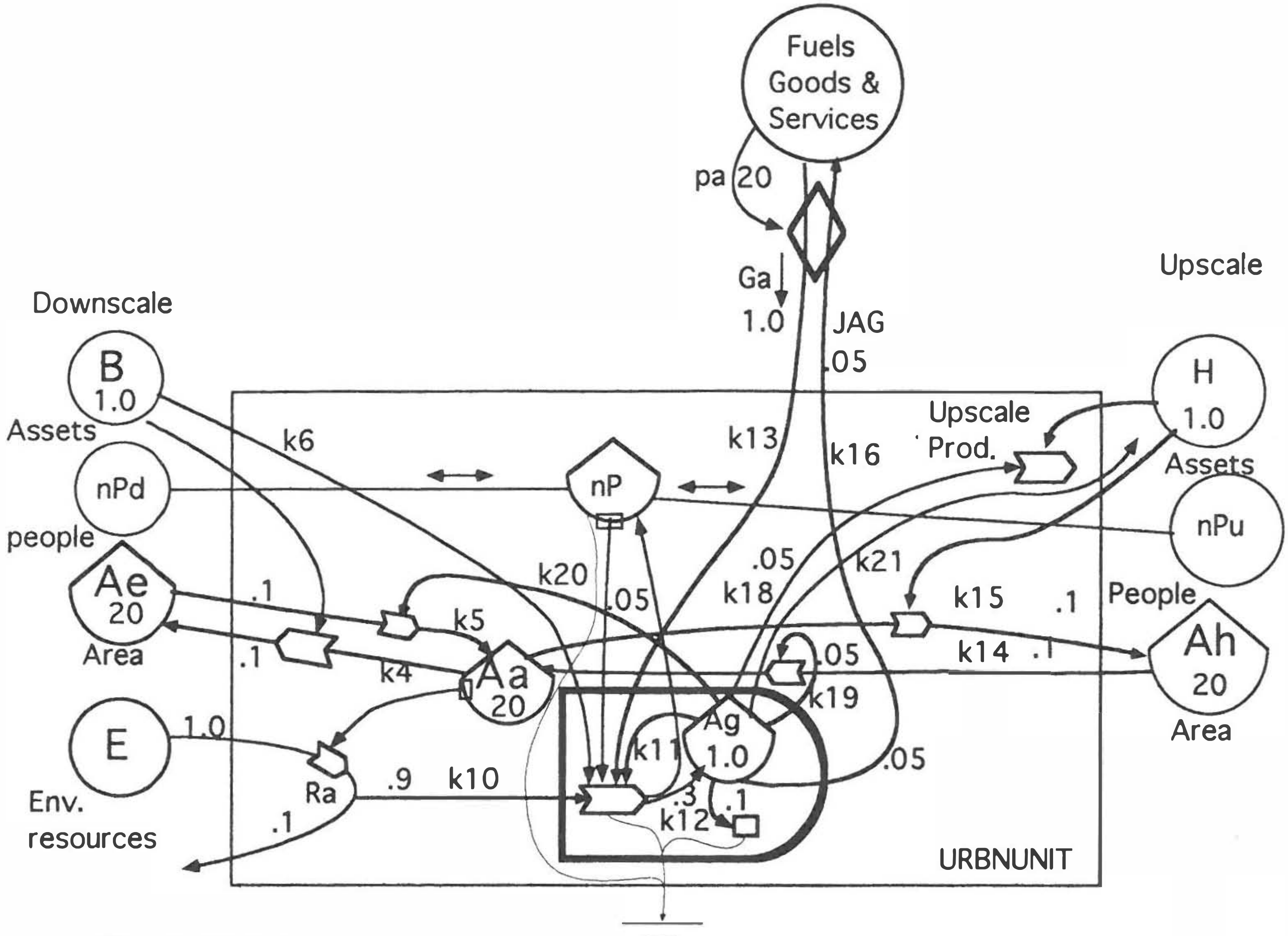


Figure 1. Main features of a simulation model of aggregated zones of a city organized as a serial energy hierarchy converging from left to right. Each zone is represented by one autocatalytic block.



$$PR = Ra*B*Ga*Ag$$

$$Jag = k16*Ag \qquad Ga = pa*Jag \qquad Ae = A - Ag - Ah$$

$$Ra = E*Aa - k10*Ra*B*Ga*Ag \qquad Ra = E*Aa/(1 + k10*B*Ga*Ag)$$

$$dAg/dt = k11*Ra*B*Ga*Ag - k12*Ag - k19*Ag*Ah - k18*Ag*H - k20*Ag*Ae - k16*Ag$$

$$dAa/dt = k5*Ae*Ag + k14*Ag*Ae - k4*B*Aa - k15*Aa*H$$

$$dAh/dt = k15*Aa*H - k14*Ah*Ag$$

Figure 2. Details and equations for one unit in the zonal simulation model of landscape. Abbreviations: E environmental inflow; Ae area of land in environmental zone (undeveloped areas and parks); Aa agriculture-aquaculture area; Ah Area of suburban housing; nPd, nP, and nPu are populations resident in these zones; B, Ag, and H are the structural storages, biomass, agricultural assets, housing; pa price of outside inputs; Ra local environmental resource unused.

Table 1

URBNUNIT.WK1

	Sources:	Math	Calib:	Side	Units	Coefficients:	
	Environmental inflow	E =	1	E6	m3/km2/yr		
	Environ. Remainders:	Environ. area Ra =	0.1	E6	m3/km2/yr		
	Imports(fuels,elect.,G&S)	Relative price pa =	20	E-6			
	Downscale Assets	B =	1	E7	m2 assets		
	Upscale Assets	H =	1	E7	m2 assets		
	Total Area available	A =	60	E6	m2 land		
	Down scale area	Ae =	20	E6	m2 land		
	Area in use	Ag =	20	E6	m2 land		
	Upscale area	Ah =	20	E6	m2 land		
	Storages						
	Use area	Aa =	20	E~~4~~ 6	m2 ~~assets~~		
	Assets	Ag =	1	E4	m2 assets		
	G & Serv avail. to Develop.	Ga=	1.00E+00		(normalized)		
	Flows						
	E use by assets	k10*Ra*B*Ga*Ag =	9.00E-01	E6	m3/km2/yr	k10=	0.45
	Production	k11*Ra*B*Ga*Ag=	3.00E-01	E4	m2 assets	k11=	0.15
	Assets depreciation	k12*Ag	1.00E-01	E4	m2 assets	k12=	0.005
	G&S used	k13*Ga =	1.00E+00	?		k13=	1
	Land moved from upscale	k14*Ah*Ag=	1.00E-01	E6	m2 land	k14=	0.005
	Land moved upscale	k15*Aa*H=	1.00E-01	E6	m2 land	k15	0.005
	Product export	Jag=k16*Ag=	5.00E-02	E4	Asset equival.	k16=	0.05
	Ag Land Aa to Env. area Ae	k4*B*Aa =	1.00E-01	E6	m2/yr	k4=	0.005
	Env. Land Ae to agr. Aa	k5*Ag*Aa =	1.00E-01	E6	m2/yr	k5=	0.005
	Assets used by upscale systen	k18*Ag*H=	5.00E-02	E6	m2 land	k18=	0.0025
	Assets use for upscale land	k19*Ag*As=	5.00E-02	E4	m2 assets	k19=	0.000125
	Assets use for downscale land	k20*Ag*Ae=	5.00E-02	E4	m2 assets	k20=	0.000125

Table 2
Simulation Program in BASIC

```
10 REM Macintosh
20 'URBNUNIT.BAS  (model of one Zone  of landscape & City)
25 REM  H.T.Odum & Shu-li Huang 1994
30 SCREEN 1,0:COLOR 0,1
33 X =0:REM  X=1 prints bars; X=0 prints time graphs
45 IF X =1 GOTO 57
47 LINE (0,0)-(240,180),3,B
50 LINE (0,70)-(240,70),3
55 IF X=0 GOTO 62
57 LOCATE 13,1
59 PRINT "              B     Ag    H
60 LOCATE 1,1
62 REM Sources
64 H = 1
66 B = 1
68 pa = .1
70 B = 1
80 Ae = 20
90 Ah = 20
100 E = 1
80 REM Starting Conditions
82 A = 60
86 Aa = 20
94 Ag = 1
96 Ah = 20
102 Ga = 1
110 REM Scaling factors
114 Ag0 = 10
116 Aa0 = 1
120 Ah0 = 1
122 dt = .5
124 T0 = 1
126 B0 =.1
128 H0 = .1
130 REM Coefficients
140 k4 = .005
142 k5 = .005
150 k10 = .45
152 k11 = .15
154 k12 = .005
156 k13 = .005
158 k14 = .005
160 k15 = .005
```

```
162 k16 = .05
166 k18 = .0025
168 k19 = .000125
170 k20 = .000125
300 Ae = A -Aa- Ah
302 IF Ae<0 THEN Ae = 0
303 Ra = E*Aa /(1+ k10*B*Ga*Ag)
318 Ga = pa*Jag
321 Jag = k16*Ag
325 dAa = k5*Ae*Ag +k14*Ag*Ah - k4*B*Aa -k15*Aa*H
327 DAh =k15*Aa*H  -k14*Ah*Ag
340 dAg = k11*Ra*B*Ga*Ag - k12*Ag - k19*Ag*Ah -k18*Ag*H
-k20*Ag*Ae - Jag
400 Aa =Aa + dAa*dt
403 IF Aa <0 THEN Aa = 0
406 Ah = Ah + DAh * dt
409 IF Ah <0   THEN Ah = 0
510 Ag = Ag +dAg *dt
515 IF Ag <.00001 THEN Ag = .00001
600 T = T + dt
5000 REM MC
5010 REM Bar graph
5020 REM PLOTTING graphs:
5030 IF X = 0 GOTO 5200
5035 LINE (0,0)-(240,180),,B
5040 LINE (50,180)-(50,180-B/B0),3
5050 LINE (50,180-B/B0)-(80,180-B/B0),3
5060 LINE (80,180)-(80,180-B/B0),3
5065 LINE (80,180)-(80,180-Ag/Ag0),3
5070 LINE (80,180-Ag/Ag0)-(110,180-Ag/Ag0),3
5080 LINE (110,180)-(110,180-Ag/Ag0),3
5090 LINE (110,179-H/H0)-(140,179-H/H0),3
5100 LINE (140,180)-(140,180-H/H0),3
5150 LOCATE 1,25:PRINT "yrs"
5160 LOCATE 1,15: PRINT T
5180 IF X = 1 GOTO 300
5200 PSET (T/T0,179-Ag/Ag0),3
5300 PSET (T/T0,70 - Aa/Aa0),3
6000  IF T/T0 < 240 GOTO 300
7000  IF pa <30 THEN pa = pa +1
7050  IF pa>30 GOTO 7200
7060 T = 0: Ag = .1: Aa = 20: Ah = 20
7100 GOTO 300
7200 STOP
```

A simulation of the unit model was made holding the assets and populations of the zones on either side constant. Land area for the 3 sectors is held constant, being pulled into the sector with the stronger assets. In the simulation in Figure 3, the price of the inputs of fuels goods and services is varied. When the price is high, the assets within the zone do not develop, and the area is drawn away into the surrounding zones. When the price is lower, there is enough inputs to cause growth of the sectors assets up to the point where they are limited by the local environmental resources with which they must interact in the production function and by land available for expansion in the surrounding zones.

Not reported here are preliminary results of simulating the 5 unit model with outside inputs only to some zones, using normalized data starting with a rural landscape in a wilderness state. Gradually the other zones develop, each pulling area from the less central area to its left.

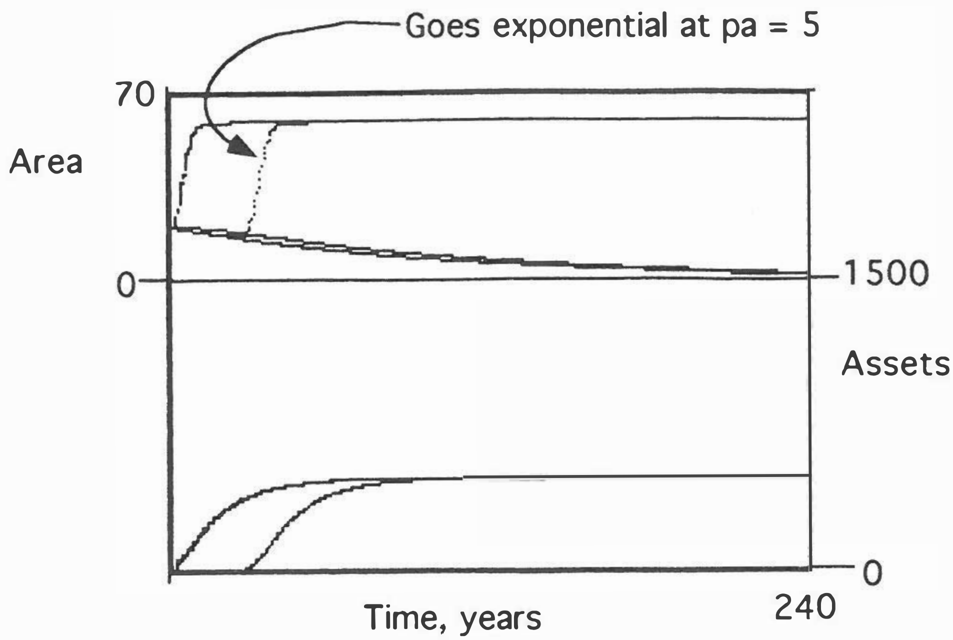


Figure 3. Simulation response of the unit model diagrammed in Figure 3 when pa (price of fuels-goods-services) is varied and the Assets and populations in adjacent zones are constant.