THE NATURAL ENERGY BASIS FOR SOILS AND URBAN GROWTH IN FLORIDA

By

Edward Joseph Regan, Jr.

University of Florida

1977

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A Thesis Presented to the Graduate Council of the
University of Florida in Partial Fullfillment of the
Requirements for the Degree of Master of Science

University of Florida
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ACKNOWLEDGEMENTS

This thesis draws on the work and inspiration of many, and in particular I wish to express appreciation to: Dr. H.T. Odum, whose language, enthusiasm, great knowledge and free spirit can only be described as an energy source; Bob Costanza for plunging into cosmic exploration and for laughing at frustrations; Tim Gayle and Ed DeBellevue for their encouragement; and Dr. Suzanne Bayley for her early critique of the methodology and constant concern for practicality. I am also deeply grateful for the moral support of Dr. Calvin Adams, who first gave me a taste for science.

Work was supported by a contract between the Energy Research and Development Administration E-(40-1)-4398 with the University of Florida, H.T. Odum, Principal Investigator, and a subcontract with Cornell University #0AF853, contracting with the National Transportation Advisory Board #HP20-11B on energy analysis of transportation alternatives.

Special thanks to Joan Breeze and Patricia Srna for their assistance in preparing the final manuscript, and to Nancie Lehman for the final typing.

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THE NATURAL ENERGY BASIS FOR SOILS AND URBAN GROWTH IN FLORIDA

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Edward J. Regan, Jr.

August 1977

Chairman: Howard T. Odum
Major Department: Environmental Engineering Sciences

The role of natural energies in stimulating economic development was studied with respect to urban growth in Florida. The study presents models, methods and quality factors for quantifying the natural energies of sun, waves, rain, aquifer water storage, ecosystem productivity, and mineral and organic soils. Additive and multiplicative models of the interaction between natural energies and fossil fuel in urban productivity were evaluated with and without feedback from urban structure and correlated with the rate of change of population as an indicator of urban and economic growth. Models were tested with data for 67 counties of Florida from 1920 to 1975.

A simulation model of soil formation in Florida which produced a steady state in about 300 years was evaluated. The time, processes, energy fluxes and successional dynamics required to form soil were used to estimate the energy embodied in mineral soils as about 8000 calories of sunlight per calorie of soil organic matter. Energy costs of organic soils were estimated from an energy analysis of Everglades peat formation as about 1000 calories of sunlight per calorie of peat. Population growth rates and natural energies were significantly correlated. When feedback from structure was incorporated, the models accounted for over 80% of the variance in the rate of urban growth. Analysis of separate factors with stepwise multiple regression indicated a changing structure of natural energy interactions for 1930, 1965-1975, and 1975. Importance of mineral soil and rain energy declined, and sun and wave energy increased.

H T Odum

Chairman

INTRODUCTION

The natural energies of sun, waves, rain, soil and vegetation contribute to the economic vitality of Florida, interacting with fuels in economic development (Browder, 1976). How do the patterns of natural energy interact with economic development? Has the pattern of interaction changed as man's systems evolved under the recent regime of cheap fossil fuel? Which natural energies are more strongly associated with urban growth?

In previous studies additive and multiplicative energy models with and without feedback from urban structure have been used to quantify the natural energy interactions of Florida (Odum and Brown, 1977; Boynton, 1975; and Kemp, 1977). The aptness of these different methodologies can be tested against economic indicators empirically, and the relative importance of individual natural energies at different points in time measured. To do so, nine methods of calculating the natural energy signatures for the 67 counties of Florida were correlated with economic productivity since 1920. Growth rates of urban structure were chosen as a measure of economic productivity and were estimated from population data, since population is the urban indicator which has been the most accurately reported for the longest time. Empirical relationships between the rate of change of population and rate of changes in housing, gasoline consumption, taxable sales and property valuations were used to test population change as an indicator of energy embodied in urban structure.

The measurement of the distribution of natural energies was a prerequisite. Data on most of the natural energy flows had been assembled for South Florida by Costanza (1975), but not the stored energy of the land surface. Soil is the part of land in which the integrated effects of most of the natural energy flows of an area may be stored. Gilliland (1975) developed a model and simulated the processes of land differentiation and phosphorus formation. A model was required for energy analysis, simulation, and calculation of energy costs and storages in the formation of Florida's mineral and organic soils. This was necessary since the energy embodied in soil was one of the factors included in the models of production that were correlated with urban growth.

The form of statistical analysis used to test the models employed a variation of a random block design with repeated measures subjected to regression analysis using the 67 counties of Florida as analysitcal units (Cox, 1971; Chichetti, 1975). Models are given in energy languages (Odum, 1971), symbols and explanations are in Appendix A. Because of the changing population and energy conditions historically, energy models were tested in three time periods. The first was tested for 1920 data, the second a pooled analysis for data for 1965, 1970 and 1975, and the third period included only data for 1975.

Theoretical Considerations

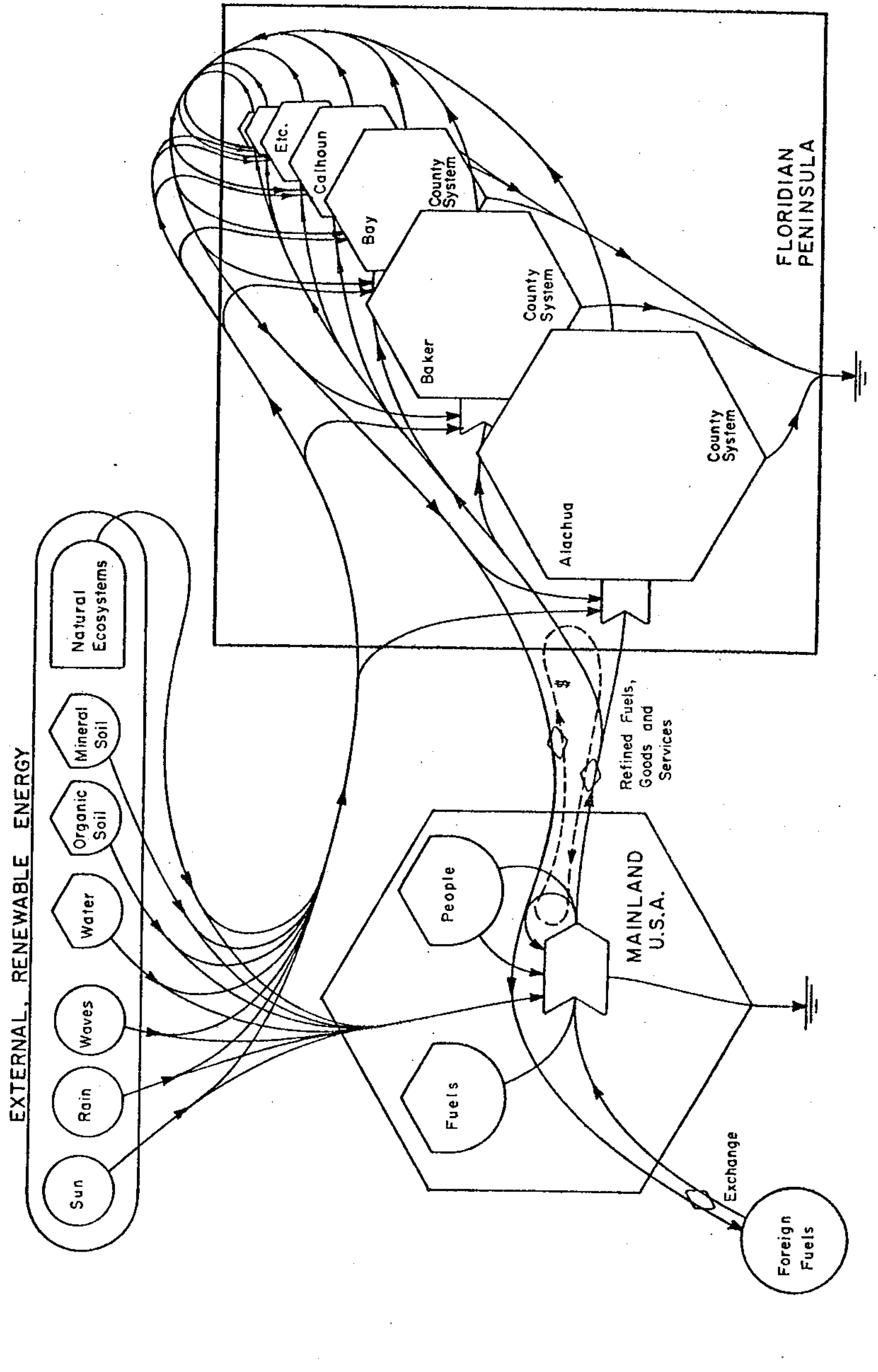
Considerations of energy theory and previous modelling efforts by others suggest several alternative models for production and growth in terms of the environmental and purchased energies available to an area.

Energy Theory of Urban Growth Based on the Interaction of Natural Energies

The maximum power principle formulated by Lotka (1922) was used by Odum (1971) to account for the design of systems of man and nature. Corollaries are proposed (Odum, 1974; Odum and Odum, 1976) which suggest that surviving systems use all energies interacting so that those of greater ability at amplification control those of large quantity. Maximum power was predicted when natural energy and fossil fuel energies were used together.

Most of the urban growth in Florida since 1920 has been facilitated by immigration. As shown by the model in Figure 1, each area, or county, has a unique set of attributes measured by its energy flow, which is its energy signature. The theory to be tested is that the total energy flow and signature of a county determines the proportion of the total immigration which is attracted to that county. It is proposed that population is part of the developing structure which contributes to energy flows, helping to maximize power. During times of expansion, growth centers develop competitive advantage over other areas with the same natural resources. The growth centers' storages of assets and information feedback to make their production and growth higher. As the growth period is passed the storages are less important. Population levels may then be expected to depend on steady energy inflows within the area and those attracted and purchased from outside. The natural energy signature of a county may correlate with population levels during growth and after growth ceases, if productivity depends on interaction of fossil fuel energies with natural energies.

Figure 1. Energy model showing competition among the counties of Florida for population and energy fluxes from the mainland U.S.A. Symbols are explained in Appendix A.


EXTERNAL, RENEWABLE ENERGY
Sun
Rain
Waves
Water
Organic Soil
Mineral Soil
Natural Ecosystems
People
Fuels
MAINLAND U.S.A.
Foreign Fuels
Exchange
$
Refined Fuels, Goods and Services
FLORIDIAN PENINSULA
Alachua
County System
Baker
County System
Bay
County System
Calhoun
Etc.

Energy Model of Urban Growth in a County

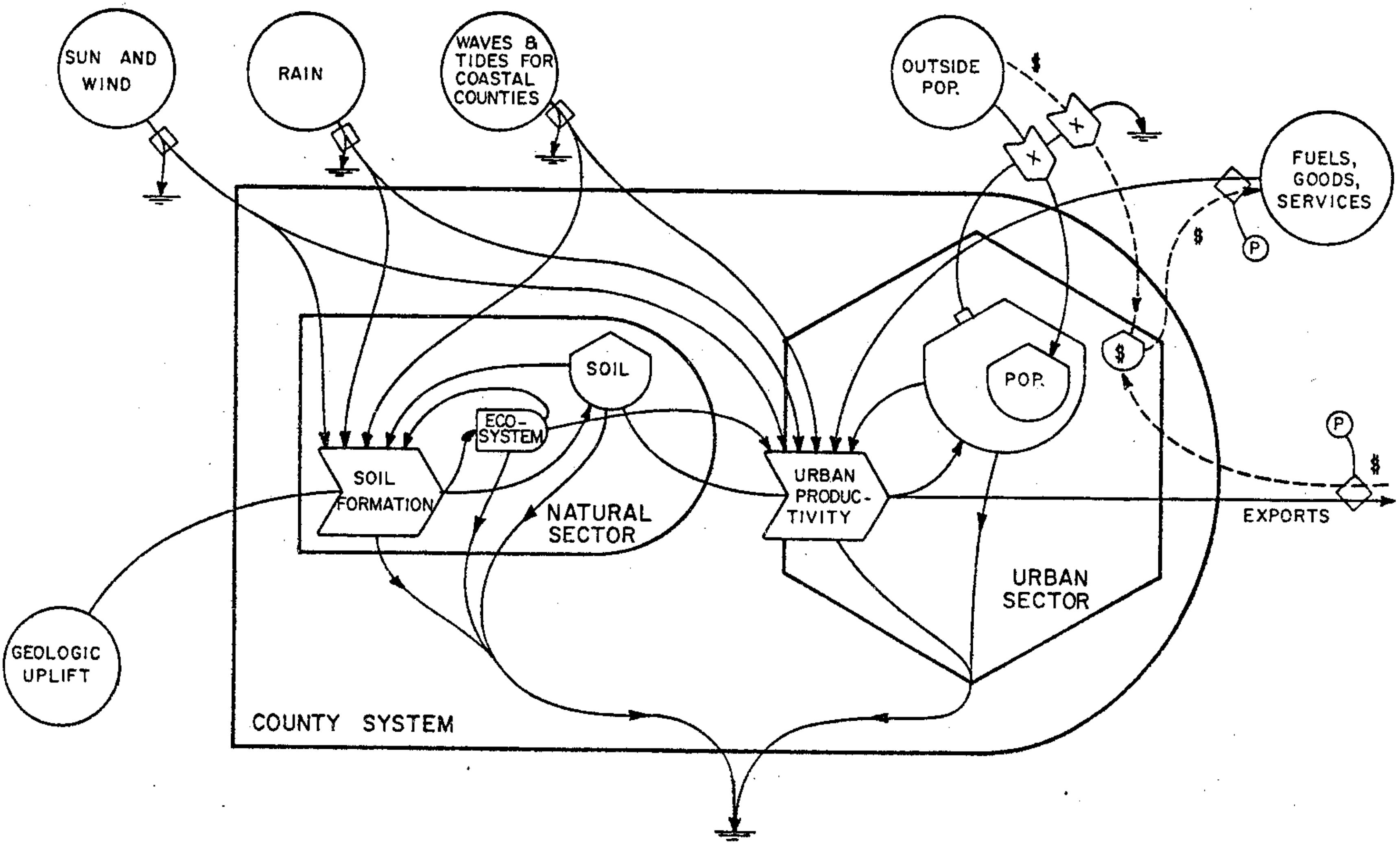
The energy model shown in Figure 2.summarizes the hypotheses for urban growth based on energy flows. It includes functions which this study evaluates: production by vegetation that generates soil; and urban production. The energies embodied in soil storage enter the urban productive process. The urban productive process shown includes agricultural, industrial and recreational sectors.

Solar, wind, rain, tide, and wave energies are renewable but limited flows entering the system from outside. The natural energies are shown entering directly into the soil and urban productive processes. In the natural sector, these energies interact with geologic uplift to provide parent materials which are further worked upon and structued by vegetation to produce soils.

In the urban sector, the natural energy flows and storages interact with fossil fuels in the productive process, for example, building beaches, providing suntans, panoramic vistas, watering lawns and providing crops. Outputs from urban production are either exported and exchanged for money or embodied in building and maintaining structure. Money, in turn, is used to buy fuels, goods and services, which enter into the productive process. Tourists and immigrants bring money into the system, hence contributing to productivity by enabling more fuels, goods and services to be bought.

The changing availability of world energies and population may have an effect on the rate of urban growth. The interaction of natural energy, population flow and fossil fuel may change because of differentially increasing prices of imported fuels.

Figure 2. Energy model of county economy showing productivity of vegetation generating soil and energy flows of urban productivity.


SUN AND WIND
RAIN
WAVES & TIDES FOR COASTAL COUNTIES
OUTSIDE POP.
$
X
X
FUELS, GOODS, SERVICES
$
P
SOIL
ECO-SYSTEM
SOIL FORMATION
NATURAL SECTOR
POP.
$
URBAN PRODUC-TIVITY
P
$
EXPORTS
URBAN SECTOR
GEOLOGIC UPLIFT
COUNTY SYSTEM

Quality Factors

Because some energy flows have more energy embodied in their form than others, one theory suggests that flows should be in units of similar energy quality.

There are two types of quality factors which have been developed in order to compare heat calories of widely divergent types with regard to the useful work they can do. Energy effect quality factors measure the energy gain achieved by investing a calorie in a process (amplifier effect). Energy cost quality factors measure the calories required to produce a calorie of a specific type. Both forms are referenced to sunlight or fossil fuel. Energy effect quality factors have the disadvantage of being process-dependent, while energy cost quality factors have the advantage of having a thermodynamic minimum. Theories have emerged which indicate that in general, the energy effect of a storage may be related to its energy cost. Dollars are another quality measure, but do not include externalities, hence their relative values are always changing.

Alternative Production Functions

In the general model for production of soil and urban growth in Figure 2, the mathematical nature of the interactions to generate productive output were not specified. There are several alternative theories about the interactions of energy and resulting contributions to growth.

Beginning with Liebig's work in the 1840's, researchers have determined the properties which contribute to a soils productive capacity. Mitscherlich extensively replicated the earlier work of Liebig and derived the equation which described the general shape of the functional relationship between yield (net primary productivity) and any factor which was potentially limiting:

$$dy/dSn = Kn[Ymax - y] \qquad (1)$$
$$y = Ymax[1-e^{-Kn\ Sn}]$$

where:

y = yield

$Ymax$ = maximum yield obtainable

Sn = any soil nutrient

Kn = constant

It was assumed that Kn was a universal constant (Jenny, 1941, p. 251). An alternative theory for the same limiting factor relationship has often been called Michaelis-Menton or Monod equation, for example where:

$$P = \frac{K_1 J}{1 + K_2 J} \qquad (2)$$

where:

J = limiting factor

P = Productivity

$K_1 K_2$ = constants

The Monod equation was used to simulate the limiting effect of sunlight in the soil formation model.

Simple addition of energy flows expressed in calories of cost of the same energy quality was tried in a study of production in South Florida by Costanza (1975). Simple multiplication of energy flows is given in production functions for many kinds of systems by Odum (1971). The Monod equation was derived from the multiplication model when one flow was limited at its source. Multiplication of energy flows with empirically determined exponents is done in economics with the Cobb

Douglas function (Allen, 1967). Long traditional in population models of growth is a feedback product from storage to production so that growth is proportional to existing storage (Lotka, 1925). Additive or multiplicative production functions can include the feedback.

Direct empirical testing of these various models is needed with data on observed growth.

Models of Soil Formation and the Soil Forming Factors

Theoretical equations for soil formation have appeared in soil science literature since 1898, when Dokuchaev was credited with publishing the first factor equation for soil formation (Jenny, 1961). The equation was of the form:

$$S = f(cl, o, p) \qquad (3)$$

where S is soil, cl is climate, o are organisms and p represents the "geologic substration."

Jenny (1941) expanded this initial equation to the now well known form which is expressed below. While Jenny was able to demonstrate instances of correlation which validated each of the factors in his equation, he did not synthesize all of the factors into a unified model.

$$s = f[cl, o, r, p, t...] \qquad (4)$$

where: s = soil

cl = climate

o = organisms

r = topography

p = parent material

t = time.

Jenny's factor equation of soil formation (1) contains both passive (topography, parent material) and active soil forming factors (organisms, climate, ...). The relative importance of the active soil forming factors was expressed by Joffe (1949):

> "Different parent materials give rise to the same kind or type of soil whenever the principle factors of soil formation, the climate and biosphere are the same . . . similar parent materials give rise to a different kind or type of soil, provided the principle factors are dissimilar."

Jenny (1941) hypothetically expanded his factor equation to:

$$ds = \left(\frac{\delta s}{\delta cl}\right)_{o,r,p,t} \cdot dcl + \left(\frac{\delta s}{\delta o}\right)_{cl,r,p,t} \cdot do + \left(\frac{\delta s}{\delta r}\right)_{cl,o,p,t}$$

$$\cdot \; dr + \left(\frac{\delta s}{\delta p}\right._{cl,o,r,t} \cdot dp + \left(\frac{\delta s}{\delta t}\right)_{cl,o,p,r} \cdot dt \qquad (5)$$

Several workers argued that Jenny's treatment of time as a separate soil forming factor was inaccurate in that the state of the soil was better defined as the integrated effect of the soil forming factors over time and that the factors most likely interacted with each other (Crocker, 1952). Wilde, published the modified equation:

$$s = \int f(cl, o, r, w, p)\, dt \qquad (6)$$

which included water table (w) as a soil forming factor (Crocker, 1952). Wilde did not present a structure for the interation of the factors.

Jenny's Storage Equation

Jenny (1941) presented equations of storage for soil properties, such as nitrogen, whose depletions limited the productive function. He expressed storage depletion processes with the differential equation (7).

$$\frac{dN}{dt} = -k_1 N; \; N = N_o e - k_1 t \qquad (7)$$

Storages reach an equilibrium that depends on balance of productivity and losses (equation 8).

$$\frac{dN}{dt} = k_2 - k_i N \qquad (8)$$

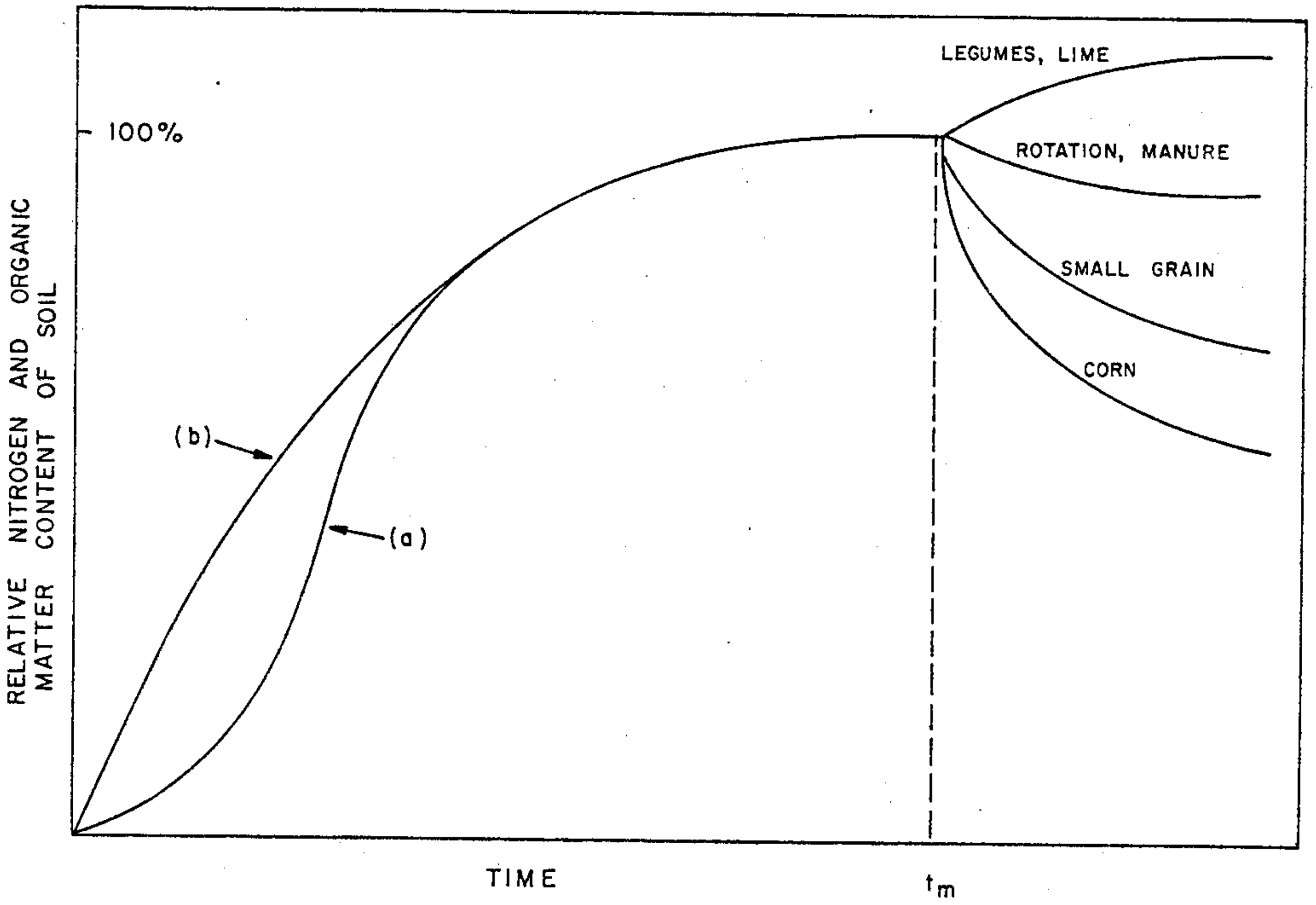
Equation (9) is the integrated form.

$$N = \frac{k_2}{k_1} \left(1 - e^{k_1 t}\right) \qquad (9)$$

Computer simulations of litter formation with the model were done by Olson (1963). A hypothetical simulation of Jenny's model is presented in Figure 3.

Soil is an integral part of ecosystem functioning, and is formed by the ecosystem in primary succession (Witkamp, 1971). There are many examples of ecosystem simulation models, some of which have incorporated aspects of soil into their structure, mostly as a storage of organic material. For example Botkin (1976) simulates forest succession over a 380 year period with a model of which includes soil organic matter and moisture. Apparently, few models have been specifically aimed at simulation of soil formation.

Figure 3. Hypothetical illustration of nature's building up of soil fertility and its modifications by man (modified from Jenny, pg. 257, 1941). (a) Original curve; (b) soil growth curve used in later work based on linear accumulation ($\dot{Q} = J - kQ$).


100%
RELATIVE NITROGEN AND ORGANIC MATTER CONTENT OF SOIL
(b)
(a)
LEGUMES, LIME
ROTATION, MANURE
SMALL GRAIN
CORN
TIME
t_m

Organic Matter

The work of sunlight and earth processes acting through vegetation to develop soil includes development of organic matter in the soil, much of which is structured and complex including roots, microbes, colloid structures, animals, bound nutrients such as phosphorus and nitrogen, base exchange capacity, etc. Some of this energy is stored in the chemical potential energy of organic matter that can be measured as heat of combustion in calorimetry. Other energy embodied is no longer stored, but was passed through in the process of developing the complex structure.

Pedologists have long recognized the importance of the organic cycle upon soil formation, as some have gone so far as to indicate that weathering is differentiated from soil formation by the accumulation, breakdown and translocation of organic material (Nikiforoff, 1942; Crocker, 1952).

The many functions of organic matter in soil have been summarized by Joffe (1949, pg. 83):

> "1) Organic matter, upon humification and mineralization, supplies the reagents, such as carbonic and other inorganic and organic acids, that react with the mineral components of the soil. These reagents set off a series of reactions which release desirable and sometimes undesirable substances for plants and are the starting point in the creation of the soil body.
>
> "2) CO_2 released in the process of humification and mineralization, besides forming carbonic acid, becomes available for atmospheric absorption by the plant.
>
> "3) The bases and other mineral constituants released in the processes of humification and

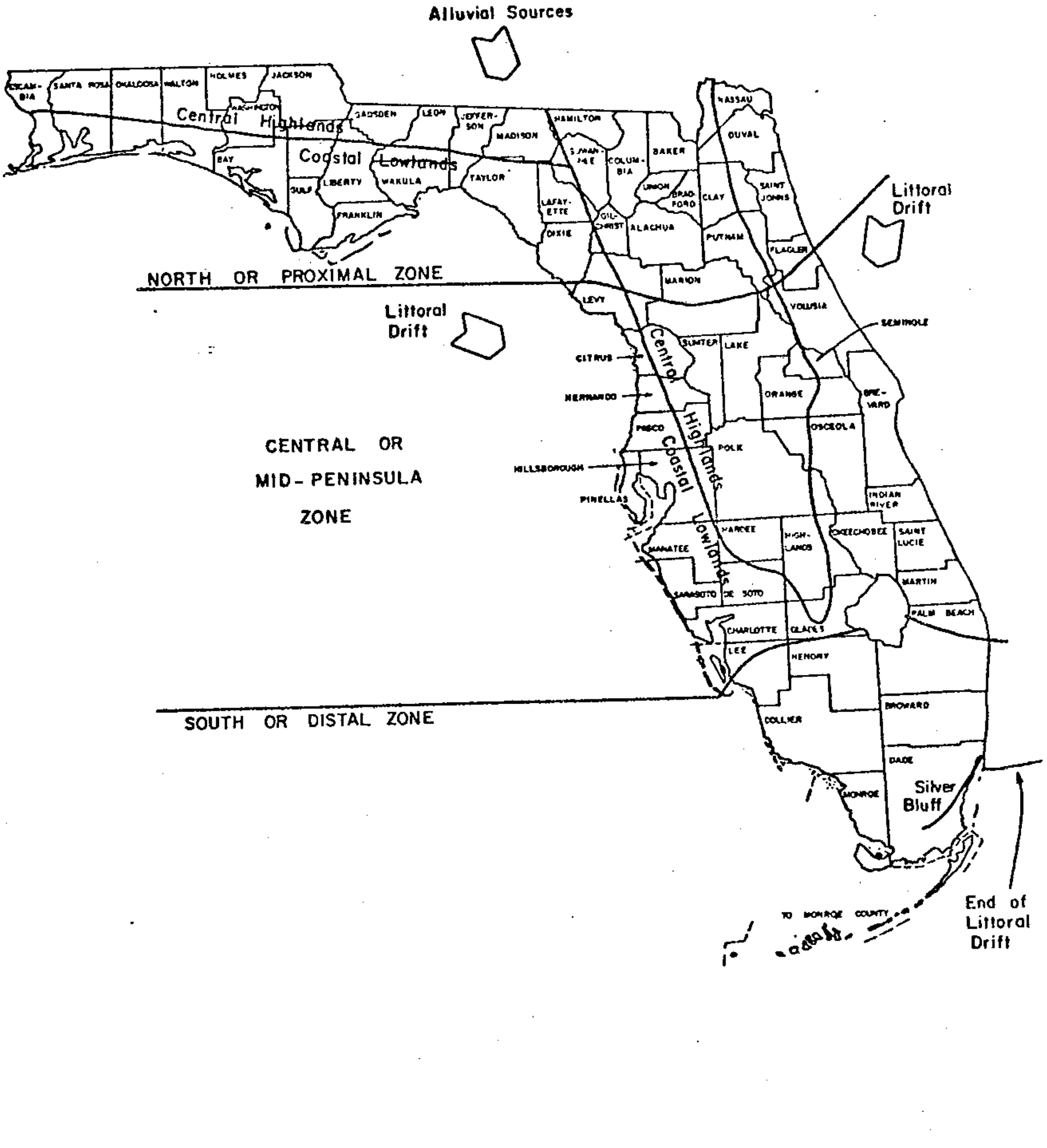
> mineralization, serve as the primary source of the natural supply of plant nutrients. They, like the acids produced in these processes, are active in shaping the soil body. The bases help to regulate the acidity and alkalinity of the soil.
>
> "4) Stabilization of the structure of the soil (through colloidal action).
>
> "5) The humified portion of organic matter, the humus, has a considerable capacity to absorb cations, the degree of absorption increasing with the stage of decomposition.
>
> "6) Organic matter plays an important part in regulating the moisture regime of the soil. As organic matter decomposes, its capacity for water increases."

Study Area

Correlations of growth with models of energy flow and storage were made for 67 counties of Florida as shown in the map in Figure 4.

Florida has a wide range of independent variation in natural energies. The shallow and flat topography of South Florida's toe thickens northward to provide variation in aquifer water storage. Florida's east coast has relatively large waves compared to the west coast, enabling comparisons of relatively high and low energy coastlines. Rainfall is most intense in the southeast and northwest corners of the state, diagonal to the perpendicular factors of aquifer storage and wave energy. Because of the relatively complex geological history of the state, soil types are scattered throughout. For statistical correlations it was possible to treat the energies of sun, rain, stored water, waves and soils as independent factors.

Figure 4. Map of study area showing the spatial distribution of soil parent material origins and the boundaries of counties. Coastal Lowlands and Central Highlands discriminations after Cooke (1949); Proximal, Mid Peninsula, and Distal Zones after White (1970).


Alluvial Sources
Littoral Drift
Central Highlands
Coastal Lowlands
NORTH OR PROXIMAL ZONE
Littoral Drift
CENTRAL OR MID-PENINSULA ZONE
Central Highlands
Coastal Lowlands
SOUTH OR DISTAL ZONE
Silver Bluff
End of Littoral Drift
ESCAMBIA
SANTA ROSA
OKALOOSA
WALTON
HOLMES
JACKSON
WASHINGTON
BAY
CALHOUN
GULF
LIBERTY
FRANKLIN
GADSDEN
LEON
WAKULA
JEFFERSON
MADISON
TAYLOR
HAMILTON
SUWANNEE
LAFAYETTE
DIXIE
COLUMBIA
GILCHRIST
BAKER
UNION
BRADFORD
ALACHUA
NASSAU
DUVAL
CLAY
SAINT JOHNS
PUTNAM
FLAGLER
MARION
LEVY
VOLUSIA
SEMINOLE
CITRUS
SUMTER
LAKE
HERNANDO
ORANGE
BREVARD
PASCO
OSCEOLA
POLK
HILLSBOROUGH
PINELLAS
INDIAN RIVER
HARDEE
HIGHLANDS
OKEECHOBEE
SAINT LUCIE
MANATEE
SARASOTA
DE SOTO
MARTIN
CHARLOTTE
GLADES
PALM BEACH
LEE
HENDRY
COLLIER
BROWARD
DADE
MONROE
TO MONROE COUNTY

Calculations of energy costs of soil and simulations of soil formation were made with data from Florida. The complex geologic history of the Floridian Peninsula renders the origin of parent material for a particular soil somewhat controversial. Based on a review of the spatial distribution of geological processes and major soil orders, Florida's mineral soils can be characterized by two sources of parent material.

Very sandy soils were formed with imported material, consisting of the result of weathered and washed granite form the Piedmont plateau. The spatial distribution of transport processes of this parent material are shown in Figure 4. The deposited soils may have only rainfall for a nutrient source, as silicates such as quartz weather very slowly and contain few nutrient ions.

The other category is sedentary soil resulting from the in-place weathering of limestone. The sedentary soils are essentially continuous with the parent material beneath, which may provide a significant source of nutrients, as in the model of Figure 2. The major functional differences between these two soils is the rate of mineral influx.

Soils with more than 20% organic matter (histosols) are prevalent in Florida, covering 7 percent of the state's total area, with the Everglades of South Florida comprising the largest single deposit of peat (Beckenbach and Hammet, 1962). Organic soils have been evaluated separately from mineral soils.

METHODS

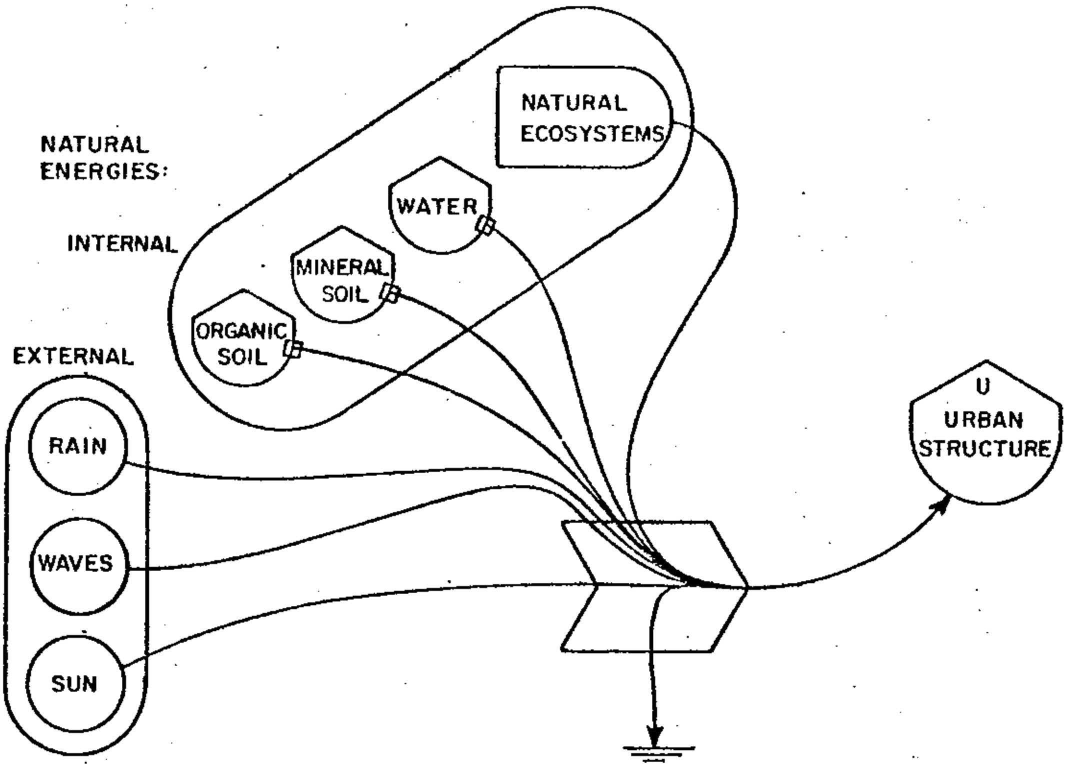
Plan of Study

A model of soil was developed and evaluated for Florida conditions. The model was simulated to obtain curves of soil formation. From the model and the time of formation, energy costs of mineral soil formation were estimated. An energy quality factor for mineral soils was calculated in terms of solar calories. Energy cost of developing peat soil was also calculated from the history of Everglades peat.

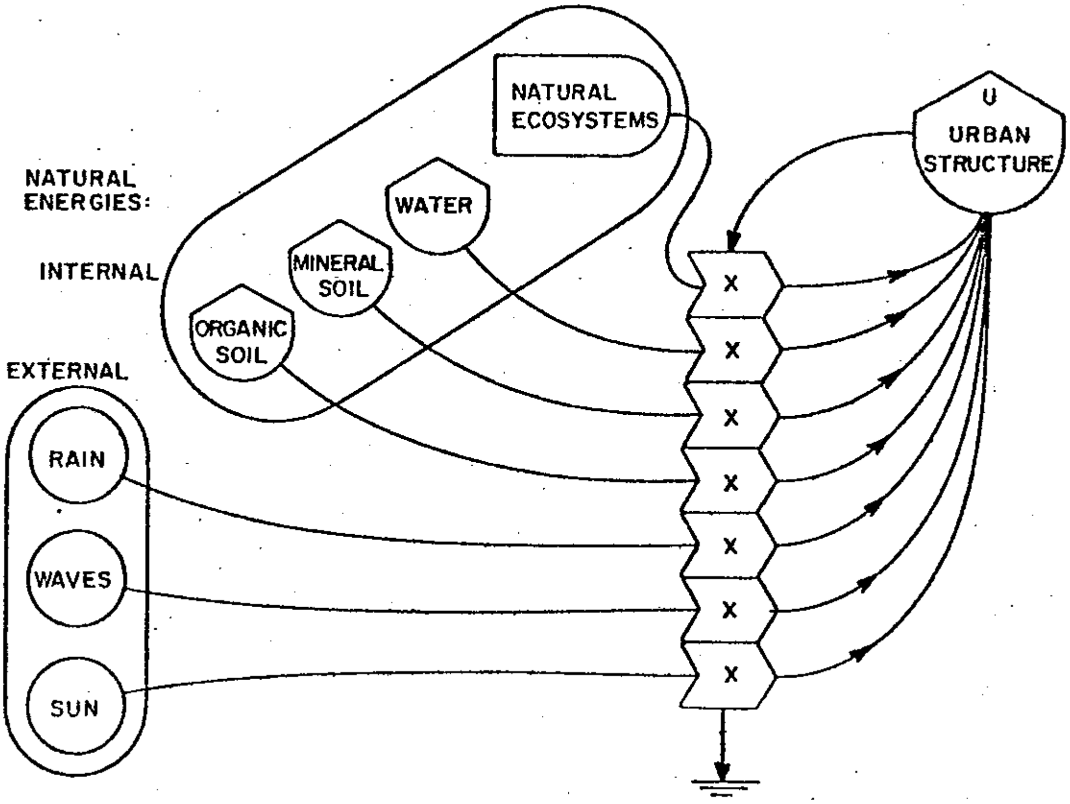
Alternative models of productive contribution to urban growth were defined and diagrammed as given in Figures 5 and 6. The outputs of the models (products, sums, etc.) were statistically correlated with urban growth using population as an indicator. Evidence that population could be used as an indicator of the energy embodied in urban growth was sought with statistical correlations between population growth and growth of some energy characteristics of urban economy.

The correlation of inputs to productive functions with population growth was done for three periods in the history of this century, examining the relative importance of different environmental energies at different times. A linear empirical multiple correlation was also run between the environmental flows and storages versus urban growth. Details of these procedures follow.

Figure 5. Energy models of additive natural energy interactions. (a) Additive interaction without feedback from structure; (b) separated processes, each with multiplicative feedback from structure, additive interaction.


NATURAL
ENERGIES:
INTERNAL
NATURAL
ECOSYSTEMS
WATER
MINERAL
SOIL
ORGANIC
SOIL
EXTERNAL
RAIN
WAVES
SUN
U
URBAN
STRUCTURE

(a)


NATURAL
ECOSYSTEMS
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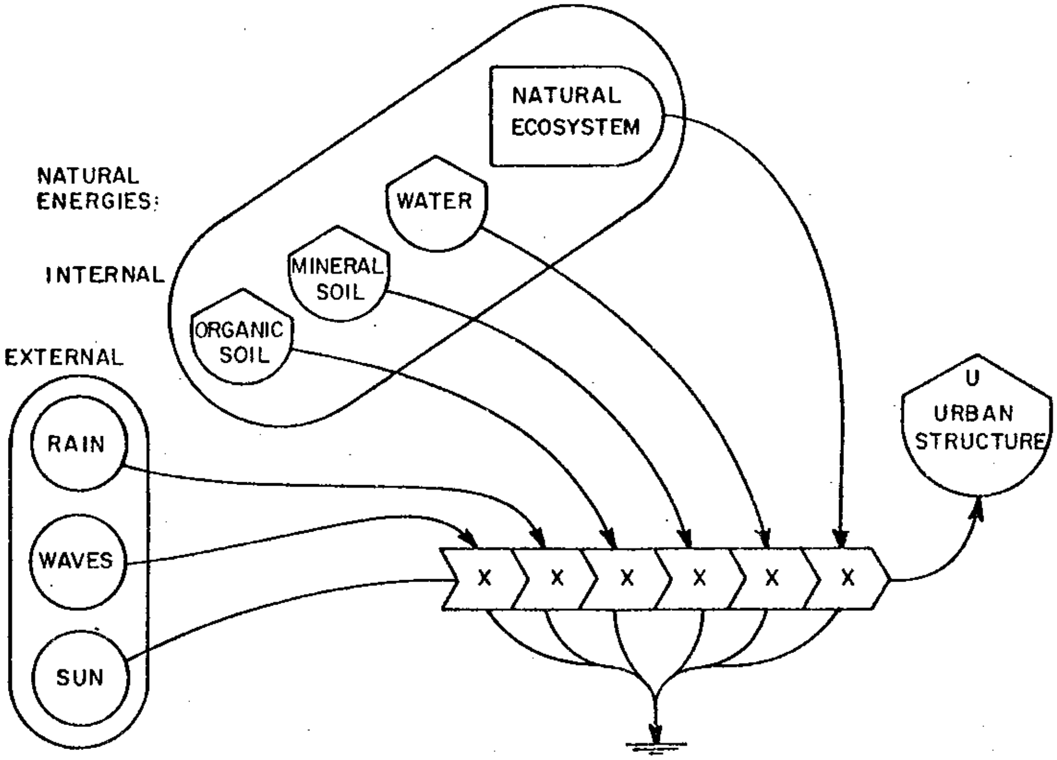
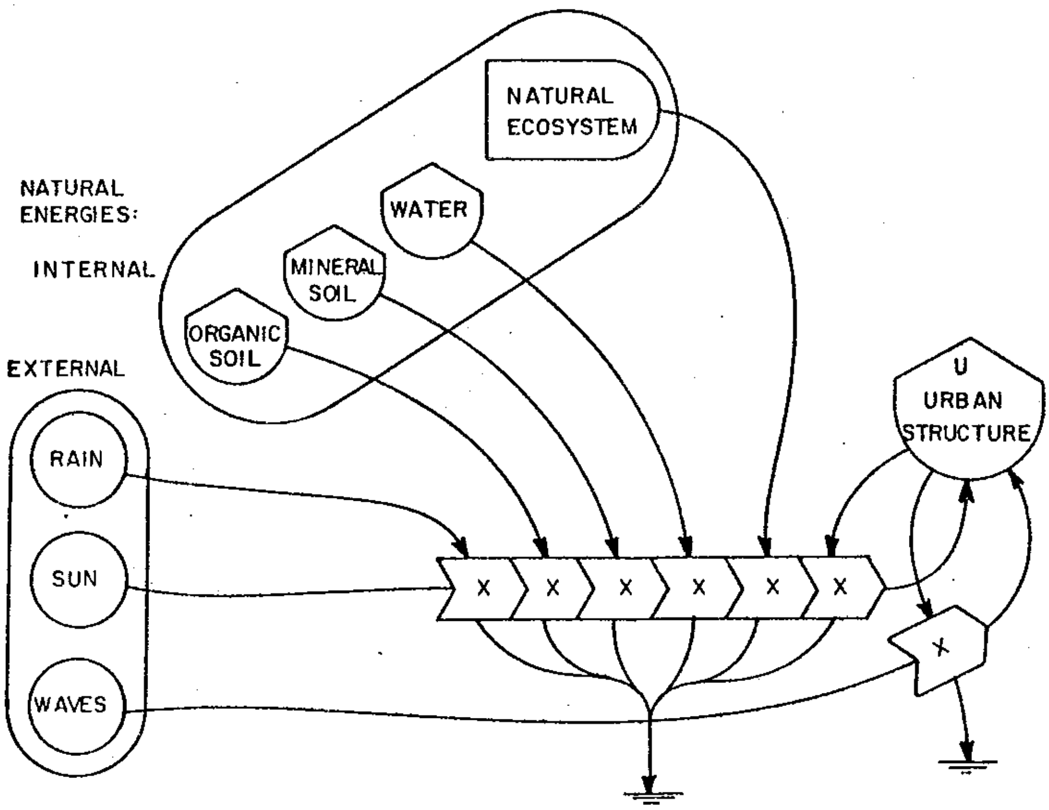
SOIL
ORGANIC
SOIL
EXTERNAL
RAIN
WAVES
SUN
U
URBAN
STRUCTURE
X
X
X
X
X
X
X

(b)

Figure 6. Energy models of multiplicative natural energy interactions. (a) Multiplicative single process interaction without feedback from structure; (b) multiplicative interactions with feedback from structure, terrestrial and coastal processes separated; (c) Model of urban growth with square drain on structure.


NATURAL ENERGIES:
INTERNAL
EXTERNAL
NATURAL ECOSYSTEM
WATER
MINERAL SOIL
ORGANIC SOIL
RAIN
WAVES
SUN
X
U
URBAN STRUCTURE

(a)


NATURAL ENERGIES:
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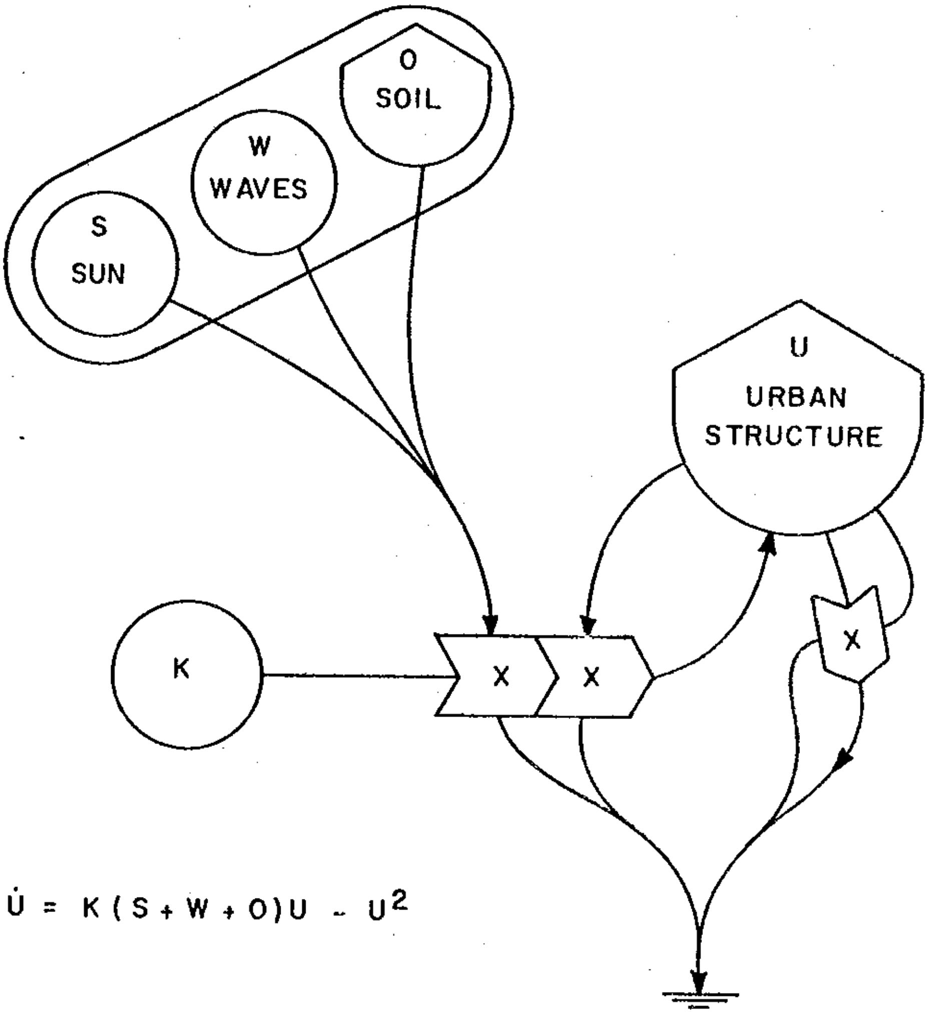
(b)



$$\dot{U} = K(S + W + O)U - U^2$$

(c)

Evaluating the Energy Embodied in Soils

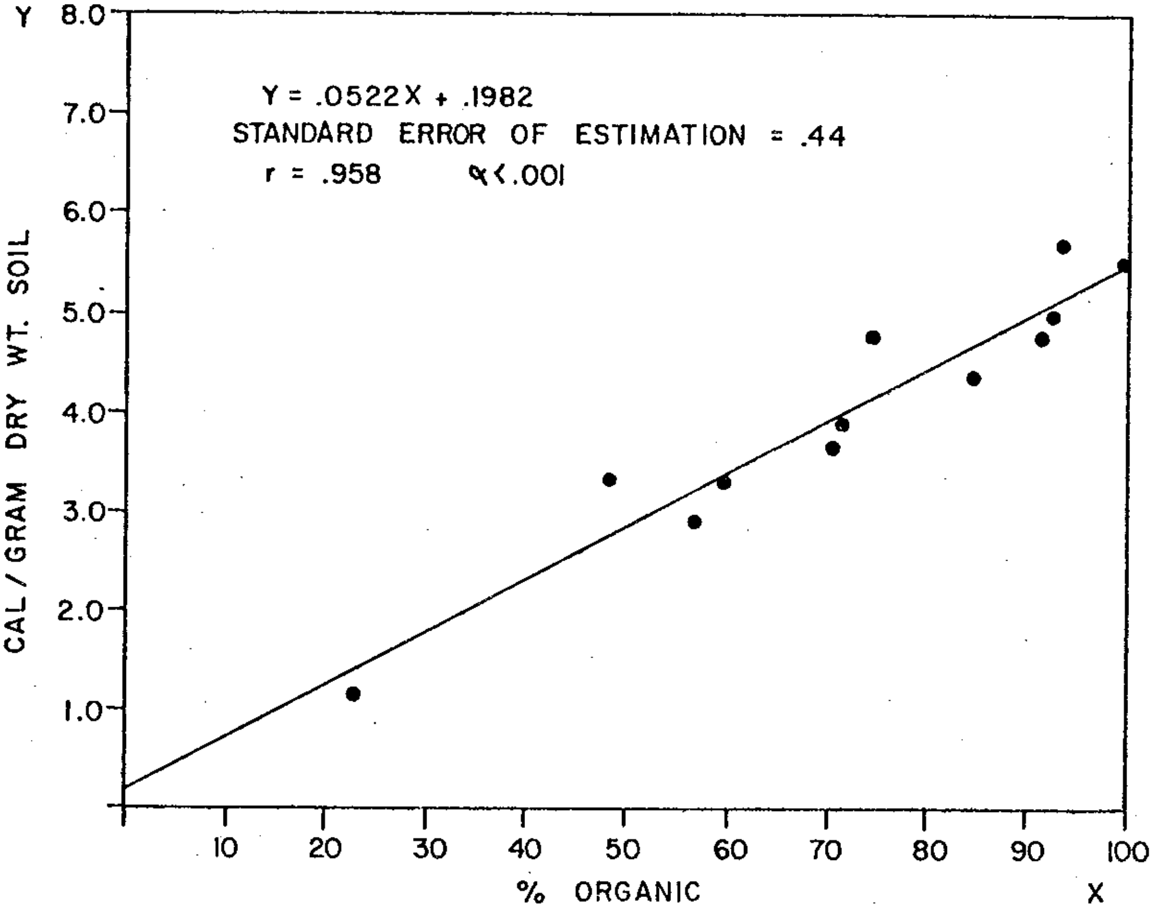
The energy embodied in soil includes the energy costs of the soil forming factors and the heat content of the soil's organic matter. Morphological and formative differences between mineral and organic soil require their energies be evaluated independently. Characteristics of Leon Fine Sands and Perrine Marl were used to evaluate Florida's mineral soils, while evaluation of Florida's organic soils was based on Everglades peat. Applying the analysis of soil energy to soils distributed throughout the state required the adoption of a scheme of soil associations. Calculations were based on 24 inches of soil depth and bulk densities.

Heat of Combustion of Soil Organic Matter

The chemical potential energy of an organic substance can be measured approximately with calorimetric methods. The potential chemical energy of a soil was calculated from its percent organic content times the heat content of the organic matter times the soil's bulk density.

Figure 7 presents the observed heat content of European organic soils derived from aquatic and marsh vegetation as a function of its percent organic matter dry weight. Since the points plotted represent five different soils from three areas in Europe, the assumption of randomly independent samples was made, in order to statistically test a linear regression fit to the data. An empirical value of 5.4 Cal/gm for 100% organic soil was found.

Figure 7. The relationship of the observed heat content of European soils with their percent organic matter. Data taken from "Quality and Value of Important Types of Peat Material": p. 18, by Alfred P. Dachnowski, 1919. United States Department of Agriculture Bulletin No. 802.


Y = .0522X + .1982
STANDARD ERROR OF ESTIMATION = .44
r = .958 α<.001
Y
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
CAL / GRAM DRY WT. SOIL
10
20
30
40
50
60
70
80
90
100
% ORGANIC
X

Using the function in Figure 7, a soil's heat of combustion was calculated as follows:

$$S_{TE} = K\ O\ B\ V + C$$

where: S_{TE} = Heat of combustion of soil, Cal/Acre

O = percent organic

V = Volume of soil, 2.4659×10^9 cm^3/Acre including 24 inches below surface

B = Bulk density of soil from equation (11) gm/cm^3

K,C = Empirical constants, Cal/gm organic matter from Figure 7.

Soil Associations

The set of associations employed in the general soil map of Florida produced by the Florida Agricultural Experiment Station and its accompanying literature was chosen (Beckenbach and Hammett, 1962; Smith et al., 1973). Virgin soil analyses were used as much as possible. Sources of data are found on the table summarizing soil characteristics in Appendix B.

Depth of Soil Evaluation

The surface layer of soil does not characterize the whole profile. It was necessary to choose a depth to which soil parameters would be integrated in order to characterize the soil. Based on literature reports of effective root depths (50% in the first foot, according to some authors), a standard soil depth of two feet was chosen (Brady, 1974; Jenny, 1941; Joffe, 1949; Russell, 1952) for integration of soil parameters.

Bulk Density

Bulk densities were not reported for most of the virgin soils evaluated. Literature values which were not specific to Florida indicated that mineral soils could be expected to have a bulk density of 1.2 to 1.5 gm/cm^3, and a well decomposed peat soil could have a density as low as .20 to .30 gm/cm^3 (Brady, 1974). A bulk density of .4 gm/cm^3 could be expected for Florida peats. The role of organic colloids in the formation of soil structure indicated that a strictly linear relationship between percent organic and bulk density could not be assumed (Brady, 1974; Jenny, 1941; Joffe, 1949; Russell, 1952).

The bulk density and percent organic matter of 12 soil types at various depths and locations were obtained, totaling 19 data points (Calhoun et al., 1974). Independent random samples were assumed and a log-linear regression was fit to the data, and statistically tested. Results are:

$$Y = -.2075 \ln (X) + 1.3978 \tag{11}$$

$$r^2 = .82 \qquad \alpha < .0005$$

$$\text{standard error of estimate} = .0108$$

where: y = bulk density, g/cm^3

X = percent organic, dry weight.

This empirical relationship was used to calculate bulk density for all soils without reported values.

Energy Costs of Mineral and Organic Soils

The solar energy cost is defined as the solar calories required to produce a unit of soil energy. The solar calories required are estimated from the solar cost of the annual rate of soil forming factors divided by the annual rate at which soil energy is stored. Soil energy storage in this study is measured as the chemical potential energy of the soil organic matter. Part of the cost of storing this energy is the weathering of parent materials. For this study, the weathering of limestone has been incorporated as part of mineral soil formation, and used as the minimum cost in the case of quartzitic soils whose weathering characteristics are more difficult to determine.

The first step was to define the general soil forming factors as fluxes which could be quantified. The work of climate was defined as the work of the kinetic energy of rain, the chemical free energy of rain, sunlight, temperature and wind. Organism work was defined as soil respiration (CO_2 evolution). Relief was defined as the kinetic energy of water head developed by slope. Parent material was defined by the gravitational work of its uplift, its heat of formation and the free energy of the nutrient concentrations in it.

If no energies were being imported or storages used in the soil forming process, the solar calorie cost of the annual energy storage would equal the local annual solar flux. But in fact, Florida's soils are formed in part by imported rain and wind energy as well as storages of phosphate in limestone rock created in the distant geologic past. Other soil forming factors, such as vegetation, are driven by the local solar flux, hence not considered a separate energy source. The fact that rain which falls on a spot was mostly generated elsewhere led to the assumption that rain was a solar energy input. A similar rationale was employed in the case of wind. The phosphate stored in limestone was treated as an energy input beyond the local solar flux because it represented a storage of energy through time. Uplift was included because it required offshore solar energy to maintain the isostatic balance.

No calorie cost for quartz sands was calculated, due to the uncertainty of the transport means (alluvial or marine), the amount of work done in transport and the distance traveled. Data on present littoral transport rates may have little bearing on the transport processes during the principle periods of sand deposition, since coastlines were known to have changed radically. These problems were able to be overcome for limestone because of the simplifying assumption of isostatic shift. The cost for limestone will also be used as a minimum cost for quartzitic sands. When costs for organic soils were evaluated, the costs associated with mineral fractions were not included.

Soil Formation Model and Evaluation

The processes and factors involved in soil formation were integrated into energy circuit models, which utilized the storage dynamics suggested by Jenny (1941) and symbols developed by Odum (1971).

Considerations of these models enabled the environmental fluxes of soil formation to be quantified, computer simulated, and the solar costs of these environmental fluxes to be estimated. The simulations were designed to enable the values assigned to the model to be tested against observed rates of soil formation as found in the literature of soil science.

The model of soil formation was evaluated with data from the literature for two types of mineral soil---one derived from marine deposits (Leon Fine Sand) and the other form weathering limestone (Perrine Marl). The model was simulated digitally, using a PLI program written for the purpose. A first order euler integration scheme was used, with all calculations carried in double precision. Simulation studies consisted of two phases, the first to test the accuracy of the vegetational succession segment of the model, the second to determine the interval required for the soil to reach steady state. The succession model was tested by assigning steady state initial conditions to all storages except leaf and support biomass, which were set at zero. The time required for soil formation was tested by setting the initial condition of soil and vegetative storages at zero. The model simulated the formation of soil from a mineral skeleton with and without nutrient inputs from weathering limestone. The energy cost of weathering limestone was used as a minimal energy cost of the soil's skeleton, since the costs of alluvial and marine quartz sands were undetermined.

Estimations of the rate of peat formation were based on biomass calculations and radiocarbon dating reported in soil literature.

A summary of estimated rates of peat formation is presented here in order to calculate the solar energy cost for organic soils. Rates of formation are calculated by dividing the depth of the formation by the age of the basal peat.

Evaluation of Energy Embodied in Urban and Population Growth

Urban indicators were correlated with population to obtain an energy equivalent for growth. Urban indicators which were readily available for all counties for only one or two population periods were regressed directly with population. When urban indicators were readily available for all counties for two or more population periods, the rate of change of these variables was correlated against the rate of change of population. Rates of change per year were calculated by subtracting the value reported at the beginning of a time interval from the value reported at the end of a time interval and dividing the difference by the number of years elapsed. Scattergrams of the urban indicators versus population were examined for evidence of non linearities. A regression of population against property value was used in conjunction with 25,000 Cal/$ quality factor to find the structure calories embodied in population.

The dependent measure, expressed in coal equivalents, can then be used to derive energy effect quality factors. These can be derived empirically, since for the linear production function:

$$y = mX$$

where y, the dependent variable, is in coal equivalents and X is in heat equivalents of natural energy, m is an energy effect quality factor. Empirical quality factors will be derived from regression equations in this fashion and compared with energy cost quality factors.

County population data for 1920, 1930 and 1940 were obtained from the U.S. Census, and data for 1950 and 1960 through 1975 were obtained from the Florida Statistical Abstracts. Urban indicator data were obtained from the same sources and include:

(a) total housing units for 1973, 1970, 1960, and 1950;
(b) property values 1971 and 1970;
(c) gasolines consumption for 1975 and 1970
and (d) taxable sales for 1974 and 1973.

Evaluation of County Production Models

In order to evaluate the urban production models of Figures 5 and 6, the natural energies and characteristics of each of the counties in Florida had to be quantified. Methods for this procedure are presented. The quality factors used in the additive models and details of evaluating the production models are also given.

Production Models Tested

Eight production models with permutations of energy interaction were tested. The four basic forms tested were additive and multiplicative models with and without feedback from urban structure as shown in Figures 5 and 6. Each of the models in Figures 5 and 6 except 6c was evaluated, including all the natural energies as shown, and tested. Empirical methods were used to evaluate each of the natural energies in the models separately. Models were subjected to a stepwise multiple regression analysis which selected only factors which contributed significantly toward explaining variance in the dependent variable. Eight of the nine models being tested make the assumption that drains are negligible. When growth approaches its maximum, productivity is either limited by inputs or balanced by drains, hence productivity no longer directly correlates with growth. The large number of inputs to a county system and the theoretical issues concerned in quantifying the use and availability of the natural energy inputs precluded a direct manipulation of the inputs which would incorporate the effect of limiting factors into the productivity function. The analysis of an early time period (1930) overcame this difficulty, since urban growth was clearly not limited at that early date. In order to account for this limiting factor phenomena, the ninth model tested incorporated drains in its structure, hence it is actually an urban growth model rather than strictly an urban production model (see Figure 6c).

The analysis performed assumed that fossil fuel external to the system was a constant equal for all counties. Different usage of fuel were only accounted for in the models which incorporated feedback loops from structure. Zucchetto's (1975) research on Dade County demonstrated the close relationship between population and total energy use, a finding replicated with contemporary (cross-sectional) analysis of the entire state in this study. In light of this relationship, the feedback loops in Figures 5b and 6b essentially indicate that the rate of fuel usage is incorporated in the model.

In Figure 5a, all the natural energies are assumed to enter the same productive process. The fossil fuel equivalents of each energy are summated, indicating the unique situation where the coefficient of flow from a storage equals one. In Figure 5b, the natural energies enter into separate productive processes with a multiplicative feedback from structure in each one, after which they add together. In Figure 6a, all natural energies enter the same productive process and are multiplied. In this version the qualities of calorie values are essentially disregarded. In Figure 6b, the natural energies, except for wave energy, enter into the same multiplicative process with feedback from structure. Wave energy enters a separate multiplier with structure, and then the two processes are added. Figure 6c contains the model which was tested in order to evaluate the urban productivity function in conjunction with urban growth when drains on structure might be considerable. Natural energies are shown interacting together additively, and then the sum interacts multiplicatively with structure. Urban structure has drains which are proportional to the square of the structure, a configuration which has logistic patterns of behavior.

Measures of Energy Interaction

Calculations based on the models in Figures 5 and 6 were made as follows:

Additive Interaction Without Feedback. The deterministic model in Figure 5a was tested as:

$$X = \sum_{i=1}^{7} q_i E_i \qquad (12)$$

where q_i is the energy quality factor for a particular energy from Table 3, E_i is the heat equivalent of the energy storage or flow per acre, and X is the computed independent variable. The empirical version of this model was developed with a stepwise linear regression employing the q_iE_i's as variables in the regression list.

Separate Process Additive Interaction with Feedback from Structure. The deterministic model in Figure 5b was tested as:

$$X = \sum_{i=1}^{7} k_i \, U \, E_i \qquad (13)$$

where U is the amount of structure present and k_i is an empirical constant. The only difference between the empirical and deterministic versions of this model is that the deterministic version forced all variables into the equation while the empirical version employed a stepwise procedure and did not incorporate all variables. The U E_i's were the variables in the regression list for the empirical version.

Multiplicative Interaction Without Feedback. The deterministic model in Figure 6a was calculated as:

$$X = E_1 \times E_2 \times \ldots E_i \qquad (14)$$

where the E_ith value was employed in the calculation only if it was greater than zero, a criteria which was pertinent only to organic and wave energy since not all counties had these attributes. The empirical version of this model was evaluated by putting ln E_i in the regression list, which would evaluate the linear regression equation as:

$$y = \beta_1 (\ln E_1) + \beta_2 (\ln E_2) \ldots \beta_i (\ln E_i) + C \qquad (15)$$

which also has the constraint employed with equation (14) in that a zero value could not enter into a calculation.

Multiplicative Interactions with Feedback from Structure, Terrestial and Coastal Processes Separated. The deterministic model in Figure 6b was calculated as:

$$X = k_1 UE_W + k_2 UE_1 \times E_2 \ldots \times E_N \qquad (16)$$

where E_W was wave energy and E_N was any non-zero natural energy. The terrestrial and coastal processes were separated in order to remove the constraints of a zero multiplication. The empirical version of this model was evaluated by employing only the variables found significant in the stepwise evaluation of equation (15).

County Characteristics

County sizes were obtained from the Florida Statistical Abstracts in miles^2 and converted to acres. Lake surface areas were excluded from unit area calculations, except in water storage calculations.

County boundaries of today were not established until 1920, which is the earliest date for any data used in this study.

Planimetry

Many parameters were obtained from maps. The method to determine the proportionate area of a specific value or quality (i.e. vegetation type) which varied over a county was to fix a tranparent grid of eqally spaced dots (manufactured by Artype Inc., Crystal Lake, Illinois) over the county and determine the proportion of dots within a county attributable to each system or isopleth of the map. Grid sizes included 50 dots/in^2 (no. HR 4118), 144 dots/in^2 (no. HR 4150), 256 dots/in^2 (no. HR 4116), and the size grid used depended upon the scale of the map. Integrated values for continuous variables (i.e. depth to base of potable aquifer) were obtained using the following equation:

$$X' = \sum_{i=1}^{N} P_i X_i \tag{17}$$

where X' is the integrated value, P is the proportion of the county in a given isopleth, and X is the value of the isopleth, and N is the number of isopleths found in a county.

Aquifer Storage

Calculations of aquifer storage potential were based on the assumption that only freshwater above sea level or the peizometric surface constituted storage, since the Ghyben-Herzberg principle indicates that further withdrawal would reduce storage due to salt water intrusion. Calculations for North Florida were based on the Floridian aquifer, while calculations for South Florida were based on the Biscayne aquifer and surface water tables. The peizometric surface of the Florida aquifer was obtained from a map by Healy (1961). The surface of the Biscayne aquifer and west coast water table was obtained from a map by Hoy (1964). The porosity of the aquifer material was assumed to be .2 (Hartwell, 1973) throughout the entire state. When the total volume of water storage (ft^3) for a county was calculated, the surface area of inland water was included in the area of the county. The chemical potential energy of the water stored was calculated as the free energy of fresh water with respect to seawater. Assuming rain has a purity of 10,000 ppm and seawater has a purity of 10,000 ppm, the chemical potential energy of this gradient can be calculated at 25°C as $\Delta F = RT \ln (99/96.5)$:

$$\frac{2.00\text{g cal} \quad 298°\text{K} \quad \text{mole} \quad \text{Cal}}{\text{deg mole} \quad 18\text{ g} \quad \quad 1000\text{ Cal}} \ln \frac{99}{96.5}$$

$$= 8.46 \times 10^{-4} \text{ Cal/gram } H_2O \qquad (18)$$

The total energy storage in water was calculated by converting ft^3 into grams of H_2O.

$$28316.8 \frac{cm^3}{ft^3} \times \frac{1 \text{ gm}}{cm^3} = \frac{28316.8 \text{ g}}{ft^3} \qquad (19)$$

Wave Energy

Calculations of wave energy were based on the equation of power/length of wave front (Costanza, 1975):

$$E_W = 1/8\ p\ g^{3/2}\ H^{5/2} \tag{20}$$

where p is the density of seawater, g is gravity, H is the average wave front, and E_W is expressed in Cal/m ÷ year. The miles of coast subjected to wave exposure for each county were obtained from the Florida Coastal Zone Atlas (1972). Average wave heights for the coast of Florida were obtained from Walton (1973). Walton's data includes the mean breaking wave height divided by the frequency of waves, which normalizes the wave height to equal energy terms for all counties. For example, Bay County had a mean breaking wave height of 2.89 ft (88.08 cm):

$$.125 \times \frac{1.0\ \text{gm}}{\text{cm}^3} \times \left(\frac{980\ \text{cm}}{\text{sec}}\right)^{1.5} \times \underline{88.08\ \text{cm}^{2.5}} \times$$

$$\frac{2.4 \times 10^{-11}\text{Cal}}{\text{erg}} \times 3.15 \times 10^7\ \frac{\text{sec}}{\text{yr}} \times \frac{100\ \text{cm}}{\text{m}}$$

$$= 2.1125 \times 10^7\ \frac{\text{Cal}}{\text{m yr}} \tag{21}$$

for the entire county:

$$2.11 \times 10^7\ \frac{\text{Cal}}{\text{m yr}} \times \frac{38\ \text{miles coast}}{\text{count}} \times \frac{1609.34\ \text{m}}{\text{mi}}$$

$$= 1.29 \times 10^{12}\ \frac{\text{Cal}}{\text{yr}} \tag{22}$$

Mineral and Organic Soil Energy

The theoretical assumptions for calculations of mineral and organic soil energy are presented in this study. The heat of combustion of soil organic matter was found to be 5.4 Cal/gram, and the calculation of the energy stored was based on a soil's percent organic matter and bulk density for the first two feet. Thirteen different soil associations were determined based on groupings of the 37 associations on the General Soil Map of Florida (Beckenbach and Hammett, 1962). The groupings chosen for spatial determinations correspond to the textures specified on the map. The value used for each grouping represented the weighted mean of organic energy for the series present, in that the value for an association, if known, was entered into the mean calculation as often as it was used to characterize a sub-association (see Appendix B for raw soil data). For example, soils dominantly thick to moderately thick acid sands were characterized as: (2 x Lakeland + 2 x Eustis + Blanton + Norfolk)/6. The characteristic groups and the Calorie values for each are presented in Table 1. Mineral and organic soils were treated throughout the analysis separately because of their different morphologies and quality factors.

Natural Vegetation

Ecosystem productivities were calculated for each county based on a weighted gross primary productivity estimate. The area of a natural vegetation system in each county was determined from the General Map

Table 1. Mean heat of combustion of characteristic soil groupings

Description of Grouping	x 10^8 Cal/acre[a]
Areas dominated by excessively drained soils	1.06
Soils dominantly thick to moderately thick acid sands	1.48
Soils dominantly thick to thin sands influenced by alkaline materials	1.24
Soils dominantly thick to thin phosphatic sands and loamy sands overlying finer textured material	2.69
Soils dominantly thin acid sand to sandy loamy overlying finer textured subsoils	2.12
Soils dominantly thick to thin acid sands, some of which overlie finer textured subsoils	1.41
Soils dominantly thick acid sands with organic pans; interspersed by soils without a pan formation	1.79
Soils dominantly thick acid sands with dark surface soils	3.14
Soils dominantly thick to thin sands overlying finer textured alkaline materials	2.35
Soils dominantly thick to thin sand to sandy loam surface soils overlying finer textured acid subsoils	2.45
Soils dominantly moderately thick to thin acid sands to sandy loams overlying finer textured acid subsoils	3.68
Soils dominantly moderately thick to thin marly material overlying limestone	1.64
Soils dominantly peats and mucks (organic)	54.7

[a] Calculated from the weighted averages of the heat of combustion of soil series present in each grouping as catagorized by Beckenbach and Hammet (1962). The heat of combustion of each soil was based on the integrated percent organic matter to a depth of two feet, bulk density and 5.4 Cal/gram dry wt. for organic matter.

of Natural Vegetation of Florida (Davis, 1967). System productivities were obtained from a compilation presented by Costanza (1975). Davis and Costanza's maps did not use similar system classifications. The assignment of productivity rates to systems defined by Davis is presented in Table 2.

A county's natural productivity was represented as a weighted average calculated as:

$$\sum_{i=1}^{17} P_i E_i \tag{23}$$

where E_i is the productivity of the particular system, and p is the proportion of the county's area which contains that system.

Rainfall

Rainfall data for each county was obtained by integrating the isopleths on the map of rainfall and potential evapotranspiration in Florida (Visher and Hughes, 1969). The number of inches of rainfall was multiplied by the area of a county to obtain the volume of water received per year, and the energy potential of this water was calculated as for the water in aquifer storage.

Sunlight

Sunlight for each county was calculated from data in Costanza, 1975.

Table 2. Assignment of productivity values to systems on the general natural vegetation map of Florida

Mapped System Davis, 1967	Corresponding System With Productivity Estimate	Gross Primary Productivity Estimate x 10^6 Cal/acre•yr
Coastal strand	Beach and dune	0.3
Pine flatwoods	Pineland	154.0
Slash pine	Pineland	154.0
Mixed hardwood	Hardwood	155.0
Sand pine	Pineland	154.0
Long leaf pine	Pineland	154.0
Cypress	Cypress	146.0
Swamp forest	Hardwood	154.0
Mangrove	Mangrove	147.0
Hardwood	Hardwood	155.0
Grassland	Grassland	71.1
Scrub Cypress	Scrub Cypress	117.4
Cabbage Palm	Grassland	71.1
Fresh H_2O Marsh	Marsh and slough	147.0
Sawgrass	Sawgrass	162.0
Wet Prairie	Marsh and slough	106.4
Dry Prairie	Grassy-scrub	71.1

Energy Quality Factors

Examples of the methods used to calculate conversion factors to convert heat equivalents to solar cost equivalents are found in Table 5 and closely follow the methods presented by Odum et al., 1977. Table 3 summarizes the values used.

Empirically Determined Quality Factors

If natural energy is in heat equivalents and urban structure is in fossil fuel equivalents, the slopes of linear regression equations of natural energy against rate of change of urban structure can be considered as conversion factors which convert one type of Calorie into another (quality factor). Single regression was used to find these values, as multiple regression only calculates the partial effect of all factors. These are energy effect quality factors.

Statistical Considerations

Statistical Computations

All statistical analyses were conducted using the SPSS package of programs available on the University of Florida's IBM 360/370 computer (Nie et al., 1975). Empirical versions of the models were run using a stepwise procedure with all variables in the regression list at equal levels of inclusion, unless otherwise noted. Limits for inclusion were $F > 1.0$ and tolerance > 0.4 (40% of variance unexplained).

Table 3. Summary of energy quality factors

Type of Energy	CE/Cal	Source
Sunlight	.0005	a
Gross Primary Production	.05	a
Wave	.2	a
Organic Soil	.5	b
Chemical Potential of Water	3.0	a
Mineral Soil	4.0	b

[a] Odum *et al*. (1977).

[b] This study.

Correlation Coefficients

R is the coefficient of multiple determination, or multiple regression correlation coefficient, while r is the simple correlation coefficient, sometimes termed the Pearson Product Moment coefficient.

Assumptions

Multiple regression analysis was used to test and evaluate models of the form:

$$Y' = \beta_1 X_1 + \beta_2 X_2 + \beta_N X_2 + C \pm E \qquad (24)$$

where Y' is the expected value of the dependent variable, β is a linear slope, X is an independent random variable, C is a constant and E is an error term. Significance tests associated with multiple regression are usually based on the following assumptions:

1. The sample is drawn at random from a population.
2. Each array of Y for a given combination of X's follows the normal distribution.
3. The regression of Y and X's is linear.
4. All of the Y arrays for a given combination of X's have the same variance.

The first assumption is necessary if one is going to generalize from a sample to a population. Since Florida is a unique geographic region and all of its counties are included in the sample, the findings of this study, while not generalizable to counties outside of Florida, can be used to make general statements about processes within the state. Therefore, the first assumption can be relaxed under the constraint that the findings are not generalized to areas outside of Florida, or by defining the sampled population as "counties within Florida." In several ways, the counties of Florida are not independent samples. This potentially confounding aspect of the methodology employed is discussed under methodological considerations and will essentially be ignored for the purposes here. The second, third, and fourth assumptions are best tested by an examination of the residuals, a procedure which has been employed in this study.

Nonstationarity

Timeseries data can only meet the first assumption if no monotonic trend is apparent (stationary) and are not autocorrelated. Urban structure is cumulative and invalidates this assumption. The two usual corrections for timeseries data are to remove the trend by obtaining the rate of change or first difference of the variable, or to regress against time and treat the residuals as the independent random variable. The first approach has been used in this study, making the rate of change of urban structure the independent variable. Ezekiel (1959) presents an adequate summary of the pitfalls and problems of time series regression analysis. These considerations are mostly applicable to a pooled cross-sectional timeseries analysis, which has the advantage of an increased sample size, such as the 1965-1975 pooled sample analysis of this study. The findings from the pooled sample were replicated in a single year cross-sectional analysis, which is the approach Cox (1971) used to substantiate his findings.

Multicollinearity

Multicollinearity refers to a high ($r > .8$) incorrelation among the independent variables (Neter and Wasserman, 1974). Multicollinearity has the effect of making it difficult to separate the effects of the variables and leads to fluctuation of estimates of regression coefficients from sample to sample. Prior to the collection of data for this study, there was reason to believe that Florida provided a wide range of independent variation in natural energies, as discussed in the section on the study area.

For this reason, multicollinearity was expected to have a minimal effect on the analysis. However, the intercorrelations among the independent variables were tested and the constraint imposed on stepwise regression procedures that no variable be introduced into the equation if more than 60% of its variance was explained by variables already in the equation.

Standard Betas

Multiple regression can be used to measure the relative strength of associations among independent variables. The relative importance of a variable is measured with its standardized beta coefficient, which is calculated from the partial slope coefficient as:

$$\mathrm{Beta}_i = \beta_i \frac{S_{X_i}}{S_y} \tag{25}$$

where S_{X_i} refers to the variance estimate of the i^{th} independent variable, S_y refers to the variance of the dependent variable, β_i is the partial slope coefficient and Beta_i is the standardized beta-coefficient for that independent variable. The standard betas have been called "beta weights" and in most simple causal models involving one way causation are equivalent to what have been called path coefficients (Blalock, 1972, p. 453).

Significance Tests

Significance testing of the overall regression equation is based on the variance ratio F;

$$F = \frac{\text{SS reg}/i}{\text{SS resid}/(N-i-1)} \qquad (26)$$

where SS reg is the sum of squares explained by the regression, SS resid is the sum of squares explained by the entire regression equation and i is the number of independent variables. In this study, the hypotheses being tested employ a null hypothesis of no relationship ($\rho = 0$ or $\mu_a = \mu_b = \mu_c$ . . . etc.). The F distribution was then used to evaluate alpha, (Type I error) or the probability of falsely rejecting a true null hypothesis, using i and N-i-1 degrees of freedom. The criterion alpha has been set at 0.05, or less than 5 chances out of a hundred that the observed relationship occurred by chance.

The coefficient of multiple determination, or multiple correlation coefficient R, when squared, represents the variation in Y explained by the combined linear influence of the independent variables. R^2 can be interpreted as the "goodness-of-fit" of the equation. It can also be used to calculate the F ratio:

$$F = \frac{R^2/i}{(1-R^2)/(N-i-1)} \tag{27}$$

A significant R only indicated that at least one regression coefficient is significant. There are two approaches used for testing the significance of individual regression coefficients, the standard regression method and the hierarchial method (Kerlinger and Pedhazur, 1973). The standard regression method tests the increment in R^2 caused by the addition of the independent variable, with all other variables already in the equation. The hierarchial method tests the total influence of a variable when it is added to the equation in a specific order. The hierarchial method is generally more powerful and assumes the causal order among the variables. Since no causal order is assumed, the partial increase in R for each independent variable will be tested, using the standard regression method as follows:

$$F = \frac{\text{incremental SS due to } X_i}{\text{SSres}/(N-K-1)} = \frac{r^2 y(i \cdot 1, 2, \ldots K)/1}{1-R^2 y \cdot 12 \ldots i \ldots k)/(N-K-1)} \tag{28}$$

Types of Covariance

Correlation analysis detects two sorts of associations between variables.

It is important to note that in a productive process, correlation will only detect limiting factors. This can be easily seen in the mathematics of a single variable regression, and the principles extend directly to multiple regression procedures. The form of a linear regression equation is:

$$Y = \beta X + C \tag{29}$$

where:

$$\beta = \frac{\Sigma(XY) - n\,\overline{X}\,\overline{Y}}{\Sigma(X^2) - n(\overline{X})^2} \tag{30}$$

$$a = \overline{Y} - \beta\,\overline{X} \tag{31}$$

The spread of data points around this line is measured as:

$$r = \frac{n\,\Sigma\,(XY) - n\,\overline{X}\,\overline{Y}}{\sqrt{[n\Sigma X^2 - (\Sigma X)^2][N\Sigma Y^2 - (\Sigma Y)^2}} \tag{32}$$

When the covariance term ($N\Sigma(X\ Y)$) differs from the multiplied means of the variables ($n\ \overline{X}\ \overline{Y}$), r differs from zero. This occurs if X and Y vary from the mean together, either consistently together or inversely. In a typical production process, the output function as a function of X has a hyperbolic asymptote, where the output's response to varying levels of 'X' is very great in the area with steepest slope, but only slight at levels of production approaching the asymptote. The covariance with X is great at the low end of the production function and less at the high end. A variable may be essential in a process yet not correlate well with the output, if it is not limiting the process.

RESULTS

In the sections that follow are given the energy embodied in soil formation, the soil model and its simulation, estimates of time of soil formation, the energy cost of mineral soil and organic soil, and correlation results relating urban growth to county production models.

Energy Embodied in Soil Formation

Results of calculating the energy embodied in the soil forming factors of Florida are given in Table 4. The soil forming factor with the largest flux of heat equivalent calories is sunlight, followed in order of decreasing energy flux by CO_2 evolution (organisms), wind, temperature, the chemical energy of rain, the heat of formation for new parent material, the kinetic energy of rain, the kinetic energy developed by slope, the chemical free energy of P concentrated in Florida limestone, and the gravitational work of uplift. These calorie values range through nine orders of magnitude with the climatic forces being relatively close together in magnitude.

The solar energy embodied in each flow is given in Table 5. In order of increasing energy costs, the energies rank as following: sunlight, CO_2, evolution, wind, temperature, rain, heat of formation, enriched Florida limestone and geologic uplift. The rank order of

Table 4. Estimates of the energy of soil forming factors[1] in Florida

Soil Forming Factor	Environmental Flux	Description of Energy Parameter	Numerical Value of Flux Marine Deposit Cal/m^2·yr	Numerical Value of Flux Limestone Origin Cal/m^2·yr	Note
Climate	Rain	chemical potential energy of water	1.18×10^3	1.18×10^3	a
		kinetic energy of rainfall	3.27	3.27	b
	Sunlight	insolution of earth's surface	1.63×10^6	1.63×10^6	c
	Temperature	maximum carnot efficiency of temperature flux	2.09×10^3	1.97×10^3	d
	Wind	kinetic energy of moving air	2.59×10^3	2.59×10^3	e
Organisms	CO_2 evolution	metabolism	8.0×10^3	8.0×10^3	f
Relief	Slope	kinetic energy of water head developed by slope	3.27×10^{-2}	3.27×10^{-2}	g
Parent Materials	Uplift	gravitational work of uplift	5.5×10^{-6}	5.5×10^{-6}	h
	Parent material	heat of formation: added by limestone flux	-	1.0×10^2	i
		energy of P concentration in Florida limestone added by limestone flux	-	3.3×10^{-4}	j

[1] s = f (climate, organisms, relief, parent materials and time), after Jenny, 1941.

Notes to Table 4

a. Seawater has an average salt concentration of 35,000 ppm. Assuming that rain has a purity of 10,000 ppm, the chemical potential energy of this gradient can be calculated at 25°C (RT ln (99/96.5)).

$$2.00 \; \frac{\text{cal}}{\text{deg mole}} \quad \frac{298°\text{K}}{18 \text{ g}} \quad \text{mole} \quad \frac{\text{Cal}}{1000 \text{ Cal}} \; \ln \frac{(99)}{(96.5)}$$

$$= 8.46 \times 10^{-4} \text{Cal/gram}$$

With 55 inches of rain ($1.397 \times 10^6 \text{cm}^3/\text{m}^2$) the total energy flux is 1.18×10^3Cal/yr ($\text{cm}^3/\text{m}^2 \times \text{g/cm}^3 \times$ Cal/gram), regardless of the surface on which it falls.

b. Using an average drop diameter of 3.5 mm the drop velocity can be estimated to be 14.5 ft/sec (Ekern, 1954). Kinetic energy of falling rain can be calculated as 1/2 mv^2, regardless of the surface on which it falls.

$$\frac{.5 \times 1.4 \times 10^6}{\text{m}^2 \cdot \text{yr}} \quad \frac{210.25 \text{ ft}^2}{\text{sec}^2} \times \frac{921.03 \text{ cm}^2}{\text{ft}^2} \times \frac{2.39 \times 10^{-11} \text{Cal}}{\text{erg}}$$

$$= 3.27 \text{ Cal/m}^2 \cdot \text{yr}$$

c. The mean yearly value for Tampa, Lakeland, West Palm Beach and Miami is 446.5 ly/day (Costanza, 1975).

$$\frac{446.5 \text{ ly}}{\text{day}} \quad \frac{365 \text{ day}}{\text{yr}} \quad \frac{1 \text{ cal}}{\text{cm}^2} \quad \frac{10000 \text{ cm}^2}{\text{m}^2} = 1.63 \times 10^6 \; \frac{\text{Cal}}{\text{yr/m}^2}$$

d. A theoretical maximum amount of work which temperature differentials in Florida exert in soil forming processes assuming that there is a specific heat of 5 cal/gram · °C for the soil material (Brady, 1971), that the temperature change of the soil material is equal to the average annual change in ambient air temperature, and that work is being done at maximum power, or 50% of the carnot efficiency (Carnot efficiency = $J_h \Delta T/T$). The annual average high temperature is 28°C, low is 16°C (Florida Statistical Abstract, 1976).

Bulk density = 1.43 for Marine deposits, 1.35 for limestone derived soils.

$$J_h = \frac{1.43\ \text{g}}{\text{cm}^2} \times \frac{6.09 \times 10^5 \text{cm}^3}{\text{m}^2}\ \frac{12°\text{C} \times 2\ \text{half cycle}}{\text{half cycle}\quad \text{yr}} \times \frac{5\ \text{cal}}{\text{g°C}}\ \frac{\text{Cal}}{1000\ \text{cal}} =$$

$$1.05 \times 10^5\ \text{Cal/m}^2 \cdot \text{yr}$$

$$\frac{1.05 \times 10^5\ \text{Cal} \times 12°\text{K} \times .5}{\text{m}^2\text{yr}\quad 301°\text{K}} = 2.09 \times 10^3\ \text{Cal/m}^2 \cdot \text{yr}$$

for marine sands

$$= 1.97 \times 10^3\ \text{Cal/m}^2 \cdot \text{yr}$$

for limestone derived soils.

e. Wind energy = $1/2\ mv^2d/h$ where v is the mean value of 9 mph, d is the eddy diffusion constant and h is the height at which the wind speed was measured (assumed to be 100 ft., as the data were taken mostly from airport control towers (after Costanza, 1975)).

$$\frac{.5 \times .0012\ \text{g} \times 81\ \text{mph}^2 \times 1998\ \text{cm}^2}{\text{cm}^3 \qquad\qquad \text{sec}^2\text{mph}^2} \quad \times$$

$$\frac{1 \times 10^4\text{cm}^2 \times 2.39 \times 10^{-11}\ \text{Cal} \times 10000\ \text{cm}^2 \times 3.15 \times 10^7\text{sec}}{\text{sec} \qquad\qquad \text{erg} \qquad\qquad \text{m}^2 \qquad\qquad \text{yr}} \quad \times$$

$$\frac{\text{ft}}{100\ \text{ft}\ 30.48\ \text{cm}} \quad = \quad 2.59 \times 10^3\ \frac{\text{Cal}}{\text{m}^2\text{yr}}$$

f. At an average soil temperature of 23°C, data from Kucera and Kirkham (1971) suggest that CO_2 evolution is 416 mg/m^2/hr, from roots and soil microorganisms.

$$\frac{416\ \text{mgCO}_2 \times .273\ \text{gC} \times 8760\ \text{hr} \times 8\ \text{Cal} \quad \times \quad \text{g}}{\text{m}^2\text{hr} \qquad\qquad \text{gCO}_2 \qquad\qquad \text{yr} \qquad \text{gC} \quad 1000\ \text{mg}} = 8.0 \times 10^3\ \frac{\text{Cal}}{\text{m}^2\text{yr}}$$

g. Assuming an average slope of 1 cm/m, imparting potential energy to 55 inches a year. Potential energy = mgh.

$$\frac{1.397 \times 10^6\text{g} \times 980\ \text{cm} \times 1\ \text{cm} \times 2.39 \times 10^{-11}\ \text{Cal}}{\text{m}^2 \cdot \text{yr} \quad \text{sec}^2 \qquad\qquad\qquad\qquad \text{erg}}$$

$$= 3.27 \times 10^{-2}\ \text{Cal/m}^2 \cdot \text{yr}$$

h. Assuming 3.0 cm per 1000 yrs (Gilliland, 1973), the potential energy of up lift = mgh.

$$\frac{2.65\ \text{g} \quad 10000\ \text{cm}^2 \quad 3.0\ \text{cm} \quad 980\ \text{cm} \quad 3.0\ \text{cm}}{\text{cm}^3 \qquad \text{m}^2 \qquad\qquad\qquad \text{sec}^2} \times \frac{2.39 \times 10^{-11}\ \text{Cal}}{\text{erg}}$$

$$= \quad 5.5 \times 10^{-6}\ \text{Cal/m}^2 \cdot \text{yr}$$

i. Limestone. ΔF_f° = 270 Cal/gfw (Clark, 1966).

Based on assumptions of notes e and f, Table 5:

$$270\ \frac{\text{Cal}}{\text{gfw}} \quad \frac{39\ \text{g}}{\text{m}^2\text{yr}\ 100\text{gfw}} = 1.0 \times 10^2\ \frac{\text{Cal}}{\text{m}^2\text{yr}}$$

j. See notes f and h, Table 5:

$$\frac{.0084 \times 10^4\ \text{Cal}}{\text{m}^2} \quad \frac{39\ \text{g}}{\text{yr}\ 1.35\ \text{g} \times 6.096 \times 10^5\text{cm}^3} = 3.3 \times 10^{-4}\ \frac{\text{Cal}}{\text{m}^2\text{yr}}$$

Table 5. Solar energy costs* of soil forming factors

Factor	Environmental Flux	Energy** Origin*		Cost Calorie/ Calorie	Note
Climate	Rain	not local	Derived from planetary budget, ratio for chemical cost	2013.	a
	Sunlight	local	By definition	1.0	b
	Temperature	local	Carnot efficiency	815.	c
	Wind	not local		324.	
Organisms	CO_2 evolution	local	Photosynthetic	204.	d
Parent Material	Uplift	not local	Isostatic balance	$5.92\text{x}10^{11}$	e
	Mineral particles	not local	Heat of formation: limestone	$1.55\text{x}10^{4}$	f
		not local	Erosion: quartz sand	$4.8\text{x}10^{9}$	g
	Nutrient Concentrations	not local	chemical free energy: limestone of P concentration	$6.6\text{x}10^{9}$	h

[*] Soil forming processes are ultimately driven by solar or geothermal energy sources (see Fig. 2). The energy cost of a soil forming process is defined as the solar energy heat equivalents required to generate one heat equivalent of a soil forming process.

[**] A non local origin indicates either a spatial or temporal concentration of solar energy.

Notes to Table 5

a. The total rain of the world is 520,000 km^3/yr (100 cm/yr times the area of the earth, Ryabchiko, 1975). The energy cost of rain is taken as the ratio of solar energy to the chemical potential energy of rain water (see note 1, Table 4), assuming an albedo of .34 (Houghton, in Eagleson, p. 37), earth's radius as 3956 miles, and earth surface as $5.1 \times 10^{14} m^2$.

$$\frac{3.14 \times 1.565 \times 10^{7} mi^{2} \times 2.589 \times 10^{6} m^{2} \times 2\ cal\ \ 1 \times 10^{4} cm^{2}}{mi^{2}\quad cm^{2}min\quad m^{2}} \times$$

$$\frac{Cal \times .66 \times 5.25 \times 10^{5} min}{1000\ cal\quad yr\ \ 5.1 \times 10^{14} m^{2}} = 1.73 \times 10^{6} \frac{Cal}{m^{2}yr}$$

$$\frac{520{,}000\ km^{3} \times 1 \times 10^{15} cm^{3}\ 1\ gram \times 8.843 \times 10^{-4}\ Cal}{yr\quad km^{3}\quad cm^{3}\quad gram\ 5.1 \times 10^{14} m^{2}}$$

$$= 8.59 \times 10^{2} \frac{Cal}{m^{2}yr}$$

$$\frac{1.73 \times 10^{6}\ Cal\ sunlight\quad m^{2}yr}{m^{2}yr\quad 8.59 \times 10^{2}\ Cal\ water} = 2.013 \times 10^{3} \frac{Cal}{Cal}$$

b. Assuming that the energy driving the heat change was derived from the locally received sunlight, the energy cost can be taken as the ratio of 1.63×10^{6} Cal sunlight/yr · m^2 to 2.00×10^{3} Cal temperature work/m^2 · yr = 815.

c. The average kinetic energy of wind is 5.329×10^3 Cal/$m^2 \cdot$ yr (Hubbert, 1971); the ratio of 1.73×10^6 Cal sunlight/$m^2 \cdot$ yr to 5.329×10^3 Cal wind/$m^2 \cdot$ yr is 324. It is assumed that the locally-derived energy for generating wind is negligible.

d. Assuming that the organic matter was derived from local sunlight, the cost can be calculated as 1.63×10^6 Cal/8×10^3 Cal = 203.7. This is twice the energy cost of primary productivity (see note f, Table 4).

e. Isostatic balance is maintained by the removal of mass from one area and the deposition of mass in another. Marine sedimentation occurs on Florida's coastal shelf, which is roughly equal to the area of the peninsula (Gilliland, 1973; Cooke and Mosom, 1929). The energy cost is then the local sunlight plus the sunlight driving the chemical and biological processes over the area of deposition.

$$\frac{1.63 \times 10^6 \text{ Cal sunlight}}{m^2 \cdot \text{yr}} \, \frac{m^2 \text{yr} \times 2}{5.5 \times 10^{-6} \text{ Cal uplift}} = 5.92 \times 10^{11} \frac{\text{Cal sunlight}}{\text{Cal uplift}}$$

f. Florida limestone is eroding at the rate of 39 grams/$m^2 \cdot$ yr ($1.3 \times 10^6 g/m^3 \times 1 \times 10^{-6} m^3/cm^3 \times .003$ cm/yr $\times 1 \times 10^4 cm^2/m^2$). The energy cost of limestone is calculated based on the assumptions in note 5, gfw of $CaCO_3$ = 100, $\Delta F_f^\circ = -270$ Cal/gfw (Clark, 1966) and solar energy driving sedimentation processes (1.63×10^6 Cal/$m^2 \cdot$ yr).

$$\frac{1.63 \times 10^{6}\ \text{Cal}}{\text{m}^2\text{yr}}\ \frac{\text{gfw}}{270\ \text{Cal}}\ \frac{100\ \text{g}}{\text{gfw}}\ \frac{\text{m}^2\text{yr}}{39\ \text{g}} = 1.55 \times 10^{4}\ \frac{\text{Cal sunlight}}{\text{Cal limestone}}$$

g. Uplift of the continental surface is estimated to be .0036 cm/yr. Igneous rock averages 60.21% SiO_2 (Kuenen, 1941). At a bulk density of 1.43 g/cm^3, a volume of sand two feet thick by a meter square contains 6.1×10^5 g SiO_2, derived from the weathering of 1.0×10^6 g igneous rock. At a density of 2.65 g/cm^3, it would require $1 \times 10^4 m^2$ to weather this much rock in one year . (1×10^6 g $\div$ (.0036 cm x 2.65 g/cm^3 x 1×10^4cm^2/m^2)). The energy cost of quartz sand is calculated with ΔF_f° of 204 Cal/gfw and 60g/gfw (Clark, 1966).

$$1.63 \times 10^{6}\ \frac{\text{Cal sunlight} \times 1 \times 10^4\text{m}^2}{\text{m}^2\text{yr}}\ \frac{\text{gfw}}{204\ \text{Cal}}\ \frac{60\ \text{g}}{\text{gfw}}$$

$$= \frac{4.8 \times 10^{9}\ \text{Cal sunlight}}{\text{Cal quartz}}$$

Since .0036 $\pm$ .003, this ratio is considered applicable to limestone.

h. The phosphate content in Florida limestone is enriched to approximately 10% $CaPO_3$ (2.6%P) in 25×10^6 years (Gilliland, 1973). The free energy of this concentration with respect to average limestones (.023%P (Kuenen, 1941) is RT ln $\frac{(99.97)}{(97.4)}$).

$$\frac{2\ \text{cal}}{°\text{K mole}} \times 298°\text{K} \times \frac{\text{mole}}{100\ \text{g}}\ \frac{\text{Cal}}{1000\ \text{cal}}\ (.02604) = 1.55 \times 10^{-4}\ \text{Cal/g}$$

Gilliland based her calculations on 100 ft of limestone. The energy cost of the nutrient enrichment can then be calculated with the $CaCO_3$ density of $1.3 \times 10^6 g/m^3$.

$$25 \times 10^6 \text{ yrs} \times \frac{1.63 \times 10^6 \text{ Cal sunlight}}{m^2 \text{yr}} \quad \frac{g}{1.55 \times 10^{-4} \text{ Cal}} \times \frac{m^2}{3.96 \times 10^7 \text{ g}}$$

$$= \frac{6.6 \times 10^9 \text{ Cal sunlight}}{\text{Cal limestone}}$$

energy costs is seen to be directly inverse to the rank order of energy flow, with two exceptions. The exceptions are the energy cost for the kinetic energy of rain, which is considered the same as the chemical energy cost of rain, and the energy cost of slope, which is considered to be a function of geological uplift.

Note that a distinction is made in Table 5 between solar costs for Florida's energy flux which can be considered to be met locally and those which are met over larger areas, in which case the local solar energy costs are assumed negligible. This distinction was important when the final solar cost for soil formation in Florida was calculated. While it is interesting and instructive to compare the energy fluxes of all the soil forming factors, it would be double counting to attribute energy to organisms which derive their energy from sunlight. For this reason, the solar cost of soil formation is the local solar flux plus energies concentrated from other areas, such as rain, wind, and the energies embodied in parent material (see Table 5 and accompanying footnotes for details of this assumption).

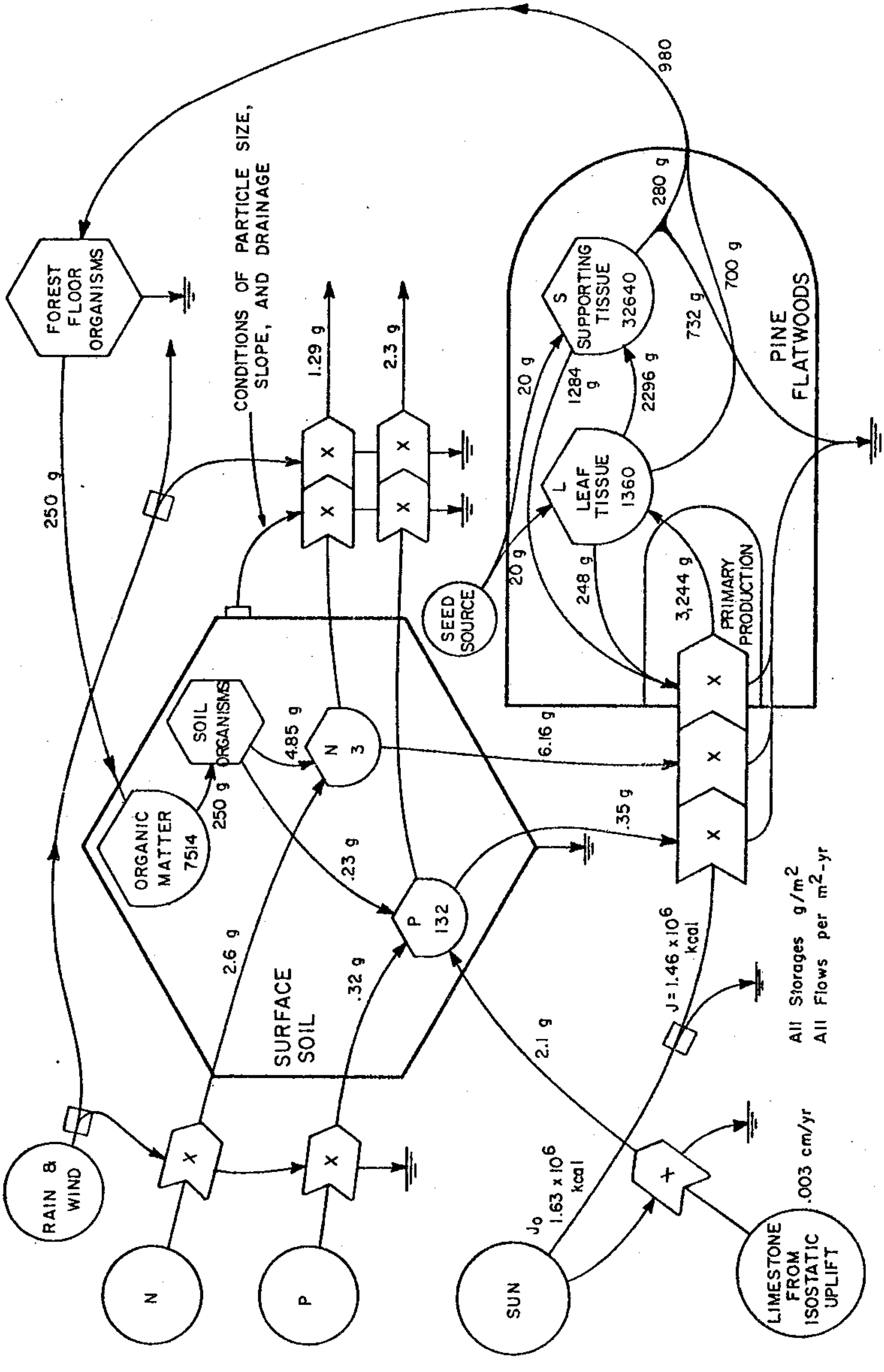
Rates of Soil Formation

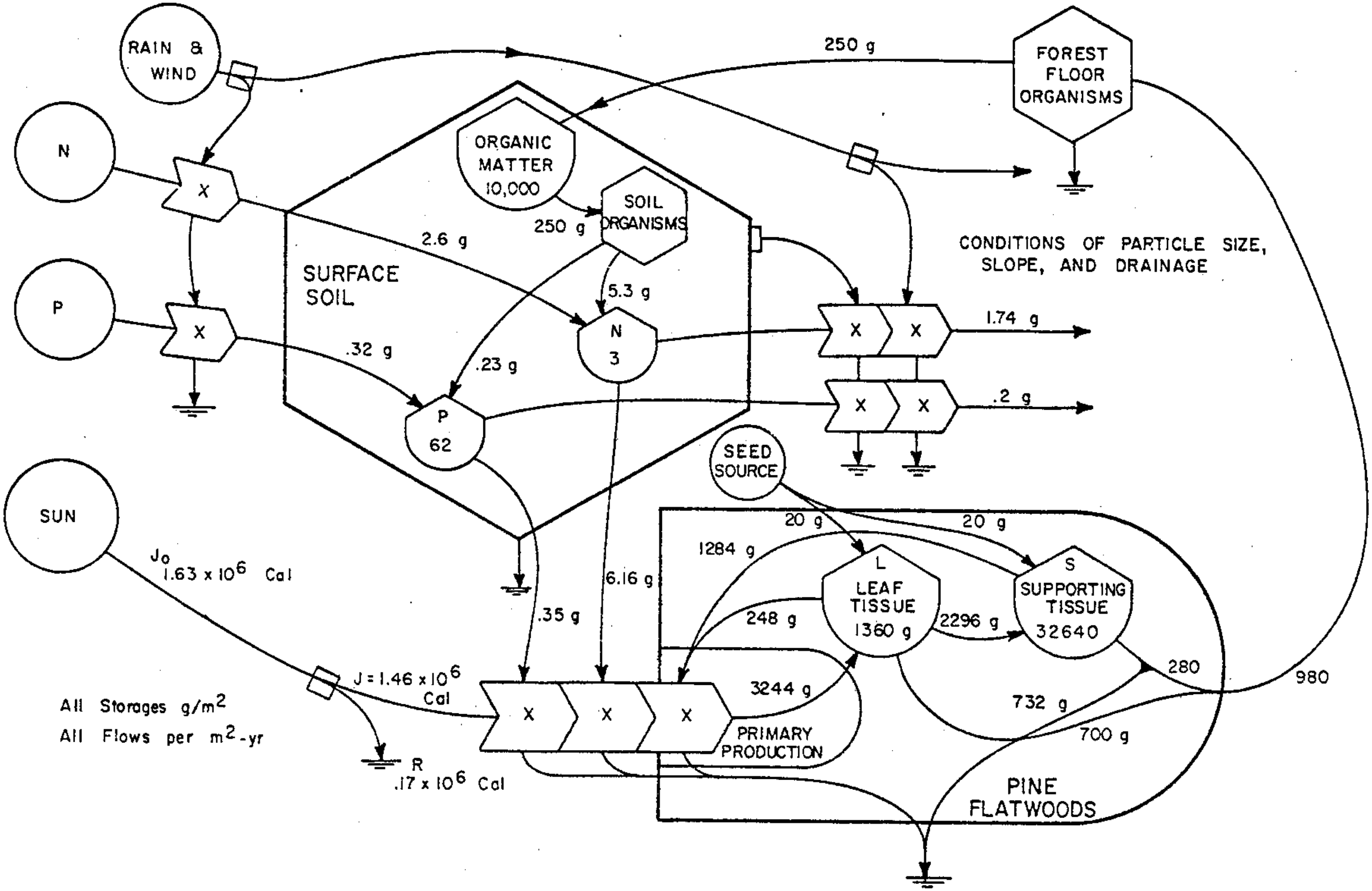
Simulation Model of Mineral Soil

The simulation model was designed to reflect the dynamics of vegetation succession on two typical Florida parent materials, well washed marine sands without nutrient input from weathering limestone (typified by Leon Fine Sands), and a sandy soil with material inputs from weathering limestone (typified by a Perrine Marl). The vegetation system was characterized by a pine flatwoods system. While a mesic hardwood may be considered to be the climax community for Florida, pine flatwoods represent a system held from succession by fire in a steady state and was very prevalent over the state (Monk, 1961).

The final, evaluated model for both soils is given in Figure 8. Figure 8a is the model of limestone derived soil, Figure 8b is the model of soil derived from marine washed sands. Table 6 contains calculations and notes on the values used in the models. The soil system consists of three storages, including organic matter, phosphorous and nitrogen. Nitrogen and phosphorous are shown entering the soil through the action of rain and wind and leaving the system via leaching and volatilization losses. The nutrients cycle within the system are fixed in living plant tissue and litter or soil organic matter.

Figure 8. Models of Florida soil formation with simplified successional dynamics. (a) Soil formed from weathering limestone, evaluated at steady state for Perrine Marl and pine flatwoods vegetation; (b) soil formed from marine deposited quartz sands evaluated at steady state for Leon Fine Sand, pine flatwoods vegetation; (c) differential equations describing the systems.


RAIN & WIND
N
P
SUN
LIMESTONE FROM ISOSTATIC UPLIFT
.003 cm/yr
Jo 1.63 x 10^6 kcal
J = 1.46 x 10^6 kcal
FOREST FLOOR ORGANISMS
250 g
CONDITIONS OF PARTICLE SIZE, SLOPE, AND DRAINAGE
1.29 g
2.3 g
980
SURFACE SOIL
ORGANIC MATTER 7514
250 g
SOIL ORGANISMS
4.85 g
.23 g
N 3
P 132
2.6 g
.32 g
2.1 g
6.16 g
.35 g
SEED SOURCE
20 g
20 g
L LEAF TISSUE 1360
S SUPPORTING TISSUE 32640
248 g
1284 g
2296 g
3,244 g
PRIMARY PRODUCTION
732 g
700 g
280 g
PINE FLATWOODS
X
+
All Storages g/m2
All Flows per m2-yr


RAIN & WIND
N
P
SUN
250 g
FOREST FLOOR ORGANISMS
ORGANIC MATTER 10,000
250 g
SOIL ORGANISMS
SURFACE SOIL
2.6 g
5.3 g
N 3
.32 g
.23 g
P 62
X
CONDITIONS OF PARTICLE SIZE, SLOPE, AND DRAINAGE
1.74 g
.2 g
SEED SOURCE
20 g
20 g
1284 g
L LEAF TISSUE 1360 g
S SUPPORTING TISSUE 32640
248 g
2296 g
280
980
6.16 g
.35 g
3244 g
732 g
700 g
PRIMARY PRODUCTION
PINE FLATWOODS
Jo 1.63 x 10⁶ Cal
J = 1.46 x 10⁶ Cal
R .17 x 10⁶ Cal
All Storages g/m²
All Flows per m²-yr

Differential equations for the system are given with:

J_o = insolation

P = phosphorous

N = nitrogen

L = leaf tissue biomass

S = supporting tissue biomass

O = soil organic matter (humus).

Where:

$$
\begin{aligned}
J_o &= J + R \\
J &= K_o RNP(K_3L + K_2S) \\
R &= \frac{J_o}{1 + K_o NP(K_3 1 + K_2S)} \\
K_o &= \frac{J}{RPN(K_3L + K_2S)} \\
L &= K_4 RNP(K_3L + K_2S) - K_6L - K_7L - K_3RNPL \\
S &= K_7L - K_2RNPLS - (1/k_9 + K_{10})S \\
O &= K_{11}(K_6L + K_{10}S) - K_{13}O \\
N &= J_{21} + K_{19}\,O - K_{22}N - K_{23}RNP(K_3L + K_2S) \\
P &= K_{14}O + J_{17} + J_{24}^{*} - K_{16}P - K_{18}\,RNP(K_3L + K_2S).
\end{aligned}
$$

*Set at zero for soil derived from marine deposited quartz sands.

(c)

Table 6. Sources, storages and flows for Florida soil formation from parent material

Mathematical Expression	Note	Description	Numerical Values		Source
			Marine Sand	Marl	
Jo	a	Solar influx	$1.63\text{x}10^6\frac{\text{Cal}}{\text{m}^2\text{yr}}$	$1.63\text{x}10^6\frac{\text{Cal}}{\text{m}^2\text{yr}}$	Costanza (1975)
J	b	Solar influx dissipated as heat in photosynthetic process	$1.46\text{x}10^6\frac{\text{Cal}}{\text{m}^2\text{yr}}$	$1.46\text{x}10^6\frac{\text{Cal}}{\text{m}^2\text{yr}}$	Odum (1971) Odum & Odum (1976)
R	c	Solar influx remaining for utilization in photosynthesis	$.17\text{x}10^6\frac{\text{Cal}}{\text{m}^2\text{yr}}$	$.17\text{x}10^6\frac{\text{Cal}}{\text{m}^2\text{yr}}$	Steady state calculation
$K_4RPN(K_3L+K_2S)$	d	Gross primary productivity	$3244\ \frac{\text{g}}{\text{m}^2\text{yr}}$	$3244\ \frac{\text{g}}{\text{m}^2\text{yr}}$	Costanza (1975)
K_3RPNL	e	Feedback energy from leaf biomass contributing to photosynthesis	$248\ \frac{\text{g}}{\text{m}^2\text{yr}}$	$248\ \frac{\text{g}}{\text{m}^2\text{yr}}$	Steady state calculation
K_2RPNL	f	Feedback energy from structure contributing to photosynthesis	$1284\ \frac{\text{g}}{\text{m}^2\text{yr}}$	$1284\ \frac{\text{g}}{\text{m}^2\text{yr}}$	Steady state calculation
L	g	Leaf biomass	$1360\ \frac{\text{g}}{\text{m}^2}$	$1360\ \frac{\text{g}}{\text{m}^2\text{yr}}$	Whittaker (1966) in Leith (1975)
S	h	Woody tissue biomass	$32640\ \frac{\text{g}}{\text{m}^2}$	$32640\ \frac{\text{g}}{\text{m}^2}$	Whittaker (1966) in Leith (1975)

Table 6. Continued

Mathematical Expression	Note	Description	Numerical Values		Source
			Marine Sand	Marl	
K_6L	i	Leaf litter fall	700 $\frac{g}{m^2yr}$	700 $\frac{g}{m^2yr}$	Carter <u>et al</u> (1973)
K_7L	j	Energy flow to supporting tissue	2296 $\frac{g}{m^2yr}$	2296 $\frac{g}{m^2yr}$	E. Odum (1971)
K_9S^2	k	Metabolic cost to support woody structure	732 $\frac{g}{m^2yr}$	732 $\frac{g}{m^2yr}$	Whittaker (1966) & Golly (1965)
$K_{10}S^2$	l	Litter fall from woody structure	280 $\frac{g}{m^2yr}$	280 $\frac{g}{m^2yr}$	Carter <u>et al</u> (1973)
$K_{11}(K_6L+K_{10}S^2)$	m	Decay on forest floor	75%	75%	Johnson <u>et al</u> (1968)
0	n	Organic matter in soil	10000 $\frac{g}{m^2}$	7514 $\frac{g}{m^2}$	Gammon <u>et al</u> (1953) Calhoun <u>et al</u> (1974)
$K_{13}0$	o	Loss from organic matter	250 $\frac{g}{m^2yr}$	250 $\frac{g}{m^2yr}$	Steady state calculations
$K_{14}K_{13}0$	p	Phosphorous made available from decomposition of organic matter	.23 $\frac{g}{m^2yr}$	.23 $\frac{g}{m^2yr}$	Brady (1974)
$K_{19}K_{13}0$	q	Nitrogen made available from decomposition of organic matter	5.3 $\frac{g}{m^2yr}$	5.3 $\frac{g}{m^2yr}$	Brady (1974)

Table 6. Continued

Mathematical Expression	Note	Description	Numerical Values Marine Sand	 Marl	Source
J_{17}	r	Influx of phosphorus in rain and dry fallout	.32 $\frac{g}{m^2 yr}$	.32 $\frac{g}{m^2 yr}$	Brezonik et al (1969) Hendry & Brezonik (1969)
J_{21}	s	Influx of nitrogen in rain and dry fallout	2.60 $\frac{g}{m^2 yr}$	2.60 $\frac{g}{m^2 yr}$	Hendry & Brezonik (1976)
$K_{18}RPN(K_3L+K_2S)$	t	Uptake of phosphorus in photosynthesis	.35 $\frac{g}{m^2 yr}$	.35 $\frac{g}{m^2 yr}$	Ovington (1968)
$K_{23}RPN(K_3L+K_2S)$	u	Uptake of nitrogen in photosynthesis	6.16 $\frac{g}{m^2 yr}$	6.16 $\frac{g}{m^2 yr}$	Ovington (1968)
P	v	P storage exclusive of P stored in soil organic matter	62 $\frac{g}{m^2 yr}$	132 $\frac{g}{m^2 yr}$	Gammon (1953) Calhoun (1974) Brady (1974)
N	w	N storage exclusive of N stored in soil organic matter	2 $\frac{g}{m^2}$	2 $\frac{g}{m^2}$	Gammon (1953) Calhoun (1974) Odum (1970)
J_{16}	x	P loss in erosion and solution	.2 $\frac{g}{m^2 yr}$	2.3 $\frac{g}{m^2 yr}$	Steady state calculation
J_{22}	y	N loss in erosion and solution	1.74	1.74 $\frac{g}{m^2 yr}$	Steady state calculation
J_{24}	z	P influx due to weathering and uplift	0.0	2.1 $\frac{g}{m^2 yr}$	Gilliland (1973)

Notes to Table 6

a. The mean yearly values for Tampa, Lakeland, West Palm Beach and Miami is 446.5 ly/day (Costanza, 1975).

$$\frac{446.5\ \text{ly}}{\text{day}}\ \frac{365\ \text{day}}{\text{yr}}\ \frac{1\ \text{cal}}{\text{cm}^2}\ \frac{10000\ \text{cm}^2}{\text{m}^2} = 1.63 \times 10^6\ \frac{\text{Cal}}{\text{m}^2 \cdot \text{yr}}$$

b. The gross primary productivity is 3244 grams/$\text{m}^2 \cdot$ yr. Literature values indicate a ratio of 100 heat calories of sunlight dissipated for each calorie of sugar produced (E. Odum, 1971; p. 56; Odum and Odum, 1976, p. 79).

$$3244\ \frac{\text{gr}}{\text{m}^2\text{yr}}\ \frac{4.5\ \text{Cal}}{\text{gr}}\ \frac{100\ \text{Cal sun}}{\text{Cal sugar}} = 1.46 \times 10^6\ \frac{\text{Cal}}{\text{m}^2 \cdot \text{yr}}$$

c. Photo synthesis is limited by light. $R = J_0 - J = .17 \times 10^6$ Cal/yr $\cdot\ \text{m}^2$, when photosynthesis is at the steady state specified in note b.

d. Woodnell, 1968, measured 40.0 Cal/$\text{m}^2 \cdot$ day (Costanzana, 1975).

$$\frac{40\ \text{Cal}}{\text{m}^2\text{day}}\ \frac{365\ \text{days}}{\text{year}}\ \frac{1\ \text{gr}}{4.5\ \text{Cal}} = 3244\ \frac{\text{g}}{\text{m}^2\text{yr}}$$

e. One of the objects of the model is to simulate the changing P/R ratio evidenced in succession. Data from Golly (1965) indicate that a ratio of 2.12 is appropriate for a broomsedge community in early successional stages (see note k for late succession). Respiration costs in the model are split into two components as follows: respiration associated with productivity and the metabolic cost of woody support tissues. Based on this assumption, the total respiration associated with productivity is calculated to be 1532 $g/m^2 \cdot yr$ (1/2.12 x 3244 $g/m^2 \cdot yr$). The feedback attributed to the leaf biomass was found by balancing the inputs and outputs from the leaf biomass storage (see notes i and j).

$$(3244 - 700 - 2296) \frac{g}{m^2 yr} = 248 \frac{g}{m^2 yr}$$

f. The same rationale as in note e was employed (see notes j, k, l).

$$(2296 - 732 - 280) \frac{g}{m^2 yr} = 1284 \frac{g}{m^2 yr}$$

g. Standing biomass of a pine system reported as 34,000 g/m^2 dry weight, 4% of its leaf matter (Whittaker, 1966, in Leith, 1975).

$$.04 \times 34000 \frac{g}{m^2} = 1360 \frac{g}{m^2}$$

h. See note g. (34000 - 1300) g/m^2 = 32646.

i. Whittaker reports a net productivity of 980 $g/m^2 \cdot yr$ (see note g). The percentage of leaf matter in litterfall was found by Carter et al. (1973) to be roughly 70%. A value of 700 $g/m^2 \cdot yr$ was chosen.

j. Energy flow to the woody structure was calculated from the turnover times for woody tissue reported in the literature (E. Odum, 1971, p. 375-376). Turnover times range from 12.4 yrs in an oak-pine forest to 20 yrs for mature broad-leafed evergreen temperature forests. A value of 14.22 yrs was chosen.

$$\frac{32640\ \mathrm{g}}{\mathrm{m}^2\ \ 14.22\ \mathrm{yrs}} = 2296\ \frac{\mathrm{g}}{\mathrm{m}^2\mathrm{yr}}$$

This value is considered rough and was determined after experimentation with various values for this flow.

k. See note e. The metabolic cost of woody structure was determined as the difference between the respiration costs early in succession (P/R = 2.12) and the respiration costs late in succession with net productivity and gross primary productivity (see notes d and g). Gross-Net-Production Respiration = Structure Respiration.

$$\frac{(3244)}{(3244 - 980)} = 1.43$$

$$(3244 - 1532 - 980)\ \frac{\mathrm{g}}{\mathrm{m}^2\mathrm{yr}} = 732\ \frac{\mathrm{g}}{\mathrm{m}^2\mathrm{yr}}$$

The relatively large P/R ratio for late succession reflects the general opinion that pine systems are not climax communities in Florida, but are functional climaxes due to the influences of fire (Monk, 1968; Veno, 1974).

l. See note i.

m. The turnover time for litter is quite short, in the order of a year or two (Carter, et al., 1973). The turnover time for litter and humus is longer, for example, 60 years in a temperate zone (New Hampshire) forest receiving approximately 48 inches of rain (Johnson et al., 1968). Based on the warmer climate and greater rainfall of Florida, a turnover time of 40 years seems reasonable. Based on the storage of organic matter (see note 14), the input to soil humus was thus calculated to determine the amount of decomposition which occurred on the forest floor.

$$\frac{10000\ \text{g}}{\text{m}^2\ 40\ \text{yr}} \quad \frac{\text{m}^2\text{yr}}{980\ \text{g}} = .75$$

n. Organic storage in the soil was calculated from the reported value of 1.22% organic for the first two feet of Leon Fine Sand (Gammon, et al., 1953). Bulk density was calculated from the empirical formula, BD + -.2075 ln (% Organic) + 1.3978.

$$\frac{1.35\quad \text{g}\quad 6.096 \times 10^5\ \text{cm}^3\quad .0122}{\text{cm}^3 \qquad\qquad \text{m}^2} = 10000\ \frac{\text{g}}{\text{m}^2}$$

Likewise solving for the Perrine Marl (Calhoun, et al., 1974)

$$\frac{1.43\quad \text{g}\quad 6.096 \times 10^5\ \text{cm}^3\quad .00862}{\text{cm}^3 \qquad\qquad \text{m}^2} = 7514\ \frac{\text{g}}{\text{m}^2}$$

o. Steady state calculation, input = output to soil organic matter.

p. Calculated from .09% (Brady, 1974, p. 364). P by dry wt in humus.

$$.0009\quad 250\ \frac{\text{g}}{\text{m}^2\text{yr}} = .23\ \frac{\text{g}}{\text{m}^2\text{yr}}$$

q. The N in humus varies from 2.12% (Odum and Pigeon, Eds., 1970) to 2.5% (Brady, 1974). Using the lower figure:

$$\frac{.0212\qquad 250\qquad \text{g}}{\text{m}^2\text{yr}}\quad 5.3\ \frac{\text{g}}{\text{m}^2\text{yr}}$$

r. Total phosphorous concentration for central Florida range from .077 mg/liter and .033 mg/liter (Hendry and Brezonik, 1976; Brezonik, et al., 1969 in Gilliland, 1976). Assuming 55 inches of rain per year (Vishner, 1969) and a mean concentration of .055 mg/liter, the annual loading rate was calculated.

$$\frac{55\text{ in}}{\text{yr}}\;\frac{2.54\text{ cm}}{\text{in}}\;\frac{1\times10^4\text{ cm}^2}{\text{m}^2}\;\frac{.055\text{ mg}}{\text{liter}}\;\frac{\text{liter}}{1000\text{ cm}^3\;1000\text{ gm}}$$

$$= \quad .077\ \frac{\text{g}}{\text{m}^2\text{yr}} \ .$$

Dry fallout has a loading rate of $.24\ \frac{\text{g}}{\text{m}^2\text{yr}}$.

Total phosphorous influx $= .32\ \frac{\text{g}}{\text{m}^2\text{yr}}$.

The dry fallout rates are most likely high due to modern agricultural activities.

s. Total nitrogen influx was determined from the TKN + NO_3 concentrations in rain and dry fallout (Hendry and Brezonik, 1976). Total nitrogen = 1.44 mg/liter in a rainfall. Total nitrogen in dry fallout = 1.8 g/m^2 · yr.

As in note r:

$$\frac{1.44\text{ mg}}{\text{liter}}\;\frac{55\text{ in}}{\text{yr}}\;\frac{1\times10^4\text{ cm}^2}{\text{m}^2}\;\frac{\text{liter}}{1000\text{ cm}^3}\;\frac{\text{g}}{1000\text{ gm}} = .79\ \frac{\text{g}}{\text{m}^2\text{yr}}$$

Total nitrogen $= 2.60\ \frac{\text{g}}{\text{m}^2\text{yr}}$

t. For each unit of P taken up by the tree system .33 units are retained. (Ovington, p. 95 in Eckardt, 1968) (see note p). Calculated for P released from organic matter:

$$\frac{.23\ \text{g}}{\text{m}^2\text{yr}\quad .66} = .35\ \frac{\text{g}}{\text{m}^2\cdot\ \text{yr}}$$

u. For each unit of N taken up by the tree system .15 units are retained (Ovington, p. 95 in Eckardt, 1968). Calculated from N released from organic matter (see note q):

$$\frac{5.3\ \text{g}}{\text{m}^2\text{yr}\quad .86} = \frac{6.16\ \text{g}}{\text{m}^2\text{yr}}$$

v. Leon Fine Sands have a total P content of .0086% in the first two feet of soil (Gammon _et al_., 1953). Total P is then calculated based on bulk density as in note n.

$$\frac{1.35\ \text{g}\qquad 6.096\times 10^5\text{cm}^3\qquad .000086}{\text{cm}^3\qquad\qquad \text{m}^3} = 71\ \frac{\text{g}}{\text{m}^2}$$

Assuming .09% P by dry wt in humus, the portion of P contained in the organic fraction is determined (see notes n and p).

$$\frac{10000\ \text{g}}{\text{m}^2}\ .0009 = 9\ \frac{\text{g}}{\text{m}^2}$$

P stored in the mineral fraction of the soil is then 71 - 9 = 62 g/m^2. Perrine Marl is .016% P and solving in a likewise manner (see note n).

$$\frac{1.43\ \text{g}\qquad 6.096\times 10^5\text{cm}^3\qquad .00016}{\text{cm}^3\qquad\qquad \text{m}^2} = 139\ \frac{\text{g P}}{\text{m}^2}$$

Stored in the organic fraction:

$$\frac{7514\ \text{g}\quad .0009}{\text{m}^2} = 7\ \text{g P}$$

Total P stored in the mineral fraction of Perrine Marl = 132 g P.

w. Leon Fine Sand has a total N content of .026 in the first two feet of soil (Gammon, 1953). Solving as in note v:

$$\frac{1.35\ \text{g}}{\text{cm}^3}\ \frac{6.096 \times 10^5\ \text{cm}^3}{\text{m}^2}\ .00026 = 214\ \frac{\text{g N}}{\text{m}^2}$$

$$\frac{10{,}000\ \text{g O.M.}\quad .0212}{\text{m}^2} = 212\ \frac{\text{g N}}{\text{m}^2}$$

$2\ \frac{\text{g N}}{\text{m}^2}$ is stored in the inorganic fraction.

For Perrine soil, with N = .017% (Calhoun, et al., 1974):

$$\frac{1.43\ \text{g}}{\text{cm}^3}\ 6.096 \times 10^5\ \text{cm}^3\ .00017 = 148\ \frac{\text{g N}}{\text{m}^2}$$

Assume 2 g N stored in the inorganic fraction.

x. Input = output at steady state.

y. Input = output at steady state.

z. Erosion is balanced by isostatic shift at the rate of .003 m/1000 yr (Gilliland, 1976). Assuming that the limestone is 10% $CaPO_3$ by wt (Gilliland, 1976) the net flux of P into a soil of limestone origin can be calculated:

Limestone = $2.65 \frac{g}{cm^3}$ $CaPO_3$ = .26% P by wt

$$\frac{2.65\ g \quad .003\ cm \quad 10{,}000\ cm^2 \quad .10 \times .26}{cm^3 \qquad yr \qquad m^2} = 2.1 \frac{g\ P/m^2}{m^2}$$

Soils formed on marine washed sands are atop the phosphatic rocks and thereby do not receive this phosphorous subsidy.

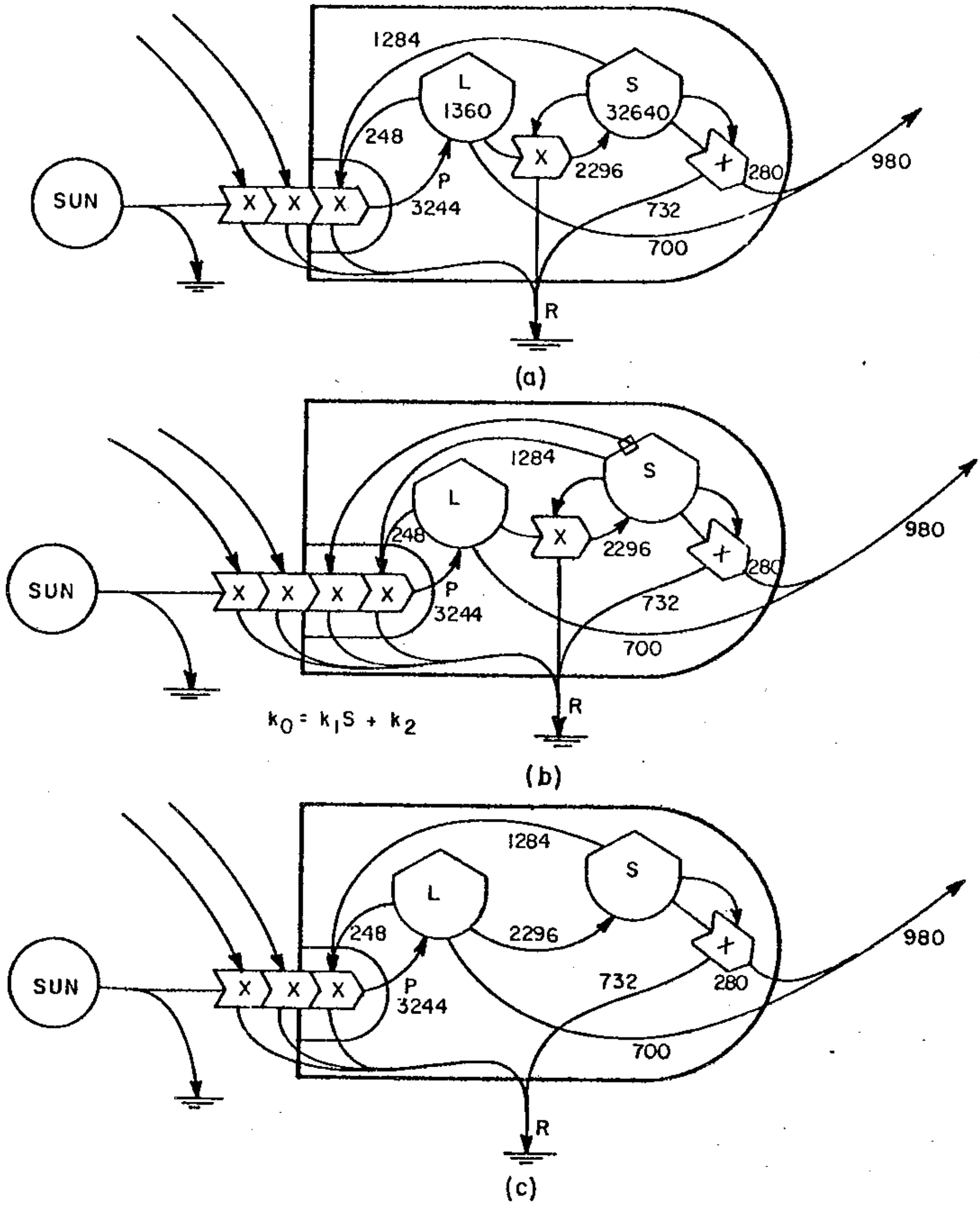
The model was arranged to produce tissue early in succession which is relatively inexpensive in energy terms. This production provides the energy necessary to produce wood structure at a slower rate, which eventually enhances the photosynthetic capability of the leaf tissue. The higher quality structure of limbs and roots spatially arranges leaves, increases the effective area and nutrient capture, and creates energy storages which allow the system to better track the growth seasons.

Model Configurations

Several configurations were tested before settling on the configuration of succession in the vegetation unit of Figure 8. The configurations of succession which were tested by simulation simulated under optimal soil conditions are presented in Figure 9. The multiplier between the leaf and supporting tissues in Figures 9a and 9b was the result of a hypothesis that the energy allocated to support structure was in proportion to the amount of support structure. The square drain on support structure in Figure 9 was the result of a hypothesis that the metabolic cost of structure increased exponentially in response to the amount of structure.

Configuration A was the first model tested, using the data of Table 6. This model tended to accumulate unrealistically large amounts of leaf tissue in the first few years due to the small drain on the tank. When a sensor of the amount of supporting structure was used to change the photosynthetic efficiency of the system (Configuration B), leaf biomass initially behaved in a realistic

Figure 9. Model configurations of successional dynamics which were tested. (a) basic Model with productivity increased by but not requiring structure; (b) with productivity controlled by structure; (c) without autocatalytic growth of structure.



L = LEAF TISSUE
S = SUPPORT TISSUE
P = GROSS PRIMARY PRODUCTIVITY
R = RESPIRATION

VALUES = GRAMS DRY WEIGHT
STORAGES = PER M^2
FLOWS = PER M^2 - YEAR

fashion, but structure took an unrealistically long time to build, in the order of 250-300 years. If simulated over long time periods, the leaf and structure storages would oscillate in a predator-prey fashion. When configuration C was tested, with a passive flow between leaf and support structure, the problem of leaf overshoot was eliminated and structure built at a realistic rate. However, when configuration C was used to simulate soil formation, the exponential drain allowed structure to accumulate at an unrealistically high rate. This final difficulty was eliminated with a first order drain on support structure, as in Figures 8a and 8b.

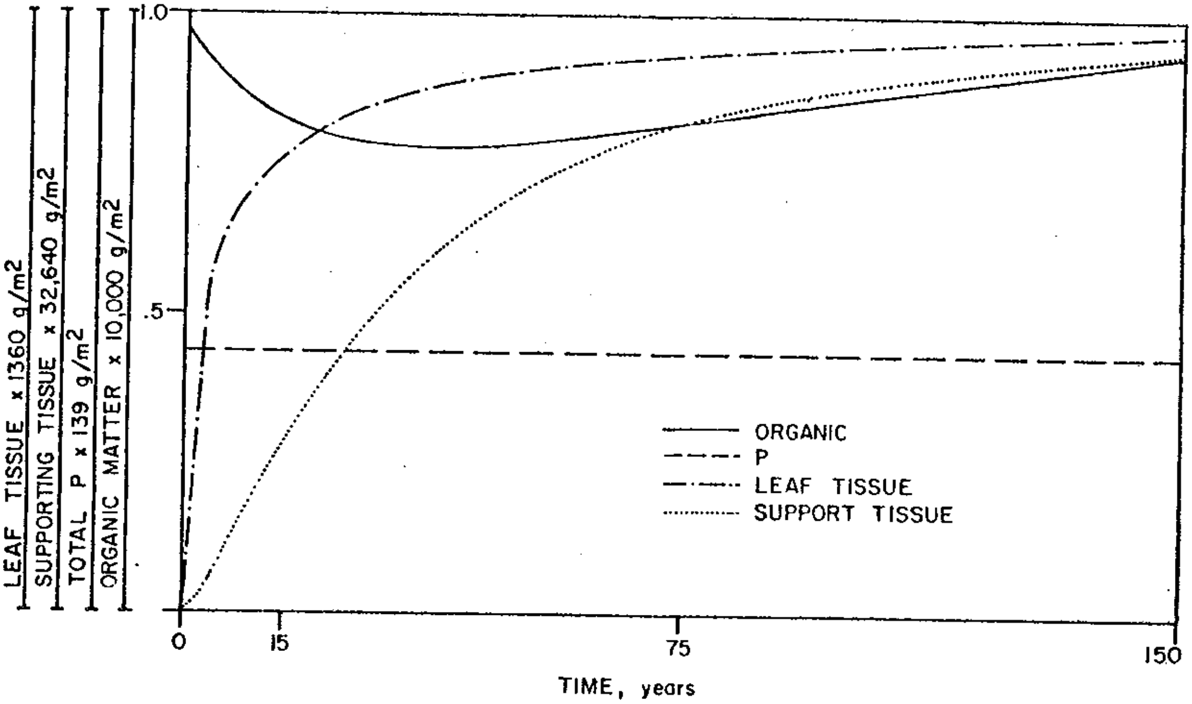
Results of Simulation

The results of simulation of vegetation succession are presented in Figure 10 and soil formation in Figure 11.

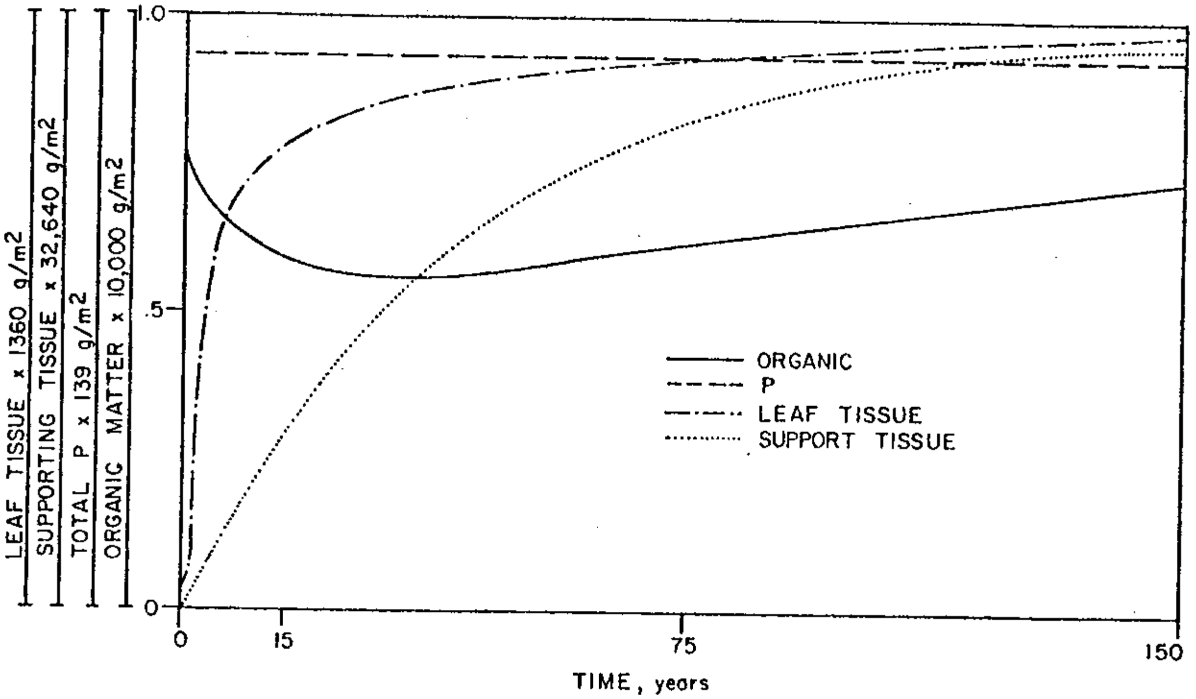
The amount of time required to reach a substantial amount of biomass through succession, about 75 years, in both Figure 10a and 10b is consistent with data from Odum (1968) and with estimations of sixty years for a mature pine stand. The results for the early stages of succession are probably high, compared to the 1000 g/m^2 stocks reported by Odum (1960) and Golley (1965). However, Florida does have a longer growing season than the Georgia fields of these studies, which would tend to increase the potential standing stocks somewhat.

Differences in the rate of soil formation for the two soil types are seen in Figure 11. The soil without limestone weathering reached maturity in 525 years (see Figure 11a). The soil with the high rate of influx of P from weathering limestone reached maturity in 375 years (see Figure 11b). Nitrogen was not shown in the plot because it very closely followed the soil organic matter.

Figure 10. Simulation results of vegetative succession: (a) marine deposited quartz sand; (b) limestone marl.

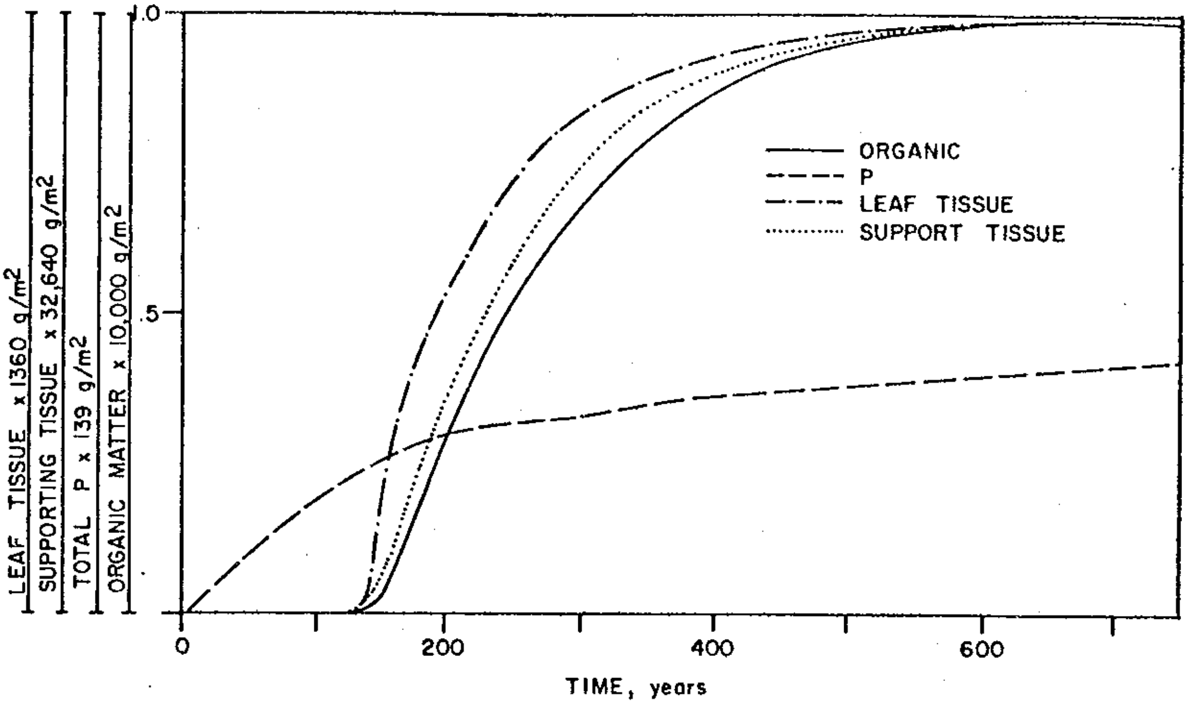

LEAF TISSUE x 1360 g/m2
SUPPORTING TISSUE x 32,640 g/m2
TOTAL P x 139 g/m2
ORGANIC MATTER x 10,000 g/m2
1.0
.5
0
15
75
150
TIME, years
ORGANIC
P
LEAF TISSUE
SUPPORT TISSUE

(A)

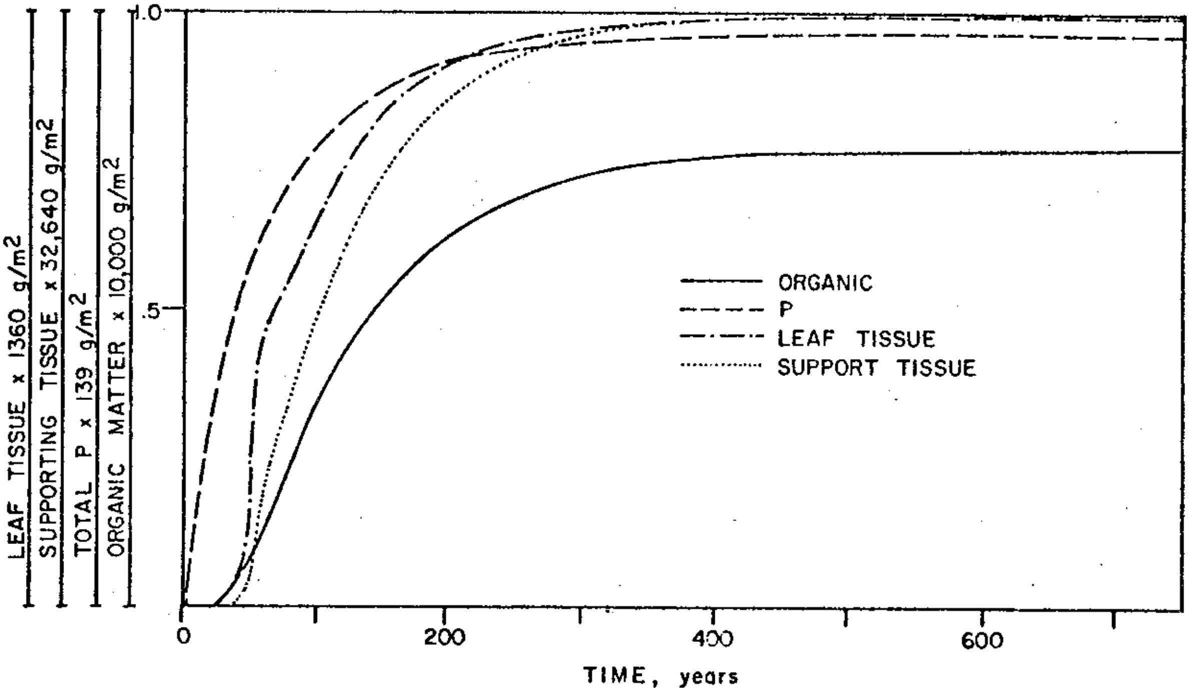

LEAF TISSUE x 1360 g/m2
SUPPORTING TISSUE x 32,640 g/m2
TOTAL P x 139 g/m2
ORGANIC MATTER x 10,000 g/m2
1.0
.5
0
0
15
75
150
TIME, years
ORGANIC
P
LEAF TISSUE
SUPPORT TISSUE

(B)

Figure 11. Results for simulation of soil formation from: (a) marine deposited quartz sand; (b) limestone marl.


LEAF TISSUE x 1360 g/m2
SUPPORTING TISSUE x 32,640 g/m2
TOTAL P x 139 g/m2
ORGANIC MATTER x 10,000 g/m2
1.0
.5
0
200
400
600
TIME, years
ORGANIC
P
LEAF TISSUE
SUPPORT TISSUE

(A)


LEAF TISSUE x 1360 g/m2
SUPPORTING TISSUE x 32,640 g/m2
TOTAL P x 139 g/m2
ORGANIC MATTER x 10,000 g/m2
1.0
.5
0
200
400
600
TIME, years
ORGANIC
P
LEAF TISSUE
SUPPORT TISSUE

(B)

Odum's (1969) summary of successional attributes included the changing biomass supported per unit energy flow (B/E) ratio, which changes from low early in succession to high late in succession, and is similar to the dynamic modeled here.

In the model, leaf tissue has a fast turnover rate and cannot reach the maximum photosynthetic rate without energy contribution from the supporting tissue. The leaf tissue has a relatively low metabolic cost, and before the supporting structure is built, the P/R ration is relatively high, a characteristic of early successional states. The metabolic cost of supporting tissue, when added to the metabolic cost of the leaf tissue, pulls the P/R ratio down while increasing the gross primary productivity. The maximum rate of photosynthesis in the model is limited by sunlight. The changing P/R ratio has the effect of initially boosting the net organic matter production with contributes to the soil organic matter. An early version of the model without successional characteristics took unrealistically long (600-750 years) times to develop vegetative structure under initially excellent soil conditions.

Time for Organic Soil Formation

Estimates of the time for organic soil formation are based on the age of peat and the depth of the formation. Estimated rates of peat formation from the literature are presented in Table 7 along with the methodology used to obtain each rate. The first five values were included to indicate the ranges in rates of peat formation found around the world. The sixth value, reported by Davis (1946) is also

Table 7. Rates of peat formation

No.	Rate CM/Year	Location	Method	Source
1	0.020	Sweden	Carbon 14 dating of basal peat	Davis and Lucas, 1959
2	0.036	Africa	Carbon 14 dating of basal peat	Davis and Lucas, 1959
3	0.064	Unspecified	Unspecified	Davis and Lucas, 1959
4	0.075	Japan	Carbon 14 dating of basal peat	Davis and Lucas, 1959
5	0.11	Michigan	Carbon 14 dating of basal peat	Davis and Lucas, 1959
6	0.14	Everglades	Ratio of SiO_2 in plant to SiO_2 in peat (1:7)	Davis, J.H., 1946
7	0.061	Everglades, Belle Glade	Carbon 14 dating of basal peat	Schroeder, Klein, and Hoy in White, 1970
8	0.0152-0.0076	Everglades	Carbon 14 dating of first 20 cm of basal peat	McDowell, Stephens and Steward, 1969
9	0.073	Everglades	Carbon 14 dating of stratified samples. 20-180 cm of profile	McDowell, Stephens and Steward, 1969

presented as a comparison although it is felt that his estimation was in error. His rate was based on the assumption that the difference in the SiO_2 content of sawgrass (0.3%) and the peat (2.2%) is solely due to the concentration effect of decomposition and neglects the input of SiO_2 from overland water and rain. He estimated the productivity of sawgrass to be a value substantially lower than recent reports, and a peat bulk density of 0.13 g/cm^3 (calculated from his estimated 180 tons dry wt/acre foot), which is substantially less than the accepted value of 0.3 g/cm^3.

The last two values in the table are based on a more detailed stratigraphic analysis of radio-carbon-dated peat then value seven. The last two values (eight and nine) indicate that the rate of peat formation accelerated through time. Value eight represents the rate of formation of the basal peat (first 20 cm) while value nine represents the maintained rate of peat formation (20 to 180 cm). This rate, of 0.073 cm/yr, is a bit higher than the seventh estimation of .061 cm/yr, representing a net production rate.

Some values may be low if peat accumulation slowed due to low water tables.

Peat and mucks are somewhat different in chemical composition than their original plant material. The sugars, starches, proteins and hemicelluloses are usually the first materials to be utilized by microorganisms, leaving the remaining material rich in cellulose, lignins, fats and waxes (Waksman and Stevens, 1929). Based on the percent composition of original plant material, if cellulose, lignin, fats and waxes were anaerobicly undecomposed, approximately 40 to 60 percent of the original plant material would remain (Brady, 1974). In lieu of an empirical value for anaerobic decomposition, this range of values was compared to decomposition rates found by back calculating from productivity, bulk density and radio-carbon dating data.

Based on the rate of peat formation, at a formation rate of 0.073 cm/yr and a bulk density of 0.3 g/cm^3, the required amount of organic matter for peat formation is roughly 730 g/cm · yr. Based on net productivity of sawgrass of 1,056 g/m · yr (Steward and Ornes, 1975), the percent organic matter having to remain per year is 69 percent. This value is substantially greater than the 14 percent assumed by Davis (1946). Retaining the steady-state standing stock of sawgrass found by Steward and Ornes (3,231 g/m^2), but using the regrowth rate of two years suggested by Loveless (1959), the percent remaining after decomposition would have to be 45 percent in order to maintain a peat formation rate of 0.073. cm/yr. These percentages (69 and 45) are in line with the percentage of original plant material theoretically not readily available for anaerobic decomposition (Brady, 1974). It was assumed that peat formation was not limited by aerobic decomposition.

The Energy Cost of Mineral Soil

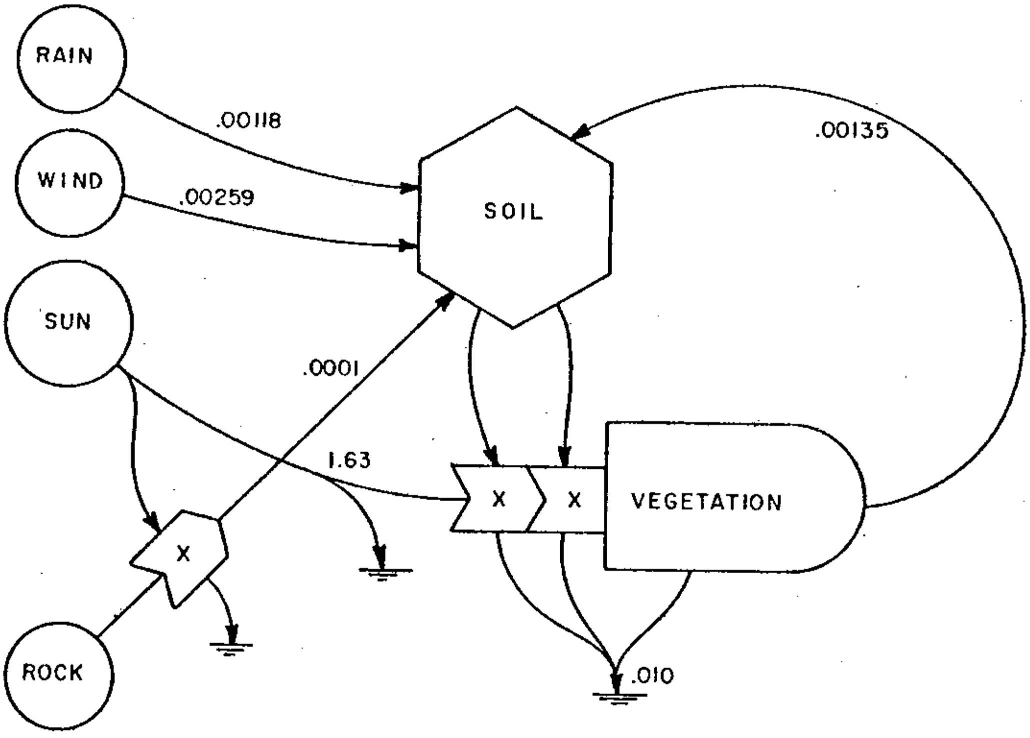
If the simulation model is correct, the energy required to maintain the storage of soil is generated at the rate of 1.35 x 10^3 Cal/m^2 · yr (250 g/m^2 · yr x 5.4 Cal/g) based on the organic content of the soil. Variability of the time required to form soil at this rate of humic production varied from 375 to 525 years, times which are relatively short but not unrealistic.

Figure 12 contains models of mineral soil formation, expressed both in heat equivalents and solar calorie costs. Table 8 contains details of the calculated solar costs for soil. The solar calories costs for each soil forming factor calorie from Table 5 were multiplied by the calorie flux from Table 4 to obtain the solar calorie equivalent for each factor. Those factors which were derived from local sunlight as by-products were not added into the calculation in order to avoid double counting. The final costs ranged from 7.15×10^3 to 8.78×10^3 solar calories per calorie of soil energy. A round value of 8.0×10^3 was used as the solar energy cost quality factor per calorie of minerial soil.

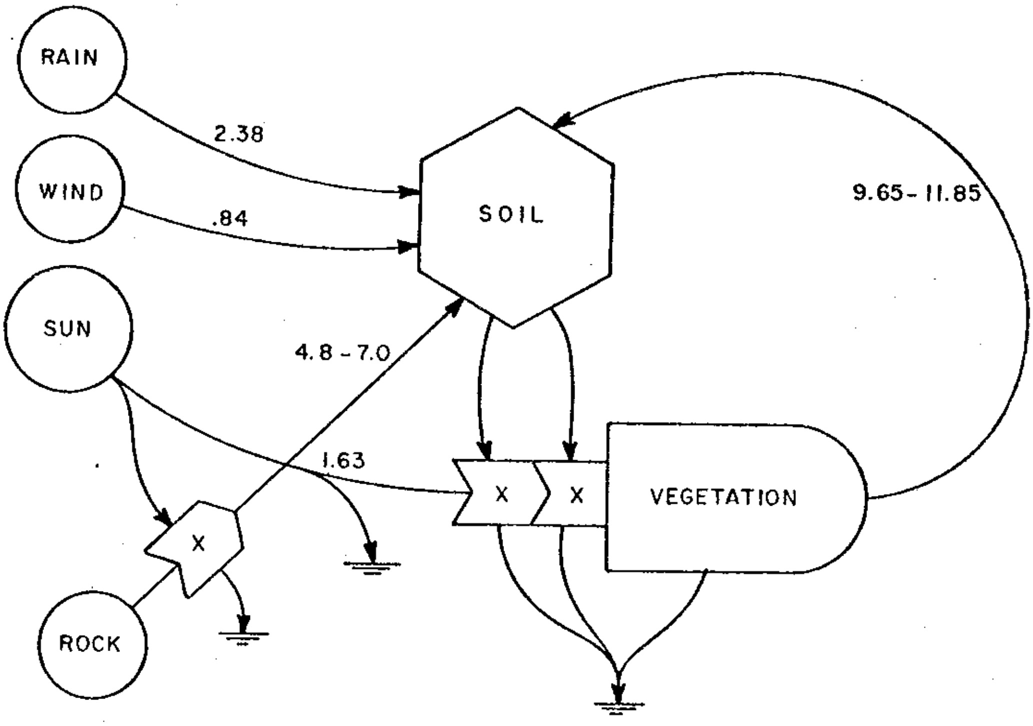
The Energy Cost of Organic Soil

Figure 13 contains the heat equivalent flows of rain, sun and organic matter into peat. Models of mineral soil formation included wind and rock energies, which were not considered necessary for peat formation, since peat is usually formed under water and is predominantly organic. The solar cost of rain was calculated by multiplying the calorie flow of rain from Table 4 by its solar calorie cost per calorie in Table 5. The solar cost of sunlight is 1.0 by definition. The solar cost of the new peat was found by adding the solar costs of sun and rain since the rain represents an import of energy.

Figure 12. Energy costs of mineral soil formation (Cal/$m^2 \cdot yr$) (a) heat equivalents (b) solar cost equivalents.


RAIN
WIND
SUN
ROCK
SOIL
VEGETATION
X
X
X
.00118
.00259
.0001
1.63
.00135
.010

(a)


RAIN
WIND
SUN
ROCK
SOIL
VEGETATION
X
X
X
2.38
.84
4.8 - 7.0
1.63
9.65 - 11.85

(b)

Table 8. Details of the energy cost of mineral soil in Florida based on Figure 17

Environmental Flux	Solar Calorie Equivalent[a] x 10^6 Cal/m^2·year	x 10^3 Cal/Cal
Sunlight	1.63	
Rain	2.38	
Wind	.84	
Uplift of Rock	3.25	
Heat of Limestone Formation[c]	1.55	
Phosphorus Concentrated in Limestone Rock[d]	2.20	
Total	11.85	8.78
Total Without Phosphorus Concentrated in Rock	9.65	7.15

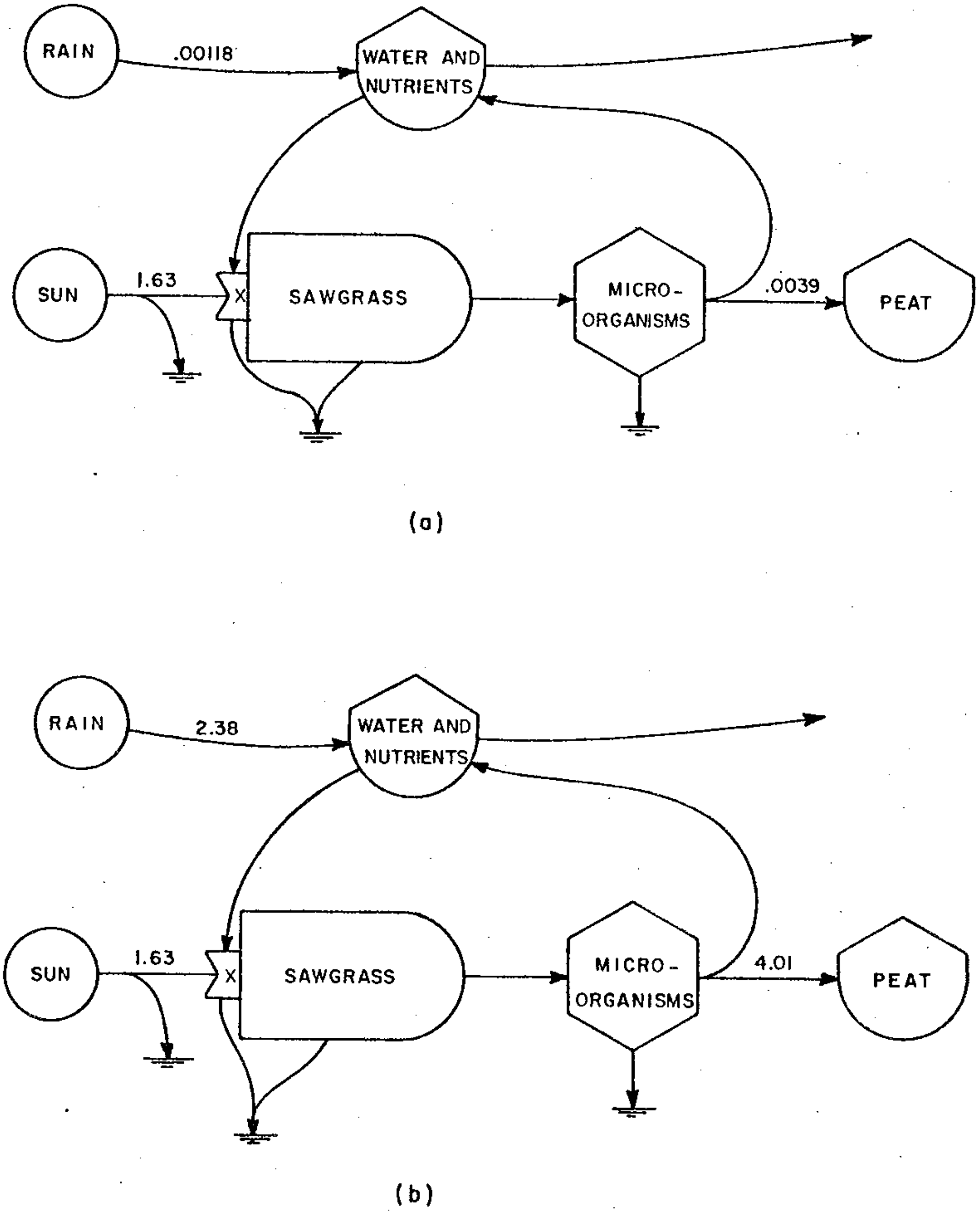
[a] Calculations made by multiplying the heat equivalents from Table 4 by their costs in Table 5.

[b] Assuming organic matter represents soil energy and is being generated at a rate of 250 g/m^2·yr with a calorie content of 5.4 Cal/gram, soil is being generated at 1.35x10^3Cal/m^2·yr. The solar calorie costs per calorie of soil are calculated by dividing the annual solar costs by the annual energy storage.

[c] Since no comparable value for quartz sand was determined, this is taken to be a minimum value.

[d] Appropriate only for phosphatic sands.

Figure 13. Heat and solar equivalents of Everglades peat formation (Cal/$m^2 \cdot yr$). (a) Heat equivalents. (b) solar equivalents.


RAIN
.00118
WATER AND NUTRIENTS
SUN
1.63
X
SAWGRASS
MICRO-ORGANISMS
.0039
PEAT
(a)
RAIN
2.38
WATER AND NUTRIENTS
SUN
1.63
X
SAWGRASS
MICRO-ORGANISMS
4.01
PEAT
(b)

The solar cost per calorie of peat was then calculated as 1,018 Cal/Cal peat (4.01/0.0039). A round value of 1.0×10^3 was used as the solar energy cost quality factor per calorie of mineral soil.

Correlation of County Production Models and Urban Growth

Statistical characteristics of variables and their independence are measured in Tables 9 and 10. In Table 11 the variance in urban growth explained by natural energies is given for each model and scattergrams are given in Figures 13 - 16. Table 12 has the effect of each variable on urban growth. Figure 17 presents a scattergram showing the relation of urban growth rates with urban density at different levels of natural energy. Finally, Table 13 contains results from multiple regression analysis of rates of change of urban structure with the rate of change of the logistic model of urban growth (see Figure 6c). Explanation of each of these follows:

Characteristics of Independent Variables

Table 9 contains the means, standard deviations, ranges, and coefficient of variation of the per acre values of the independent variables. Raw data is given in Table C-2 of the appendix. The coefficient of variation was calculated as $Sx/\overline{x}$ and is useful for comparing the relative degree of variation for each variable in a set of variables. As seen in Table 9, the variables demonstrate a wide range of variation (greater than 50%), except for sunlight, rainfall, gross primary productivity and mineral soils. While gross primary productivity and the organic contents of mineral soil are known to be quite heterogeneous on a micro level, this variability appears to be highly diminished on a county level.

Intercorrelation of Independent Variables

Intercorrelations among the independent variables are presented in Table 10. Significance was defined as $\alpha < 0.05$. This table was generated in order to examine the potential difficulties collinearity might present. The strongest correlations are between sunlight (which increases north to south) with aquifer storage (which decreases north to south) and natural productivity, which generally decreases going south as scrub cypress, wet prairie, and grassland gain dominance over the forests further north. Mineral soil and organic soil energy are inversely correlated, a tautological relationship since these categories are mutually exclusive. The percentage of variance which is explained by the relationship (r^2)

Table 9. Parameters of the independent variables for counties in Florida (N = 67)

Variable	Mean	Standard Deviation	Range	Coefficient of Variation
Sunlight per Acre x 10^6 CE/Acre·Year	3.164	0.046	0.174	0.0145
Rainfall per Acre x 10^6 CE/Acre·Year	14.19	0.986	4.772	0.0695
Aquifer Storage per Acre x 10^6 CE/Acre·Year	28.103	16.827	76.423	0.598
Wave Energy per Acre x 10^6 CE/Acre·Year	0.25	0.370	1.618	1.48
Gross Primary Production per Acre x 10^6 CE/Acre·Year	7.14	0.883	3.910	0.123
Mineral Soil Storage per Acre x 10^6 CE/Acre·Year	623.34	138.07	856.0	0.222
Organic Soil Storage per Acre x 10^6 CE/Acre·Year	918.03	2788.43	1669.0	3.03

Table 10. Correlations among independent variables

Variable (units/acre)	Rain	Aquifer	Wave	Productivity	Mineral	Organic
Sunlight	-0.2918* 67 0.008	-0.4694* 67 0.001	0.1428 67 0.125	-0.6842* 67 0.001	-0.0633 67 0.305	0.4466* 67 0.001
Rainfall		0.2203* 67 0.037	0.1127 67 0.182	0.1883* 67 0.063	-0.1318 67 0.144	0.0932 67 0.227
Aquifer Storage			-0.3923* 67 0.0001	0.3348* 67 0.003	0.2058* 67 0.047	-0.2497* 67 0.021
Wave Energy				-0.3395* 67 0.002	-0.1667 67 0.089	0.1291 67 0.149
Natural Gross Primary Productivity					0.0390 67 0.377	-0.3141* 67 0.005
Mineral Soil Energy						-0.4603* 67 0.001

LEGEND: r, coefficient of correlation
N, number of cases
alpha

* alpha = .05

is seen to not exceed 46% in any case and is only greater than 22% in one case. The 60% tolerance for stepwise regression (see Methods) appears adequate.

Correlation Results Using Models Without Limiting Factors

To review, four basic models for measuring natural energy interactions were tested, additive and multiplicative methods with and without feedback from structure. In order to test the hypothesis that some natural energies are more differentially associated with urban growth, empirical methods were used to select the energies which most strongly reduced the sum of square of error of each of the four versions of the model. The separated process model with multiplicative feedback from structure and additive interactions did not presuppose the constants involved in the additive interaction, hence the "deterministic" version of this model only differed from the "empirical" method insofar as the first model forced all factors into the regression equation and the second model entered factors in a stepwise fashion, stopping when the tolerance or F limits discussed in Methods were reached. Table 11 contains results of regression analysis of the eight models. The influence of the separate factors involved in the empirical versions will be presented in a subsequent section. As a point of vocabulary, "deterministic models" refer to calculations into which all natural energies are entered while "empirical models" refer to the results of stepwise regression. Three time periods were employed for two reasons. First, it was

Table 11. Comparison of variance in urban growth explained by the natural energy interaction models of county productivity

Model	Parameter[2]	All Natural Energies Included			Empirical Estimation[1]		
		1930	'65, '70, '75	1975	1930	'65, '70, '75	1975
Additive Interaction without Feedback from Structure (see Figure 5a)	R	.09222	0.26347*	0.24255*	0.43748*	0.49875*	0.49270
	R^2	0.00850	0.06942	0.05883	0.19139	0.23875	0.24275
	df	65.	199	65	3, 63	4, 196	3, 63
	F	α=0.229	α=0.00008	α=0.024	4.97	16.22	6.73
Separated Processes, Each with Multiplicative Feedback from Structure and Additive Interaction (see Figure 5b)	R	0.91655*	0.95202*	0.97295*	0.9107*	0.94796*	0.96556*
	R^2	0.84007	0.90635	0.94664	0.82940	0.89863	0.93230
	df	7, 59	7, 193	7, 59	3, 63	3, 197	3, 63
	F	44.3	266.8	149.5	102.1	582.11	289.2
Multiplicative Single Process Interaction Without Feedback from Structure (see Figure 5a)	R	0.09378	0.05262	0.04921	0.47654*	0.51731*	0.52962*
	R^2	0.00880	0.00277	0.00242	0.22709	0.26761	0.28050
	df	65	199	65	4, 62	5, 195	4, 62
	F	α=0.22516	α=0.229	α=0.34	4.55	14.25	6.04

Table 11. Continued

Model	Parameter[2]	All Natural Energies Included			Empirical Estimation[1]		
		1930	'65, '70, '75	1975	1930	'65, '70''75	1975
Multiplicative Interactions with Feedback from Structure Terrestrial and Coastal Processes Separated (see Figure 5b)	R	0.79872*	0.87084*	0.88629*	0.84587*	0.88715*	0.90973*
	R^2	0.63795	0.75836	0.78551	0.71550	0.78705	0.82760
	df	2, 64	2, 198	2, 64	2, 64	2, 198	2, 64
	F	56.38	310.70	117.191	80.47	365.8	153.61

[1] At final step of stepwise regression. Note that the significance of the R would be increased by using an F calculated at the last step on which a variable was entered whose reduction of error variance was in itself significant. The values shown all meet the $\alpha < 0.05$ criterion, and it was desirable to show the overall significance of the step from which the standardized betas in Table 23 were taken.

[2] Unless otherwise noted

* alpha < 0.005, for df = 3, 63, F >4.73; for df = 3, 120, F > 4.50.

desirable to pool time series data, and the best way to test the validity of this approach is to replicate the findings with unpooled data. Second, it was desired to examine changing associations of individual natural energies with urban growth through time in the stepwise regression models. The time periods used included: 1930; a pooled sample of 1965, 1970, 1975; and 1975).

Overall, it is immediately obvious that the models which included feedback from structure were much better fits to the data than were the models without feedback. Considering only the deterministic models, the additive interactions were better fits than the multiplicative interactions. Considering only the models without feedback, the empirical models were much better fits than the deterministic models. Empirical models were generally better fits than the deterministic models.

The findings indicate that: (a) natural energies are significantly correlated with urban growth and (b) the correlation is improved when feedback from urban structure is incorporated into the model. These findings lend support to the energy principle that the county system in competition which has the most available energy and structure to process that energy, will outcompete.

The hypotheses were put forth that: (a) as the energy of the overall system driving migration (i.e., the U.S. economy) changed, the linkage of patterns of urbanization to natural energies in Florida might also change, and (b) as structure increased, factors which were initially not influential would assume new importance as they became limiting. In order to test these hypotheses, the regression analyses were conducted for three timeframe samples: (a) 1930; (b) a pooled sample of 1965, 1970 and 1975; and (c) 1975. The standardized betas and significance tests for the individual factors in the empirical versions of the four basic models were used to address the above hypotheses and are presented in Table 12.

It is apparent that the energies which are important vary from model to model, but that the important energies vary only slightly from year to year. The additive interaction model without feedback from structure included wave, sun and organic soil energy as statistically significant energies. Natural productivity entered the equation, but did not meet the statistical criterion for signifcance. The significance of wave, sun and organic soil energy varied from timeframe to timeframe, but with wave and sun always holding the top two ranking betas. The importance of sun and wave in this model is consistent with Florida's advertising policy; however, the appearance of organic matter in the 1965-1975 pooled sample is not so straightforward. It may be due to increased economic importance of muck farming and resulting urbanization, or a spurious relationship due to the proximity of the southeastern coastal counties to the everglades peat extending from Lake Okeechobee to Florida Bay.

The separated processes model with multiplicative feedback from structure and additive interactions, like the model previously discussed included sun and organic soil energy, as well as aquifer water storage. Wave energy did not appear in this model. The ordering of beta was consistent in all three timeframes, and as with

Table 12. Strength of association of natural energies[a] with urban growth in stepwise multiple regressions based on the four models of natural energy interaction

Model	1930			1965, 1970, 1975			1975		
	Variable	Beta	F	Variable	Beta	F	Variable	Beta	F
Additive Interaction	Wave	.41946	* 11.922	Wave	.41191	* 38.287	Wave	.43474	* 13.675
Without Feedback	Sun	.279	3.178	Sun	.23310	* 6.547	Sun	.34880	* 5.290
From Structure	+			Organic	.14572	* 4.409	+	+	+
(See Fig. 5a)	Nat. Prod.	.21	1.626	Nat. Prod.	.12295	1.861	Nat. Prod.	.1913	1.437
			df=1,63			df=1,196			df=1,63
Separated Processes,	Sun	1.07904	*250.494	Sun	.96295	*1381.97	Sun	.9899	*708.557
each with Multiplicative	Aquifer	-.36482	* 28.417	Aquifer	-.12073	* 23.45	Aquifer	-.10586	* 8.766
Feedback from Structure and Additive Interaction (see Fig. 5b)	Organic	.08682	2.664	Organic	.08379	* 12.49	Organic	.03942	1.326
			df=1,63			df=1,197			df=1,63
Multiplicative Single	Aquifer	-.50984	* 15.519	Aquifer	-.55135	* 59.974	Aquifer	-.48888	* 19.351
Process Interaction	Wave	.29252	* 6.199	Wave	.24656	* 14.553	Wave	.21596	3.776
Without Feedback	Mineral	.24091	3.596	Rain	.17183	* 7.166			
From Structure	Rain	.15601	1.788	Mineral	.13236	3.587			
(see Fig. 6a)			df=1,63			df=1,196			

Table 12. Continued

Model	1930			1965, 1970, 1975			1975		
	Variable	Beta	F	Variable	Beta	F	Variable	Beta	F
Multiplicative Interactions With Feedback from Structure	Multiplier 1 (Aquifer x Mineral x Sun)	.30921	* 21.255	Multiplier 1	.10056	* 8.278	Multiplier 1	.224960	* 17.983
Terrestrial and Coastal Processes Separated[b]	Multiplier 2 (Wave)	.75454	*126.569	Multiplier 2	.86196	*608.236	Multiplier 2	.83620	*248.480

+ = factor did not enter into equation

* = alpha <.05; for df 1,60,F > 4.00; for df 1,120 F > 3.92

[a] All natural energies and change in urban structure in coal equivalents.

[b] Multiplier 1 is the multiplicative interaction of aquifer, mineral and sun energy with structure.
Multiplier 2 is the multiplicative interaction of structure and wave energy.

the previous model, organic soil energy was only significant in the 1965-1975 pooled sample. Aquifer energy had a consistent negative beta, signifying an inverse relationship. Although sunlight and aquifer storage tend to vary inversely in Florida (see Table 10), the negative relation to structure change is not due to this relationship, as stepwise regression only incorporated variance not explained by other variables. The negative relationship with aquifer is either spurious or explained by some other reason. One plausible explanation is the fact that aquifer storage is very strongly inversely related to depth to the aquifer, a fact which is readily demonstrated when piezometric surface and topographic maps are compared. Hence the negative association of aquifer storage with structure change may reflect difficulty and expense in obtaining a water supply. It is common for new developments in Florida to initially require private wells. In light of the large F associated with aquifer, the well explanation wil be tentatively accepted in this study.

The third model, incorporating multiplicative single process interaction without feedback from urban structure, reveals an interesting change in its structure with time. While aquifer and wave energy figured predominately in all three timeframes, in order of beta weight, mineral soil energy and rain entered the equation for the 1930 example, the relative importance of rain increased while mineral soils decreased in the 1960-1975 sample, and finally, rain and mineral soil dropped out of the 1975 equation entirely. The fourth model, incorporating multiplicative interactions with feedback from structure, terrestrial and coastal processes separated, was significant for both multipliers, but with the standardized beta consistently larger for the process interacting with wave energy.

As mentioned in the methodology, one of the assumptions concerning the validity of the multiple regression analysis is the independence of the error variance with respect to the independent variables (homoscedasticity) and that the function being fit is linear. These assumptions are best evaluated from an analysis of the regression residuals. For this purpose, the expected values of each of the four empirical models are plotted against the observed rate of urban structure change for 1975 in Figures 14 through 17.

The first model, incorporating additive without feedback, is shown in Figure 14. While most of the data points are at the lower end of the axis, the variance is fairly well distributed. The second model, incorporating additive interaction with feedback, is seen in Figure 15 to be tightly clustered at the lower end of the scale, with increasing variance as the values increase. The model is clearly heteroscedastic and appears somewhat nonlinear. The third model, multiplicative interaction without feedback, appears homoscedastic in Figure 16 while the fourth model in Figure 17 incorporating multiplicative interactions with feedback, exhibits the same problem as the second model.

To summarize, the models without feedback, while accounting for less total variance than the models incorporating feedback, were more homoscedastic. This observation suggests that there is some interaction between the amount of structure and the variance of the data.

Figure 14. Scattergram of 1975 urban growth rates versus output of additive interaction model without feedback (see Figure 5a).

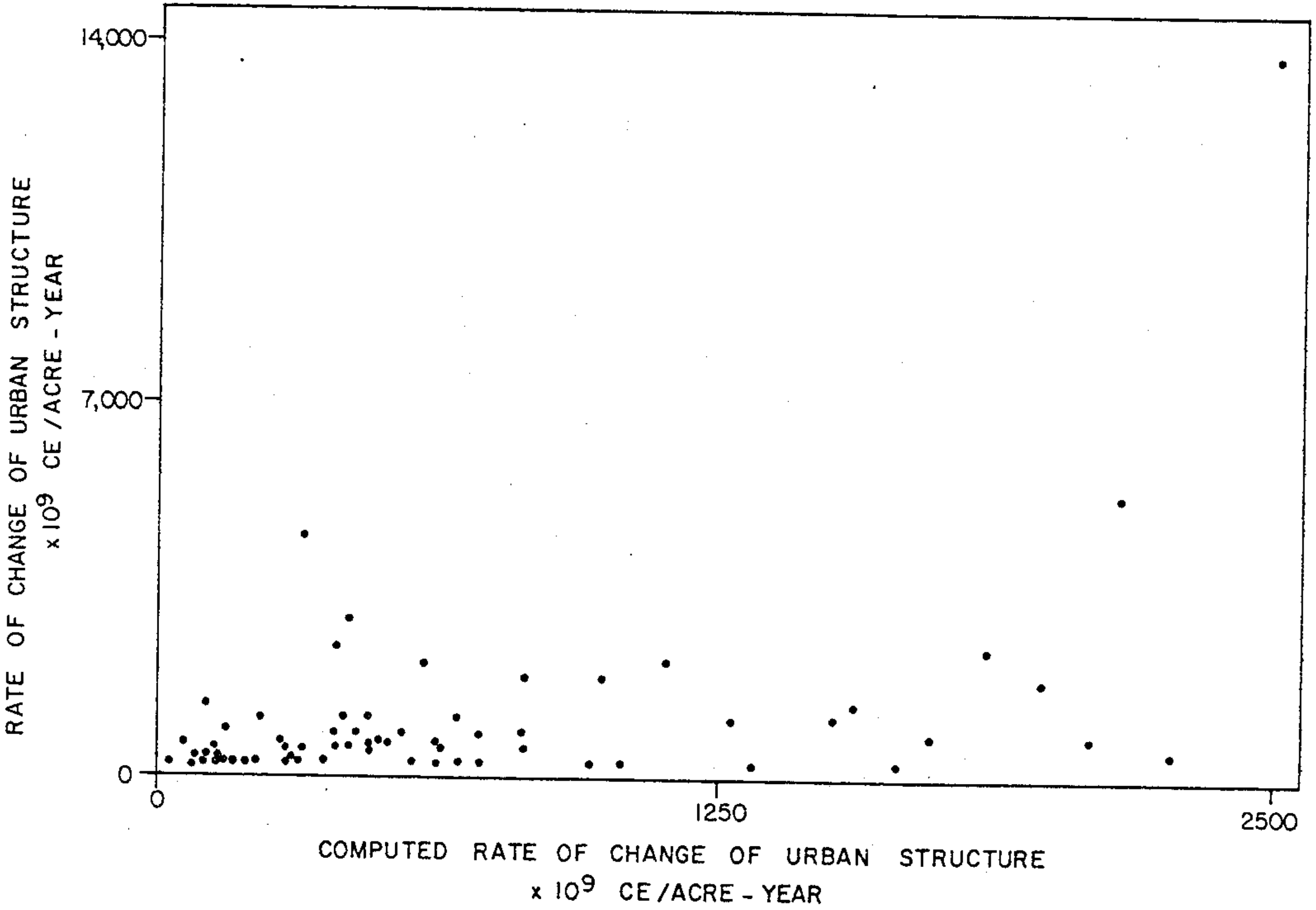

14,000
7,000
0
RATE OF CHANGE OF URBAN STRUCTURE
x 10⁹ CE / ACRE - YEAR
0
1250
2500
COMPUTED RATE OF CHANGE OF URBAN STRUCTURE
x 10⁹ CE / ACRE - YEAR

Figure 15. Scattergram of 1975 urban growth rates versus output of additive interaction models with feedback (see Figure 5b).

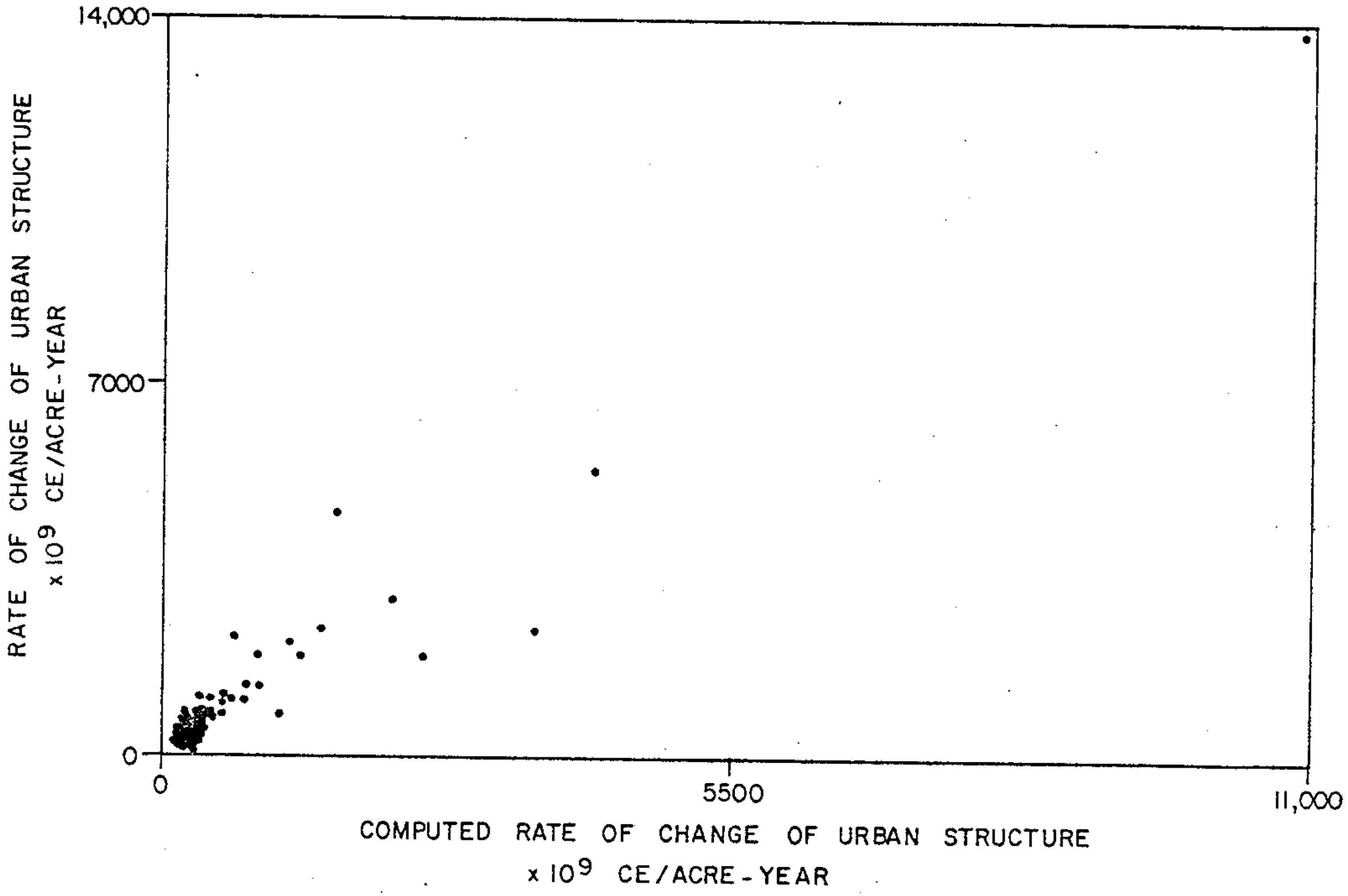

14,000
7000
0
RATE OF CHANGE OF URBAN STRUCTURE
x 10^9 CE/ACRE-YEAR
0
5500
11,000
COMPUTED RATE OF CHANGE OF URBAN STRUCTURE
x 10^9 CE/ACRE-YEAR

Figure 16. Scattergram of 1975 urban growth rates versus output of multiplicative interaction model without feedback from structure (see Figure 6a).

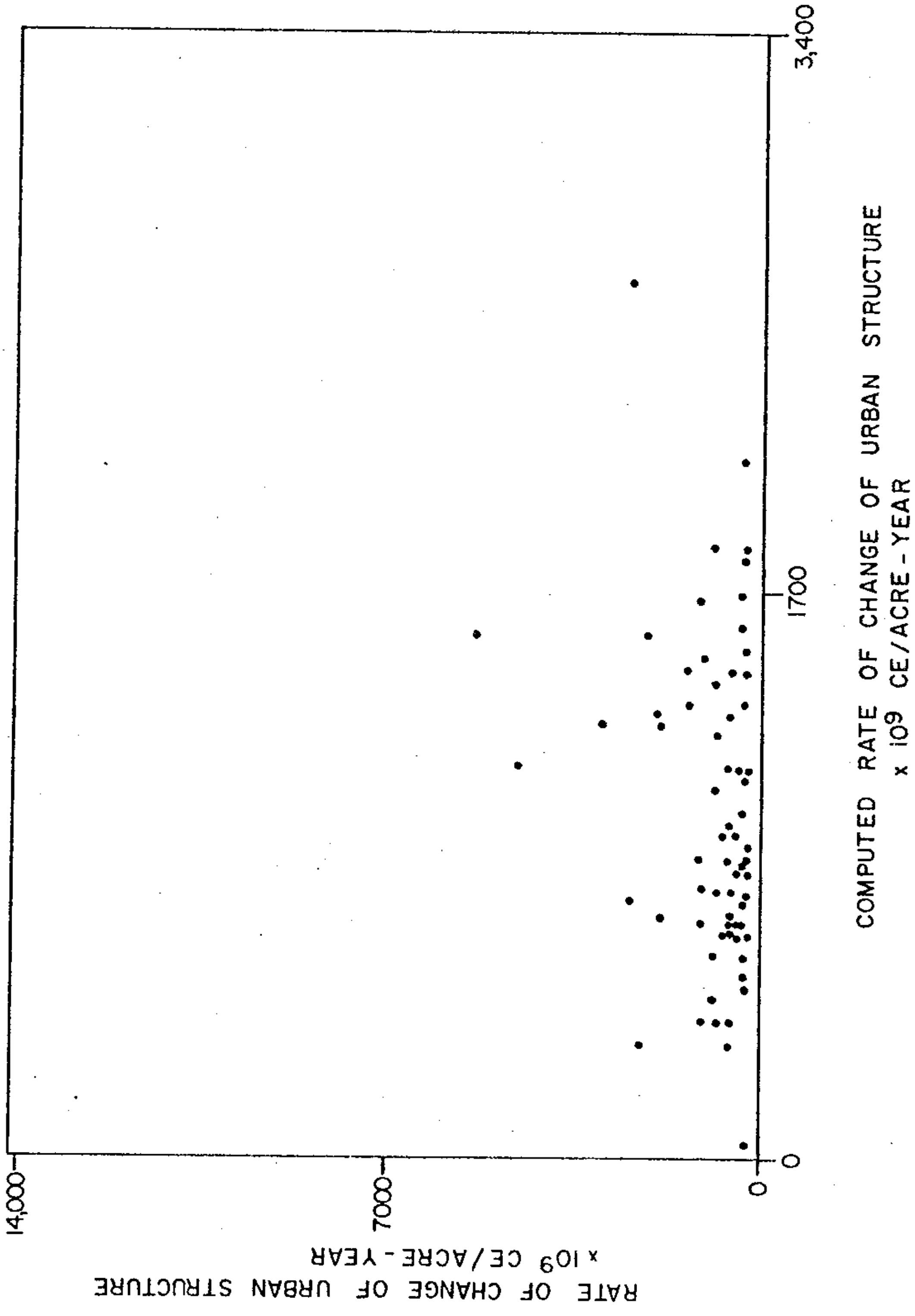
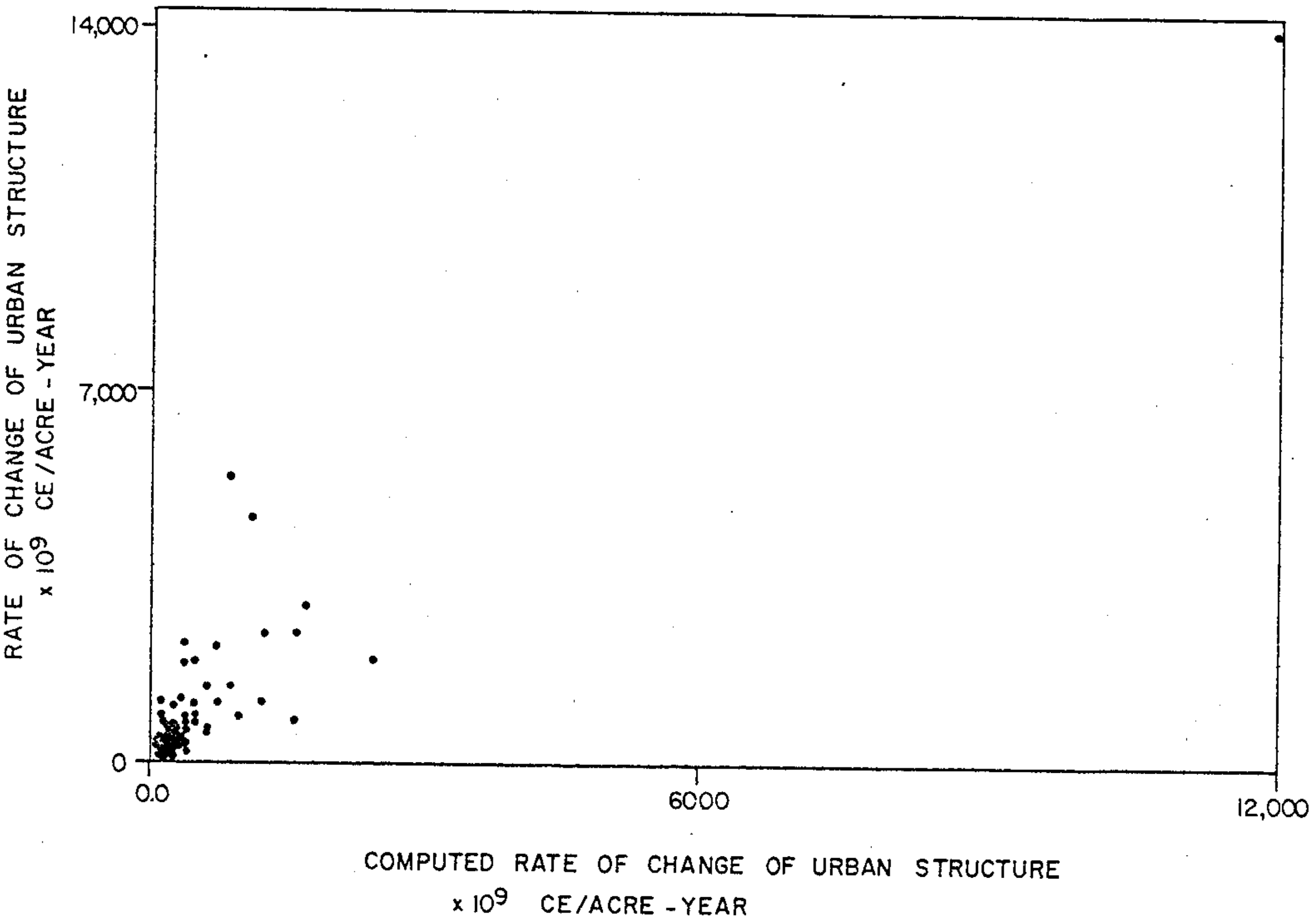

COMPUTED RATE OF CHANGE OF URBAN STRUCTURE
x 10⁹ CE/ACRE-YEAR
0
1700
3,400
RATE OF CHANGE OF URBAN STRUCTURE
x 10⁹ CE/ACRE-YEAR
0
7000
14,000

Figure 17. Scattergram of 1975 urban growth rates versus output of multiplicative interaction model with coastal and terrestrial processes separated and with feedback from structure (see Figure 6b).

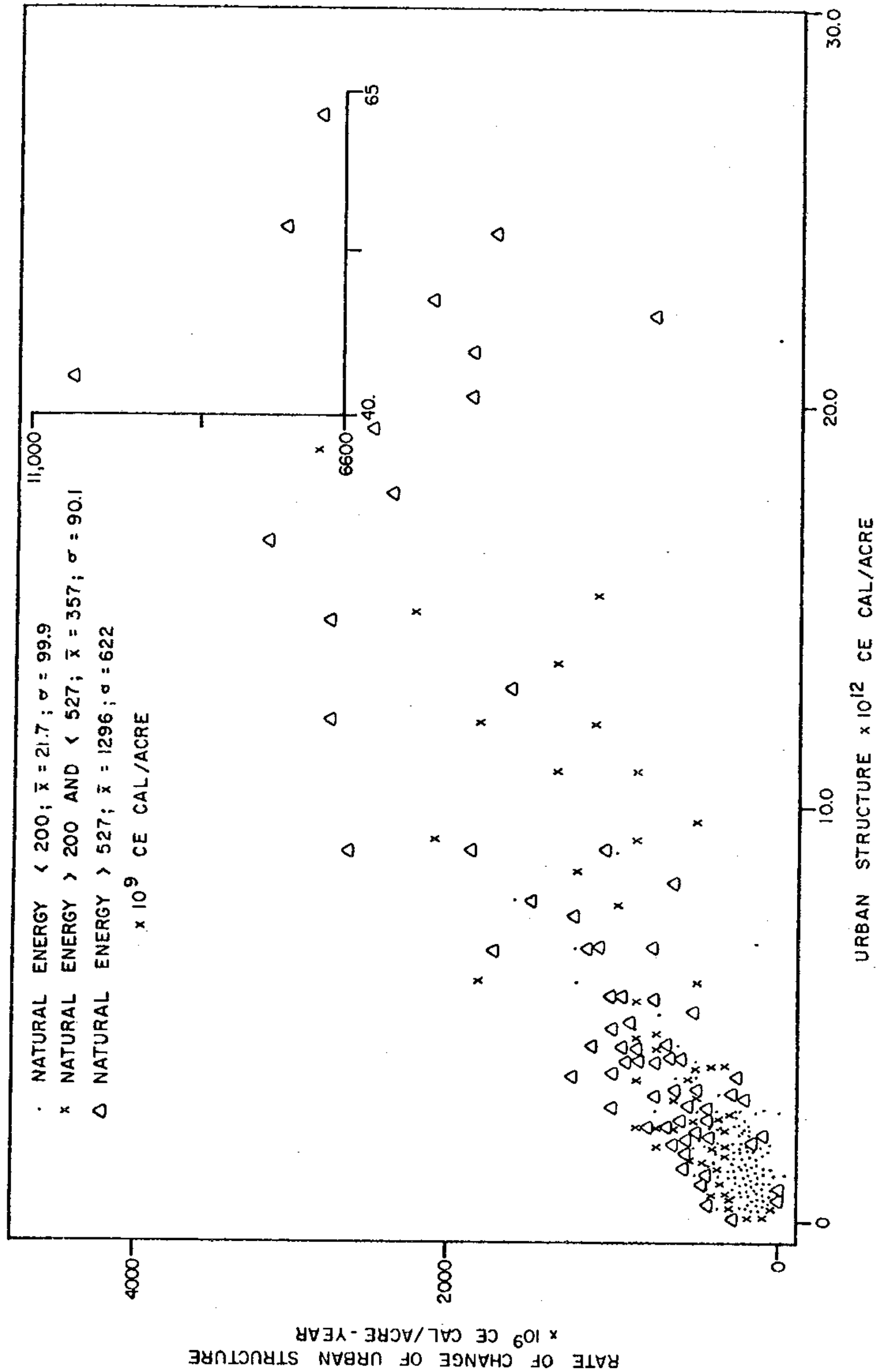

RATE OF CHANGE OF URBAN STRUCTURE
x 10^9 CE/ACRE - YEAR
14,000
7,000
0
0.0
6000
12,000
COMPUTED RATE OF CHANGE OF URBAN STRUCTURE
x 10^9 CE/ACRE - YEAR

Logistic Energy Model with Urban Growth a Function of Structure and Natural Energy

The eight basic models examined indicated that both natural energy and structure were significantly related to the rate of urban growth, but somehow the models were not as appropriate as structure increased, as indicated by the spread of variance. In order to examine these relationships further, a scatter diagram was made of the rate of urban growth with structure for counties with different levels of natural energy. The empirical, additive interaction without feedback model was used to characterize the natural energy of each county because of its evident homoscedasticity and the simplicity of its form. A model with feedback was not chosen for characterizing natural energy because of the obvious redundancy of plotting a function of structure against structure, and the multiplicative model was not chosen because it was not as appropriate a fit as the additive model. The scattergram was broken into three levels of natural energy as follows: (a) less than 200 x 10^9CE intensity per acre; (b) more than 200 but less than 527 x 10^9CE intensity per acre; and (c) more than 527 x 10^9CE intensity per acre. These levels were chosen arbitrarily in order to roughly separate the data points into three equal size sets. The entire sample including data for 1930, 1940, 1950, 1960, 1965, 1970, and 1975 was used.

The resulting diagram is given in Figure 18 and contains 463 data points. The frequency of data points at the lower end of the axis was very high, precluding a clear graphical presentation of data.

Figure 18. Scattergram of rates of changes of urban structure as a function of structure and level of natural energy for counties in Florida. Natural energy computed from empirical additive interaction without feedback from structure model. Offset axis is for county with highest computed natural energy intensity of 2500 CE Cal/acre (Pinellas).


· NATURAL ENERGY < 200; x̄ = 21.7; σ = 99.9
× NATURAL ENERGY > 200 AND < 527; x̄ = 357; σ = 90.1
△ NATURAL ENERGY > 527; x̄ = 1296; σ = 622
x 10^9 CE CAL/ACRE
11,000
6600
40.
65
0
10.0
20.0
30.0
URBAN STRUCTURE x 10^12 CE CAL/ACRE
0
2000
4000
RATE OF CHANGE OF URBAN STRUCTURE
x 10^9 CE CAL/ACRE-YEAR

However, it was noted that the three levels of natural energy were homogeneously distributed in this region.

The increase in variance as structure increases is evident in the figure. Inspection of the points characterized by different natural energy levels revealed that the higher natural energy level counties were extended further and fell into curvilinear patterns, generally decreasing rates of growth past a certain density of structure. The inflection point appeared to depend on the level of natural energy. The most densely structured county, Pinellas, was also found to have the greatest computed value of natural energy (>2500 x 10^9CE intensity/acre).

The dynamics evident in the data clearly suggested the energy model of the configuration shown in Figure 6c. The model was tested with a two factor multiple regression equation, one factor being the product of multiplying a county's computed natural energy per acre with its structure per acre, the other the product of squaring the structure. The results were highly significant and the square term's coefficient was negative as expected.

However, the influence of the changing economy of the United States suggested itself as a confounding variable. Between the fiscal years of 1974 and 1975, the rate of Florida's growth dropped sharply. This drop would of course coincide with the cumulative maximum structure of each county, perhaps biasing the observed rate of growth of each county as a function of structure, even though the data points used represented five years averages. To eliminate this effect, the regression analysis was repeated excluding the 1975 data points. The significance of the relation increased and the function maintained its form.

The results of the analysis of the model in Figure 18 are presented in Table 13 both for the model shown with a square drain, and for a model incorporating a cubic drain.

Table 13. Multiple regression analysis of urban growth with rate of change of urban structure of the logistic model in Fig. 6c

Model	Variable	Constant	Value	Error	Standard beta	F^a
Both[b]	Sun	K_1	9.04×10^6			
	Wave	K_2	7.0×10^3			
	Organic Soil	K_3	0.14			
Square Drain	U	J_o	92.005	4.32	1.42	453.0
	U^2	K_4	-1.635	0.2007	-.5435	66.39
$R = .91803$ $R^2 = .84279$						
Cubic Drain	U	J_o	92.396	2.784	1.43	1100.9
	U^3	K_4	-.2983	0.00222	-.5784	179.9
$R = .93468$ $R^2 = .87363$						

[a] All equations and factors significant at alpha < 0.001.

[b] For details of regression model from which these factors were derived, see Table D-2. In order to reduce computational rounding error, $(K_1S + K_2W + K_3O) \times .001$ was the natural energy value entered into regression analysis. 1975 data not included.

DISCUSSION

Critique of Natural Energy Measurement

Choice of boundaries had a large effect on results. The choice of two feet of depth for soil characterizations, while based on root depth considerations and examination of representative soil profiles, was necessarily arbitrary and had a great effect on the calculated energy signature of a county, especially in the multiplicative models of natural energy interaction. Tide and wind energy were omitted entirely. Despite the limitations mentioned above, correlations demonstrated the importance of natural energies in explaining the spatial allocation of urban growth over the state of Florida.

Time for Soil Formation

The accuracy of the simulation model employed in this study is unknown without validation. The time required for soil formation in simulation did approximately conform to expectations generated by the literature. Table 14 summarizes a number of estimates of the time required to form various sorts of soil. Broken rock and dry climates are seen to accompany slower rates of soil formation. A fine starting material, volcanic ash, in a west warm climate forms a soil relatively rapidly. The most rapid soil formations are seen to occur on marine sediments. Sediments are distinctly different than material laid

Table 14. Summary of rates of soil formation and weathering as reported in the literature

Starting Material	Final Product	Years[1]	Cm/yr	Location	Method of Ascertaining	Source
glacial till-rock fragments	temperate forest soil	20000	3.019×10^{-3}	Hubbard Brook forest in New Hampshire	Cation budget for six small watersheds was established. The required rock weathering was calculated.	Johnson, Likens, Borman & Pierce (1967)
broken rock	immature soil	20000	-	cold northern Europe	not specified	Narayana & Shah (1966)
$CaCO_3$ deposited by lacustrine algae	argillic horizon	12000	-	Arizona, Nevada (very dry)	dated from geologic structures	Nettleton, Witty, Nelson; Hawley (1975)
not specified	topsoil	12000	-	not specified	not specified	Bennett, in Narayana & Shah (1966)
limestone tombstone	sand	6000	1.016×10^{-2}	England	study of tombstone weathering	Goodchild, in Jenny (1941)
sand deposits	podzol	1250	4.89×10^{-2}	Sweden	estimate	Tamm, in Jenny (1941)
volcanic ash	clayey soil	1000 to 1300	4.57×10^{-2} 6.09×10^{-2}	St. Vincent Island, British West Indies	known date of eruption	Hay (1960)
loess	loess and peat deposits	1200 to 1400	4.23×10^{-2} 5.05×10^{-2}	South Canterbury, New Zealand	radiocarbon dating	Runge, Goh, Rafter (1975)
sand (quartz)	dune forest soil, young	1000	-	Michigan	known rates of retreating shoreline allowed ecological and soil studies on old dunes	Olson (1958)

Table 14. Continued

Starting Material	Final Product	Years[1]	Cm/yr	Location	Method of Ascertaining	Source
sand	stable dune vegetation system	300	-	Southport dune system, England	old maps, ages of trees, etc.	Salisbury, in Jenny (1941)
muddy marine sediments	agriculturally useful	300	1	Holland	land reclaimed from the sea	Hissink, in Jenny (1941)
lake sediments	podzolization	100	-	North Sweden	known date of lake drainage	Tamm, in Jenny (1941)
volcanic ash	fertile soil	120	5.08×10^{-1}	St. Vincent Island, British West Indies	known date of eruption	Hard, in Jenny (1941)

[1] time to form 24 inches of soil if rate of production is known.

down in shoreline processes. Dune soils are prevalent in Florida. The ages of these soils in Table 15 range from 300 to 1000 years in fairly moist temperate areas. The weathering of limestone tombstones to sand may be typical of the Florida environment.

The estimated weathering rate of Florida limestone (3.0×10^{-3} cm/yr; Gilliland, 1973) is not very different from that obtained at Hubbard Brook in New Hampshire as given in Table 14. A rough estimate from the literature of soil formation from incoherent, loose sand to a soil capable of supporting a forest would appear to be less than 1000 years and as low as 300 years for the warm, moist climate of Florida. Simulation results gave 375-525 years.

Energy Quality of Soils

The solar cost for soil can be compared with the solar costs for other energies. The energy equivalents in terms of sunlight for some forms of energy are (after Odum and Odum, 1976):

	solar Cal/Cal
Sunlight	1
Gross plant production	100
Wood, collected	1000
Coal and oil, delivered for use	2000
Energy in elevated water	6060
Electricity	8000

The solar cost for Florida mineral soil ($7.2 - 8.8 \times 10^3$ solar Cal/Cal) is near the solar costs for electricity, which has about four times the solar cost of coal and oil delivered for use, while the costs for mineral soil fall near that of collected wood. On a volume basis there is more energy embodied in peat than in mineral soil.

Soil is essentially a catalyst employing vitamins and amino acids, microorganisms and complex colloidal chemistry to enable plants to utilize sunlight. A soil body is a considerable investment of energy whose potential is only slightly tapped each growing season and which lends stability to nutrient cycles and, hence, life. It represents a high quality energy feeding back to control the lower quality, high volume energy fluxes of photosynthesis.

Addition or Multiplication of Natural Energy Interactions

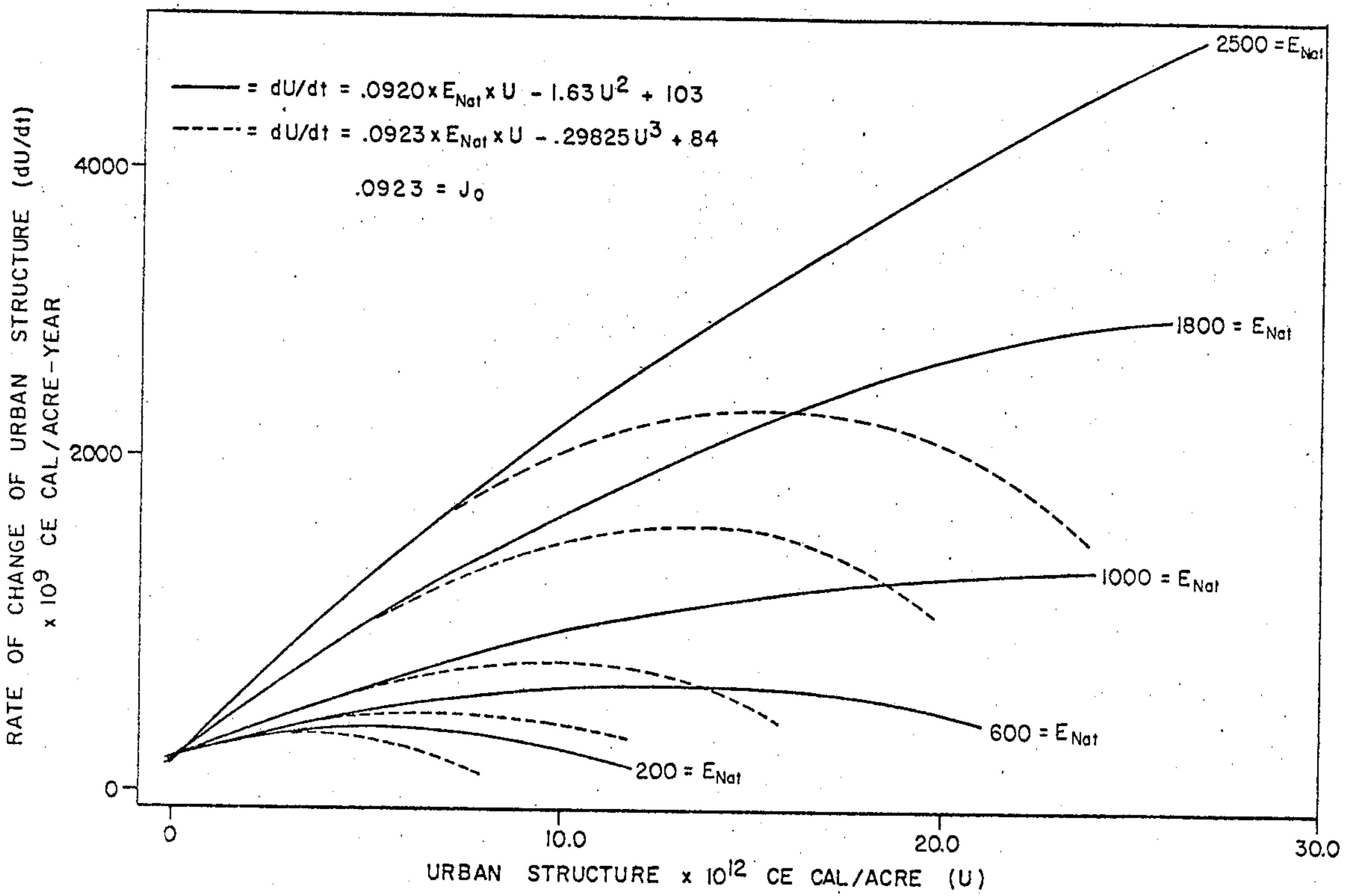
The additive energy signatures were found to correlate better than multiplicative interactions. Multiplicative energy interactions require fewer assumptions than additive, not being unit dependent, yet errors such as those in selecting boundaries may affect multiplicative interactions more than additive interactions. For example, suppose one is concerned with three energies, each of which are present with 100 units. A 10% measurement error in one of the units would yield a 3.3% error in the final sum, but would yield a 10% error in the product. The additive model has a theoretical justification in that it does not assume that a percent change in an energy results in a percent change in the productive output, whereas the multiplicative model does, which is not appropriate when limiting factors may be present, or when excess energies for one process develop new processes in which energy effects differ.

When interacting energies are expressed in units of equal value, it may be true that the energies are maximizing power when all energies have matching quantities. If so, the energy with the smallest quantity would be the most limiting and thereby the energy with the highest correlation with the output from the productive process. In Table 9, which contains the parameters of the natural energies expressed in coal equivalents, it is seen that wave energy has the smallest mean value. In Table 12, containing the results of the stepwise regressions, it is seen that wave energy, in the additive interaction process without feedback from structure, has the highest degree of correlation. The other models, with multiplicative interactions etc. do not feature wave energy as predominantly. Matching equal work values worked best in additive interactions.

Family of Curves for Growth as a Function of Storage and External Energy

Figure 19 contains theoretical plots of the rate of increase of structure at various levels of natural energy produced by the square and cubic drained models. While the curves represent variations in natural energy, they can also be interpreted to demonstrate the effect of varying the external driving function representing external world energies (J_0) from 20 to 280 percent of its present level while natural energy was held at a constant at an intensity of 1000 x 10^9CE intensity per acre. The optimal density of urban structure (in terms of urban growth, which indicates economic vitality) declines by half when the external driving constant is reduced to 60% of its present level (curve marked '600' in Figure 19).

Figure 19. Growth rate as a function of urban structure and natural energy. Curves were simulated using coefficients determined from regression analysis and different levels of natural energy or external world energies as structure was varied. Solid lines represent urban growth model with a square drain, dotted lines represent model with a cubic drain (see Figure 6c and Table 13.


—— = dU/dt = .0920 x E_{Nat} x U - 1.63 U^2 + 103
- - - - = dU/dt = .0923 x E_{Nat} x U - .29825 U^3 + 84
.0923 = J_0
2500 = E_{Nat}
1800 = E_{Nat}
1000 = E_{Nat}
600 = E_{Nat}
200 = E_{Nat}
RATE OF CHANGE OF URBAN STRUCTURE (dU/dt)
x 10^9 CE CAL/ACRE-YEAR
4000
2000
0
0
10.0
20.0
30.0
URBAN STRUCTURE x 10^{12} CE CAL/ACRE (U)

Predictive Validity of the Logistic Urban Growth Model

The regression coefficients for the logistic energy models of urban growth in Table 13 were calculated with data from the 1970-1975 period excluded, because it was feared that the data would unduely add trends to the model caused by the rapidly changing energies external to Florida, due to energy crisis. The predictive validity of the logistic energy models was tested by calculating the expected values of the 1970-1975 rate of change of urban structure and then correlating expected and observed rates of change.

The initial correlation found $r = .88$, alpha $< .0001$ for the logistic model with the square drain, while the correlation for the logistic model with the cubic drain was insignificant. Apparently the square drain model has more generality than the cubic drain model. A correlation coefficient of $r = .88$ means that the model accounted for 77% of the variance. The model was in substantial error only for Seminole County, whose growth rate was much higher than expected.

Comparison of Energy Cost and Energy Effect Quality Factors

One energy assumption which is implicit in the use of energy cost quality factors is that energy costs are related to energy effects. One advantage of using energy cost as a measure of a calorie's ability to do work is that it is not process specific, as energy effects (amplifier values) are, and that a thermodynamic minimum cost can be assumed. A thermodynamic minimum or maximum effect would be more difficult to determine for energy effect quality factors. In order to examine the relationship between energy costs and energy effects, energy effects were determined empirically from urban growth data. Urban systems contain many processes, and while the results from such a determination are highly specific to Florida and should not be generalized to other localities, they should serve to indicate the general quality of natural energies in systems of man and nature.

The empirical quality factors, which are essentially "amplifier effects," are compared to energy cost quality factors in Table 15. In the four cases where it was appropriate to calculate an error ratio, the empirical and energy cost quality factors agree to within an order of magnitude for three of the four quality factors evaluated. The error ratio for the quality factors of wave energy indicates two orders of magnitude difference. Considering the differences in meaning and possibility of measurement error, these findings indicate substantial agreement between the energy costs and energy effects. The large error ratio for wave energy is probably due to other energy effects predominant at coasts which were statistically attributed to wave energy.

Unexplained Variance

The analysis suggests that man, by some selection and elimination process, has been located according to environmental opportunities for investment in an area. However, it can not be denied that perception

Table 15. Comparison of energy cost and energy effect quality factors empirically determined for the value of natural energies in urban growth

Energy Type	A. Calculated Cal/CE	B. Empirical[a] Cal/CE	Error Ratio larger/smaller	Note
Sunlight	2000.00	8074.00	4.037	
Natural ecosystem productivity of sugar	200.00	*	*	b
Wave energy	5.00	2735.00	547.00	c
Organic soil	2.00	0.42	4.76	c
Water: rain	.33	*	*	d
Water: aquifer storage	.33	6.8	*	e
Mineral soil	.25	0.27	1.08	f

* Not shown for reason in note.

[a] The empirical quality factors are the slopes of the regression equation Y = mX + B where Y is the rate of change of urban structure/acre in CE Cals, and X is a natural energy expressed as heat equivalents per acre. Pooled data for 1960, 1965, 1970, 1975, single variable regression used.

[b] Although this coefficient was statistically significant (alpha < .05), the coefficient was negative.

[c] Calculated for countes with natural energy component greater than zero.

[d] The coefficient was not significant.

[e] The error ratio was not calculated because the coefficient, although significant, was negative. The empirical quality factor is of interest however, because the negative coefficient (see text) has been interpreted as a relationship with well depth. The quality factor measures the topographic quality of well depth.

plays an important part in decision making and that cultural lags may exist, causing populations to go where energy production is not maximized. Influences other than environmental characteristics in the models used may introduce error into the analysis. Correlations show how important the energy flows are. The multiple R regression coefficients give an estimate of the relative importance of environmental energies as opposed to other factors. As seen in Table 11, natural energies account for roughly 25% and feedback from structure roughly an additional 60% of the variance in urban growth rates. This leaves roughly 15% of the variance unexplained and attributable to either error or other factors.

The Relationship of Urban Growth to Natural Energies

As indicated by the correlation results and demonstrated by the model simulated in Figure 19 the economic vitality of a county in Florida is determined by its density of urban structure and its natural energies. Trends observed in the data indicate that, depending upon the natural energy of a county, there is an optimal density of urban structure after which the rate of urban growth declines. The logistic nature of the model which describes this behavior conforms to the parabolic energy corollary which states that maximum power occurs at 50% efficiency. The absolute value of this optimal value, as shown in Figure 19, depends also upon the energies driving urban growth which are external to Florida.

Mineral and soil energies declined in importance through time in some of the models in Table 12, and wave and sunlight energies dominated the later periods' timeframes. The productive significance of these energies may indicate the decreasing importance of agriculture to the system and the increasing importance of recreational pursuits. This change may reverse itself as fossil fuel energies external to the system decline, but cultural lags may impose economic hardships on a system dependent on excess energy for recreational pursuits.

Investment Ratio

Investment ratios of fossil fuel and natural energies have been suggested as indicators of regional economic competitiveness at steady state (Zucchetto, 1975). Investment ratio is the ratio of outside energy attracted to natural energies where both are in calorie units of the same quality. If the ratio for one area is higher than other areas, the ratio may be interpreted as indicating a low amount of unused natural resources for exploitation. The model presented here adds another interpretation that applied during growth. Lower ratios may indicate insufficient structure to compete effectively. As fossil energies decline, growth stops and the amount of structure which is optimal may also decrease, making previously uncompetitive counties competitive.

APPENDICES

APPENDIX A

THE MODELING LANGUAGE

The symbols which have been used in all models are presented and explained in Figure A-1. The symbols are from an energy language system devised by H.T. Odum and have precise mathematical expresses as well as pictoral meanings. Complete descriptions are available in Odum (1971, 1976).

Figure A-1. The symbols of the energy circuit language used in this thesis (Zucchetto, 1975, after Odum, 1971, 1972)

a. Outside source of energy supply to the system controlled from outside; a forcing function (E).

b. Constant flow source from outside; $J_2 = k_2J_0X/(k_r + k_1X)$, $J_r = k_rJ_0$, $J_1 = k_1XJ_0$.

c. A pathway whose flow is proportional to the quantity in the storage or source upstream ($J = k_1E$). The heat sink represents the energy losses associated with friction and backforces along pathways of energy flow.

d. Storage of some quantity in the system. The rate of change equals inflows minus outflows ($\dot{Q} = J - KQ$).

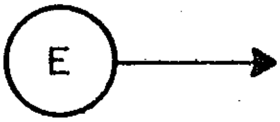
e. Interaction of two flows to produce an outflow which is some function of these flows; usually a multiplicative output, i.e., $f(X,Y) = kXY$.

f. Transactor symbol for which money flows in one direction and energy or matter in the other direction with price (P) adjusting one flow (J_1) in proportion to the other, J_2($J_1 = PJ_2$).

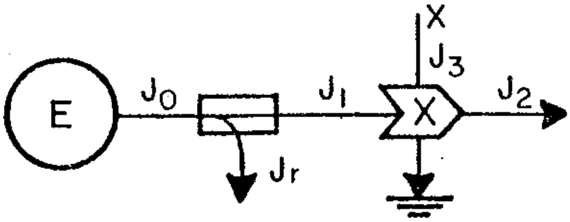
g. A combination of "active storage" and a "multiplier" by which potential energy stored in one or more sites in a subsystem is fed back to do work on the successful processing and work of that unit; autocatalytic.

h. Production and regeneration module (P-R) formed by combining a cycling receptor module, a self-maintaining module which it feeds, and a feedback loop which controls the inflow process by multiplicative and limiting actions, e.g., the green plant.

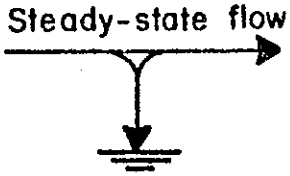
i. Sensor the the magnitude of flow, J.



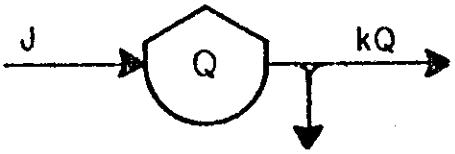
Source
(a)



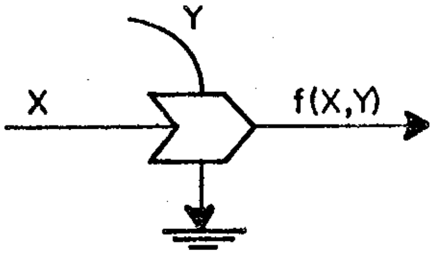
Constant Flow Source
(b)



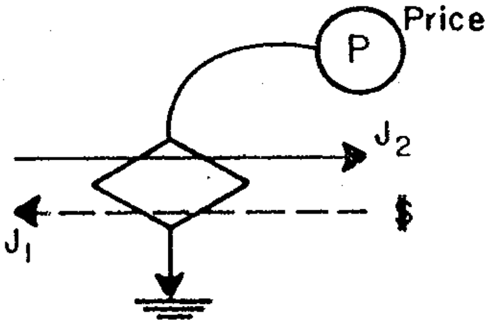
Heat Sink
(c)



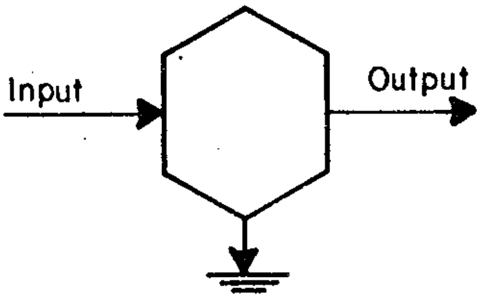
State Variable (Storage)
(d)



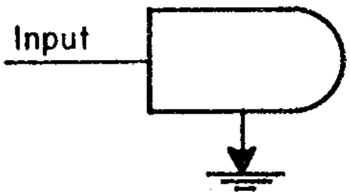
Interaction Symbol
(e)



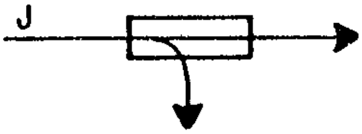
Transaction
(f)



Self - Maintaining Module
(g)



Plant Population
(h)



Sensor of Flow J
(i)

APPENDIX B

SOIL CHARACTERIZATION AND SOIL SERIES PRESENT IN MAJOR SOIL GROUPINGS USED FOR THIS STUDY

Table B-1. Characterization data for virgin Florida soil series

Series	Data Source	Number of Samples	Moisture Equivalents	Organic	Total N	Total P	CEC	Thermal[1] Energy
				----------- % -----------			ME/100 gm	$\times 10^6$ Cal/Acre
1 Arredondo	A	3	6.38	1.32	.048	.140	4.95	2.36
2 Bayboro	A	1	12.37	2.36	.144	.192	10.04	3.84
3 Bladen	A	2	9.38	.70	.055	.014	7.68	1.37
4 Blanton	A	7	2.85	.746	.019	.019	1.59	1.45
5 Bradenton	A	7	3.87	.82	.029	.036	3.46	1.57
6 Broward	A	1	2.97	1.23	.032	.005	5.64	2.21
7 Chiefland	A	2	2.52	.50	.011	.066	1.39	1.03
8 Cocoa	B	1	2.42	.81	.025	*.025	1.57	1.55
9 Delray	A	4	10.33	3.99	.206	.041	10.53	5.90
10 Eustis	B,C	2	2.04	.40	.041	.07	1.3	0.85
11 Everglades	D	2	***	87.17	2.32	.133	***	54.70
12 Fellowship	A	4	17.01	1.36	.046	.299	20.23	2.41
13 Fort Meade	A	1	9.75	2.19	.036	.268	6.26	3.62
14 Gainesville	A	4	8.36	1.33	.030	.092	5.77	2.37
15 Hernando	A	3	7.11	.70	.023	.127	3.58	1.37
16 Immokalee	A	1	2.45	.73	.018	.005	1.11	1.42
17 Jonesville	A	3	2.85	.67	.014	.030	1.84	1.32
18 Kanapaha	A	2	4.49	.61	.022	.020	2.02	1.22
19 Keri	A	1	4.51	.99	*.035	*.020	1.17	1.85
20 Lakeland	A,B	5	2.36	.87	.013	.017	1.54	1.66
21 Leon	A	6	2.5	1.22	.026	.0086	2.52	2.21
22 Manatee	A	1	8.99	2.09	.082	.0725	11.00	3.45
23 Norfolk	C	11	***	1.18	.023	.03	***	2.14
24 Ona	A	4	5.04	1.89	.048	.015	3.38	3.20
25 Orangeburg	B	2	***	1.45	*.047	*.020	1.23	2.55
26 Palm Beach	B	3	***	.65	.013	*.055	4.03	1.29
27 Parkwood	A	1	5.37	*2.82	*.083	*.058	4.25	4.43

Table B-1. Continued

Series	Data Source	Number of Samples	Moisture Equivalents	Organic	Total N	Total P	CEC	Thermal[1] Energy
				-----------	%	-------------	ME/100 gm	x 10^6 Cal/Acre
28 Perrine	B	3	49.8	.862	.017	.016	* .918	1.64
29 Plummer	A	1	2.35	.654	.019	.003	1.22	1.29
30 Pomello	A,B	1	2.21	.21	.0075	.0044	.24	0.48
31 Pompano	A	1	4.15	.90	.046	.013	2.83	1.70
32 Portsmouth	C	3	***	2.09	.032	.04	***	3.45
33 Rex	A	2	6.32	.76	.022	.011	2.02	1.47
34 Rutledge	A	1	3.44	2.02	.058	.0072	3.23	3.38
35 Scranton	A	7	5.81	1.80	.040	.037	3.62	3.08
36 St. Lucie	B	3	2.48	.72	.046	*.017	.969	1.42

* = Missing unless estimated from regression coefficients in Table 4.

[1] Including 24 inches below the surface.

A. Gammon, Nathan Jr., Henderson, J.R., Carrigaw, R.A., Caldwell, R.E., Leighty, R.G., Smith, F.B. Physical, Spectrographic and Chemical Analyses of Some Virgin Florida Soils. Florida Agricultural Experiment Stations, University of Florida, Bulletin 524, August, 1953.

B. Calhoun, F.G., Carlisle, V.W., Caldwell, R.E., Zelanzy, L.W., Hammond, L.C., and Breland, H.L. Characterization Data for Selected Florida Soils. Soil Science Research Report Number 74-1, University of Florida.

C. Rogers, L.H., Gall, O.F., Gaddun, L.W., Barnette, R.W. Distribution of Macro and Micro Elements in Some Soils of Peninsular Florida. Florida Agricultural Experiment Stations, Bulletin 34, 1939.

D. Persons, A.A. A Chemical Study of Some Typical Soils of the Florida Peninsula. Florida Agricultural Experiment Stations, Bulletin 43, 1897.

Table B-2. Soil series present in major soil groupings

Group[a]	Associations[b]	% of State[c]
Areas dominated by excessively drained soils	St. Lucie-Lakewood Pomello	3.34
	Palm Beach-Cocoa	.33
Soils dominantly thick to moderately thick acid sands	Lakeland-Eustis-Blanton	12.60
	Lakeland-Eustis-Norfolk	1.10
Soils dominantly thick to thin sands influenced by alkaline materials	Jonesville-Chiefland-Hernando	1.35
	Hernando-Chiefland-Jonesville	.16
Soils dominantly thick to thin phosphatic sands and loamy sands overlying finer textured materials	Arredondo-Gainesville-Fort Meade	1.67
	Hague-Zuber-Fellowship	.58
Soils dominantly thin acid sand to sandy loam overlying finer textured soils	Norfolk-Ruston-Orangeburg	3.64
	Magnolia-Faceville-Tifton	.72
	Shubuta-Cuthbert-Lakeland	1.07
	Kalmia-Cahaba	.09
Soils dominantly thick to thin acid sands, some of which overlie finer textured subsoils	Blanton-Klej	5.58
	Kanapaha-Blanton	.21
	Rex-Blanton	.95
	Blanton-Bowie-Susquehanna	.62
	Goldsboro-Lynchburg	1.27
Soils dominantly thick acid sands with organic pans; interspersed with soils without a pan formation	Leon-Plummer-Rutledge	14.51
	Leon-Immokalee-Pompano	8.20
	Leon-Blanton-Plummer	1.28
Soils dominantly thick acid sands with dark surface soils	Scranton-Ona	1.04

Table B-2. Continued

Group[a]	Association[b]	% of State
Soils dominantly thick to thin sands overlying finer textured alkaline materials	Adamsville-Pompano	2.29
	Sunniland-Bradenton	1.39
	Panasoffkee-Bushnell	.63
	Broward-Parkwood-Keri	2.31
Soils dominantly thick to thin sand to sandy loam surface soils overlying finer textured acid subsoils	Coxville-Bladen-Weston	.69
	Leaf-Bladen-Rains	.20
	Plummer-Rutledge	2.41
	Bayboro-Portsmouth-Rains	.12
Soils dominantly moderately thick to thin acid sands to sandy loams overlying finer-textured alkaline materials	Pompano-Charlotte-Delray	4.11
	Manatee-Felda	1.23
Soils dominantly moderately thick to thin marly materials overlying limestone	Perrine-Ochopee	2.84
Soils dominantly peats and mucks	Everglades-Brighton-Pamlico	6.64

[a] Determined by Smith et al. Florida Agricultural Experiment Station, Bulletin 717, June 1973.

[b] Underlined series in each association were entered into calculations as specified in Methods. Soil characterization data for each series given in Table B-1.

[c] Calculations by V.W. Carlisle equating weights of separations representing individual soil associations shown on the General Soil Map of Florida, 1973, with total land area.

APPENDIX C

IDENTIFICATION CODES, LAND AREAS, NATURAL ENERGIES, URBAN INDICATORS AND POPULATION DATA FOR COUNTIES IN FLORIDA FROM WHICH URBAN STRUCTURE AND IT'S RATE OF CHANGE WERE DERIVED

Table C-1. Identification codes and land areas for counties in Florida

Identification Code	County	Land area in square miles
1	Alachua	915.7
2	Baker	584.6
3	Bay	747.4
4	Bradford	293.7
5	Brevard	1,011.0
6	Broward	1,218.7
7	Calhoun	560.8
8	Charlotte	703.0
9	Citrus	559.7
10	Clay	593.0
11	Collier	2,006.2
12	Columbia	784.1
13	Dade	2,041.9
14	De Soto	647.7
15	Dixie	692.4
16	Duval	765.7
17	Escambia	665.0
18	Flagler	487.3
19	Franklin	536.2
20	Gadsden	512.3
21	Gilchrist	346.3
22	Glades	752.8
23	Gulf	564.7
24	Hamilton	514.2
25	Hardee	629.2
26	Hendry	1,186.7
27	Hernando	484.3
28	Highlands	1,042.8
29	Hillsborough	1,037.8
30	Holmes	481.8
31	Indian River	506.4
32	Jackson	935.2
33	Jefferson	605.2
34	Lafayette	548.7
35	Lake	960.6
36	Lee	785.0
37	Leon	670.2
38	Levy	1,082.5
39	Liberty	838.6
40	Madison	702.9
41	Manatee	739.2
42	Marion	1,599.5
43	Martin	556.0
44	Monroe	1,034.1
45	Nassau	650.0
46	Okaloosa	944.3
47	Okeechobee	777.2

Table C-1. Continued

Identification Code	County	Land area in square miles
48	Orange	910.0
49	Osceola	1,310.0
50	Palm Beach	2,023.0
51	Pasco	741.6
52	Pinellas	264.7
53	Polk	1,860.7
54	Putnam	778.7
55	St. Johns	604.7
56	St. Lucie	583.5
57	Santa Rosa	1,031.8
58	Sarasota	587.3
59	Seminole	304.9
60	Sumter	555.1
61	Suwannee	685.8
62	Taylor	1,050.6
63	Union	241.0
64	Volusia	1,061.9
65	Wakulla	600.6
66	Walton	1,052.5
67	Washington	585.3

Table C-2. Natural energies of Florida counties

County[a] Code	Sun $\times 10^6$ CE/Acre•Yr	Rain $\times 10^6$ CE/Acre•Yr	Aquifer Water Storage $\times 10^6$ CE/Acre•Yr	Wave $\times 10^6$ CE/Acre•Yr	Natural Gross Primary Productivity $\times 10^6$ CE/Acre•Yr	Mineral Soil $\times 10^6$ CE/Acre	Organic Soil $\times 10^6$ CE/Acre
1	3.145	13.3	41.7	0.0	7.70	711.	368.
2	3.122	14.3	35.1	0.0	7.70	556.	0.
3	3.122	15.2	12.9	0.53	7.54	800.	0.
4	3.135	13.3	44.5	0.0	7.70	596.	740.
5	3.184	14.2	24.5	1.14	5.10	604.	3379.
6	3.245	15.0	6.0	0.32	6.40	204.	16695.
7	3.119	15.4	33.2	0.0	7.70	560.	0
8	3.225	13.1	6.1	0.13	6.53	636.	0
9	3.169	14.2	14.2	0.09	7.66	640.	0
10	3.135	13.3	45.8	0.0	7.70	675.	0
11	3.245	14.0	7.2	0.13	6.30	583.	352.
12	3.126	13.3	33.0	0.0	7.69	571.	0
13	3.261	15.6	3.1	0.53	5.18	388.	7255.
14	3.217	13.9	33.2	0.0	6.17	692.	0
15	3.148	14.3	14.2	0.06	7.66	843.	0
16	3.122	13.6	31.3	0.53	7.43	635.	0
17	3.110	16.7	78.4	0.32	7.55	636.	0
18	3.151	13.5	10.6	0.84	7.30	651.	0
19	3.138	14.2	7.4	0.67	6.92	408.	0
20	3.116	14.3	31.7	0.0	7.72	728.	0
21	3.141	13.4	19.0	0.0	7.71	528.	0
22	3.222	12.7	31.5	0.0	4.66	863.	1459
23	3.132	14.6	12.1	0.39	7.60	516.	0
24	3.116	13.3	32.1	0.0	7.68	544.	1167.
25	3.208	14.5	42.1	0.0	7.70	651.	160.
26	3.237	13.6	11.9	0.0	6.55	883.	2103.
27	3.178	14.7	22.5	0.16	7.68	632.	0
28	3.208	12.1	43.1	0.0	7.05	631.	2159.

Table C-2. Continued

County[a] Code	Sun X 10^6 CE/Acre·Yr	Rain X 10^6 CE/Acre·Yr	Aquifer Water Storage X 10^6 CE/Acre·Yr	Wave X 10^6 CE/Acre·Yr	Natural Gross Primary Productivity X 10^6 CE/Acre·Yr	Mineral Soil X 10^6 CE/Acre	Organic Soil X 10^6 CE/Acre
29	3.196	14.5	26.2	0.0	7.68	735.	0
30	3.103	15.1	64.0	0.0	7.73	696.	0
31	3.202	14.8	28.9	0.72	5.94	636.	5379
32	3.110	14.6	58.5	0.0	7.72	675.	0
33	3.119	14.1	29.1	0.67	7.69	544.	0
34	3.132	13.9	29.8	0.05	7.70	600.	0
35	3.178	13.5	49.8	0.0	7.69	483.	928
36	3.237	12.8	10.0	0.31	7.30	732.	0
37	3.122	14.5	23.7	0.0	7.72	716.	0
38	3.154	13.5	13.8	0.07	7.68	623.	0
39	3.126	15.2	24.7	0.0	7.70	572.	0
40	3.119	13.3	43.3	0.0	7.71	632.	528
41	3.208	14.2	20.6	0.14	7.33	679.	0
42	3.157	14.4	30.8	0.0	7.71	727.	276
43	3.217	13.1	10.4	0.73	7.25	767.	847
44	3.278	14.0	2.3	0.62	4.79	132.	1447
45	3.116	13.8	28.6	0.40	7.68	640.	0
46	3.110	16.7	50.7	0.32	7.61	576.	0
47	3.208	12.0	31.2	0.0	3.82	767.	280
48	3.181	13.4	36.3	0.0	7.26	632.	607
49	3.193	14.2	35.1	0.0	6.32	683.	0
50	3.234	14.2	10.7	0.39	6.89	364.	13363
51	3.184	14.2	41.5	0.18	7.68	707.	0
52	3.199	14.4	1.9	1.59	6.05	616.	0
53	3.193	13.6	60.3	0.0	7.35	687.	523
54	3.148	13.7	29.0	0.0	7.69	607.	759
55	3.138	13.5	21.3	1.61	7.09	616.	0
56	3.211	14.8	21.3	0.58	5.72	988.	719

Table C-2. Continued

County[a] Code	Sun X 10^6 CE/Acre•Yr	Rain X 10^6 CE/Acre•Yr	Aquifer Water Storage X 10^6 CE/Acre•Yr	Wave X 10^6 CE/Acre•Yr	Natural Gross Primary Productivity X 10^6 CE/Acre•Yr	Mineral Soil X 10^6 CE/Acre	Organic Soil X 10^6 CE/Acre
57	3.110	16.8	73.4	0.27	7.59	619.	0
58	3.217	13.8	12.4	0.49	6.50	815.	0
59	3.172	13.8	24.2	0.0	7.13	644.	0
60	3.172	14.0	39.4	0.0	7.70	616.	0
61	3.126	13.3	23.9	0.0	7.71	583.	0
62	3.132	14.2	20.7	0.11	7.65	440.	0
63	3.126	13.3	37.4	0.0	7.70	564.	0
64	3.163	13.8	13.0	0.98	6.61	432.	0
65	3.129	14.8	10.2	0.34	7.66	556.	0
66	3.110	16.5	39.4	0.25	7.71	663.	0
67	3.113	15.7	23.3	0.0	7.71	608.	0

[a] See Table C-1 for county identification

[b] Heat equivalents of these energies can be found from conversion factor in Table 3.

Table C-3. Urban indicators for counties in Florida

County[a] Code	Property Valuation x 10^6 $ 1970	Property Valuation x 10^6 $ 1971	Gasoline Consumption X 10^6 Gallons 1970	Gasoline Consumption X 10^6 Gallons 1971
1	754.0	754.0	54.3	79.6
2	54.2	67.1	4.8	8.8
3	501.0	544.2	39.5	53.9
4	68.3	86.0	10.1	17.4
5	2365.3	4110.5	100.0	118.3
6	5561.8	6316.6	268.0	403.6
7	40.8	43.6	4.3	5.1
8	288.9	323.4	12.3	17.4
9	195.5	219.5	10.3	18.3
10	159.9	171.6	10.9	24.9
11	548.2	631.0	24.9	38.5
12	112.6	184.5	22.3	30.5
13	11700.4	12812.0	505.7	647.5
14	82.6	91.2	8.1	9.3
15	32.4	37.1	5.4	6.0
16	3314.8	3551.4	216.8	282.4
17	1050.6	1368.4	81.7	103.7
18	46.5	56.2	3.2	5.2
19	43.3	68.2	4.2	5.2
20	120.8	125.9	13.4	18.1
21	22.5	35.2	1.5	2.2
22	69.1	72.5	3.2	3.2
23	64.5	66.2	4.0	4.3
24	45.9	48.1	13.2	13.7
25	128.5	132.1	7.5	10.4
26	127.7	140.7	8.2	11.6
27	120.0	132.9	9.3	17.7
28	296.7	316.3	15.4	23.9
29	2990.4	3227.5	233.6	342.9
30	41.8	45.1	5.2	7.9
31	340.2	389.0	23.4	36.8
32	139.2	145.5	18.1	22.9
33	38.5	43.3	4.8	7.3
34	36.5	31.3	1.5	1.6
35	540.4	571.4	36.4	50.6
36	850.0	956.5	51.5	79.3
37	850.8	1104.5	46.0	69.3
38	90.2	97.2	9.3	11.8
39	29.7	30.7	2.1	2.9
40	77.2	84.8	6.7	8.9
41	639.8	684.7	36.3	47.5
42	526.1	677.0	51.3	74.0
43	298.4	348.2	19.0	26.2
44	434.8	545.2	23.8	31.3
45	114.5	228.9	13.3	17.5
46	360.8	729.0	38.4	49.4

Table C-3. Continued

County Code	Property Valuation X 10^6 \$ 1970	Property Valuation X 10^6 \$ 1971	Gasoline Consumption X 10^6 Gallons 1970	Gasoline Consumption X 10^6 Gallons 1971
47	79.4	90.2	8.1	11.2
48	2103.6	2721.4	172.0	242.9
49	315.1	360.6	20.4	30.8
50	3356.8	4203.8	142.0	209.4
51	366.2	467.0	25.7	48.5
52	2792.5	3016.4	182.7	252.8
53	1781.5	1947.2	110.1	145.4
54	210.9	227.2	16.8	21.3
55	253.0	302.1	19.7	26.3
56	405.3	457.3	31.5	45.3
57	225.4	244.8	17.6	24.7
58	1011.2	1128.3	50.4	66.3
59	470.7	609.1	32.0	57.5
60	85.1	92.6	14.3	22.4
61	93.7	102.5	11.0	16.8
62	91.2	103.4	15.0	13.9
63	21.4	34.9	2.6	3.3
64	1075.6	1216.9	78.0	109.0
65	54.6	57.6	3.1	6.0
66	82.6	85.8	12.7	13.0
67	47.4	52.1	5.9	7.3

Table C-4. Urban indicators for counties in Florida

County Codes	Total Housing Units X 10^3 1950	1960	1970	1973	Total Retail Sales X 10^6 $ 1973	1974
1	13.5	22.0	33.5	41.4	290.0	368.7
2	1.3	2.0	2.4	3.2	10.5	12.3
3	11.2	21.7	27.0	31.7	219.1	273.3
4	2.7	4.0	4.6	5.2	20.4	28.4
5	9.1	36.9	78.0	88.5	501.5	572.4
6	29.3	128.6	253.3	331.0	2517.4	3117.6
7	1.8	2.4	2.7	3.0	9.5	11.9
8	1.8	6.2	13.8	18.8	76.9	101.5
9	2.1	4.5	9.8	17.7	51.4	68.4
10	3.5	7.2	11.0	15.3	40.2	57.8
11	1.8	6.0	17.6	28.5	191.3	272.7
12	4.7	6.4	8.5	10.0	70.0	83.8
13	165.1	348.9	453.9	525.4	4793.5	5784.0
14	2.5	3.4	4.1	5.4	20.1	26.5
15	.9	1.6	1.9	2.2	6.6	8.5
16	84.0	141.3	174.3	193.3	1954.2	2119.8
17	30.0	52.3	65.1	75.0	502.7	597.0
18	1.0	1.7	1.9	2.5	11.3	16.4
19	2.3	3.1	3.4	4.0	6.9	9.8
20	6.9	9.6	10.3	11.4	45.5	46.8
21	.7	1.0	1.3	1.7	4.3	5.9
22	.7	1.0	1.4	1.9	3.9	4.8
23	2.1	3.6	3.8	4.2	12.7	108.0
24	1.8	2.3	2.6	2.9	8.1	12.0
25	2.7	4.1	4.8	6.0	26.6	32.0
26	1.7	2.6	4.0	5.2	28.5	45.2
27	2.1	4.4	7.8	13.9	40.2	50.8
28	5.0	8.6	12.5	17.6	71.2	87.1
29	76.0	135.4	168.6	204.8	2016.9	2126.7
30	2.6	3.5	4.1	4.5	11.5	13.3
31	4.0	9.7	14.1	18.6	110.2	135.4
32	7.6	11.0	11.4	13.1	60.1	74.7
33	2.2	2.8	2.7	3.1	9.3	10.5
34	.8	1.1	1.1	1.2	2.1	3.1
35	11.3	21.8	28.3	36.4	201.2	235.5
36	8.8	21.0	43.5	63.4	460.8	563.3
37	11.7	21.1	32.6	42.9	384.9	418.7
38	2.6	3.6	4.8	6.5	22.3	27.6
39	.6	1.0	1.3	1.4	1.4	2.4
40	3.4	4.3	4.3	5.0	12.9	16.1
41	12.9	30.3	42.8	52.5	290.6	363.0
42	10.6	18.0	26.1	34.6	282.0	295.8
43	3.2	7.5	12.4	19.4	98.9	135.1
44	8.2	16.7	20.7	25.5	155.7	205.4
45	3.4	5.3	6.8	8.6	25.5	45.0
46	37.8	17.9	27.3	33.0	183.0	223.5

Table C-4. Continued

County Codes	Total Housing Units X 10^3				Total Retail Sales X 10^6 $	
	1950	1960	1970	1973	1973	1974
47	6.1	2.0	3.7	5.5	29.7	38.4
48	1.0	88.4	117.3	143.7	1705.9	1938.4
49	4.5	7.9	10.5	14.6	74.3	119.8
50	42.8	89.4	141.2	189.3	1363.1	1653.9
51	6.5	14.9	34.8	51.1	188.3	254.1
52	66.6	165.8	228.8	285.3	1742.5	1919.7
53	36.3	64.1	80.5	97.7	746.0	881.1
54	7.0	10.9	13.0	16.2	67.3	80.9
55	7.0	10.6	11.7	14.0	81.5	102.3
56	6.4	14.0	18.9	25.5	180.2	208.5
57	4.4	8.7	12.2	16.8	47.4	61.3
58	12.1	34.8	56.2	75.1	516.7	589.3
59	7.8	18.2	28.4	42.9	289.1	331.5
60	2.9	4.1	5.3	7.3	26.0	31.9
61	3.6	4.7	5.2	6.3	32.7	40.5
62	2.7	4.4	5.0	5.6	25.9	36.1
63	1.0	1.3	1.7	2.1	4.2	6.5
64	26.9	52.4	70.6	84.2	539.9	685.0
65	1.3	1.9	2.7	3.8	7.3	9.7
66	3.6	5.6	6.6	7.4	22.5	24.2
67	2.7	3.7	4.2	5.1	13.4	17.7

Table C-5. 1920-1975 population of counties in Florida (x 10^3 People)

County[a] Code	1920	1930	1940	1950	1960	1965	1970	1975
1	31.7	34.4	38.6	57.0	74.1	92.5	104.8	130.8
2	5.6	6.3	6.5	6.3	7.4	8.4	9.2	12.3
3	11.4	12.1	20.7	42.7	67.1	70.1	75.3	91.6
4	12.5	9.4	8.7	11.5	12.4	14.0	14.6	16.3
5	8.5	13.3	16.1	23.7	111.4	182.8	230.0	252.0
6	5.1	20.1	39.8	83.9	333.9	467.2	620.1	876.3
7	8.8	7.3	8.2	7.9	7.4	7.6	7.6	8.3
8	***	4.0	3.7	4.3	12.6	21.8	27.6	42.2
9	5.2	5.5	5.8	6.1	9.3	14.6	19.2	35.3
10	5.6	6.9	6.5	14.3	19.5	23.3	32.1	47.7
11	***	2.8	5.1	6.5	15.8	25.7	38.0	62.7
12	14.3	14.6	16.9	18.2	20.1	23.2	25.3	28.8
13	42.7	143.0	267.7	495.1	935.0	1122.9	1267.8	1438.0
14	25.4	7.7	7.8	9.2	11.7	13.2	13.1	18.2
15	***	6.4	7.0	3.9	4.5	5.1	5.5	6.6
16	113.5	155.5	210.1	204.0	455.4	508.9	528.9	578.3
17	49.4	53.6	74.6	112.7	173.8	194.4	205.3	224.9
18	2.4	2.5	3.0	3.4	4.6	4.7	4.5	6.6
19	5.3	5.8	6.0	6.3	6.6	7.3	7.1	7.9
20	23.5	29.9	31.5	36.5	42.0	41.6	39.2	39.1
21	***	4.1	4.3	3.5	2.9	3.2	3.6	5.1
22	***	2.8	2.7	2.2	3.0	3.6	3.7	5.1
23	***	3.2	7.0	7.5	9.9	9.7	10.1	10.9
24	9.9	9.5	9.8	8.9	7.7	7.8	7.8	8.6
25	***	10.3	10.2	10.1	12.4	13.5	14.9	18.5
26	***	3.5	5.2	6.1	8.1	11.2	11.9	15.9
27	4.5	4.9	5.6	6.7	11.2	14.6	17.0	28.5
28	***	9.2	9.2	13.6	21.3	26.5	29.5	42.8
29	88.3	153.5	180.1	249.9	397.8	449.2	490.3	605.6

Table C-5. Continued

County[a] Code	1920	1930	1940	1950	1960	1965	1970	1975
30	7.8	12.9	15.4	13.9	10.8	11.1	10.7	12.5
31	***	6.7	9.0	11.9	25.3	31.6	36.0	46.3
32	31.2	31.9	34.4	34.6	36.2	34.9	34.4	41.2
33	14.5	13.4	12.0	10.4	9.5	9.3	8.8	9.4
34	6.2	4.4	4.4	3.4	2.9	2.9	2.9	3.1
35	12.7	23.2	27.3	36.3	57.4	61.3	69.3	86.7
36	9.5	15.0	17.5	23.4	54.5	80.7	105.2	156.5
37	18.1	23.5	31.6	51.6	74.2	86.1	103.0	133.2
38	9.9	12.5	12.6	10.6	10.4	11.6	12.8	15.6
39	3.0	4.1	3.7	3.2	3.1	3.2	3.4	3.9
40	15.4	15.6	16.2	14.2	14.2	14.0	13.5	14.4
41	4.6	22.5	26.1	34.7	69.2	84.2	97.1	123.5
42	24.4	29.6	31.2	38.2	51.6	64.1	69.0	93.5
43	***	5.1	6.3	7.8	16.9	24.1	28.0	47.7
44	19.6	13.6	14.1	30.0	47.9	51.4	52.6	55.7
45	11.3	9.4	10.8	12.8	17.2	19.0	20.6	29.1
46	***	9.9	12.9	27.5	61.2	73.8	88.2	102.0
47	2.1	4.1	3.0	3.5	6.4	9.5	11.2	17.0
48	19.9	49.7	70.1	115.0	263.5	308.9	344.3	424.6
49	7.2	10.7	10.1	11.4	19.0	22.1	25.3	36.7
50	18.7	51.8	80.0	114.7	228.1	294.9	349.0	477.8
51	8.8	10.6	14.0	20.5	36.8	53.9	76.0	130.2
52	28.3	62.1	91.9	159.3	347.7	450.2	522.3	666.6
53	38.7	72.3	86.7	124.0	195.1	214.6	228.6	276.0
54	11.6	18.1	18.7	23.6	32.2	34.4	36.4	43.5
55	9.2	18.7	20.0	25.0	30.0	30.7	31.0	40.2
56	7.9	7.1	11.9	20.2	39.3	47.2	50.8	69.1
57	13.7	14.1	16.1	18.5	29.5	34.0	37.7	46.9
58	***	12.4	16.1	28.8	76.9	97.2	120.4	163.2
59	11.0	18.7	22.3	26.9	54.9	73.0	23.7	136.4

Table C-5. Continued

County[a] Code	1920	1930	1940	1950	1960	1965	1970	1975
60	7.9	10.6	11.0	11.3	11.9	14.1	14.8	20.6
61	19.8	15.7	17.1	17.0	15.0	16.1	15.6	18.9
62	11.2	13.1	11.6	10.4	13.2	13.6	13.6	14.6
63	***	7.4	7.1	8.9	6.0	7.2	8.1	10.4
64	23.4	42.7	53.7	74.2	125.3	155.0	169.5	212.4
65	5.2	5.5	5.5	5.3	5.3	6.1	6.3	8.8
66	12.1	14.6	14.2	14.7	15.6	15.5	16.1	18.0
67	11.8	12.2	12.3	11.9	11.2	11.5	11.5	14.1

[a] See Table C-1 for county identification.

***Data not available.

APPENDIX D

DETAILS OF STATISTICAL ANALYSIS OF COUNTY PRODUCTION MODELS

Table D-1. Final regression equations based on models of energy interaction with all natural energies included

Model	Sample	Results[a]
Additive Interaction	1930	Y = (S + R + W + A + N + M + 0) Not significant
Without Feedback From Structure	Pooled 1965 1970 1975	Y = 131.4 x (S + R + W + A + N + M + 0)/1000 +345
See Figure 5a	1975	Y = 166.3 x (S + R + W + A + N + M + 0)/1000 + 571
Separated Processes Additive Interaction	1930	Y = 168.25 x S x U - 7.64 x R X U - 21.16 x W x U - 1.34 x A x U - 53.6 x N x U + .22 x M x U + .01 x 0 x U - 10.7
Each with multiplicative Feedback From Structure	Pooled 1965 1970 1975	Y = 29.49 x S x U - 10.97 x R x U + 17.8 x W x U - 1.02 x A x U + 5.8 x N x U + .23 x M x U + .01 x 0 x U + 31.79
See Figure 5b	1975	Y = -7.6 + S x U - 9.1 x R x U + 6.9 x W x U - 2.4 x A x U + 31.68 x N x U + .19 x M x U + .01 x 0 x U + 78.55
Multiplicative Single	1930	Y = (S x R x W x A x M x N x 0) Not significant
Process Interaction Without Feedback From Structure	Pooled 1965 1970 1975	Y = (S x R x W x A x N x M x 0) Not significant

Table D-1. Continued

Model	Sample	Results[a]
See Figure 6a	1975	$Y = (S \times R \times W \times A \times N \times M \times O)$ Not significant
Multiplicative Interaction	1930	$Y = .475 \times S \times R \times A \times N \times M \times O \times U \times .001 + 130.5 \times W \times U + 68.7$
With Feedback From Structure Terrestrial and Coastal Processes	Pooled 1965 1970 1975	$Y = .269 \times S \times R \times N \times M \times O \times U \times .001 + 87.9 \times W \times U + 297$
Separated See Figure 6b	1975	$Y = .239 \times S \times R \times A \times N \times M \times O \times U \times .001 + 102.8 \times W \times U + 483$

[a] Y = Rate of change of urban structure x 10^9 CE/Acre·Year
U = Urban structure x 10^{12} CE/Acre
S = Sunlight/Acre·Year
R = Rain/Acre·Year
W = Wave/Acre·Year
A = Aquifer water storage/Acre
N = Natural gross primary productivity/Acre·Year
M = Mineral soil/Acre
O = Organic soil/Acre

Natural Energies = 10^6 CE

Table D-2. Final stepwise regression equations based on models of natural energy interactions

Model	Sample	Results[a]
Additive Interaction	1930	$Y = 268W + 57.8$
Without Feedback From Structure	Pooled[b] 1965 1970 1975	$Y = 1400.4 \times W + 4520.8 \times S - .07 \times 0 - 14168$
See Figure 5a	1975	$Y = 1955.8 \times W + 9137 \times S - 28570$
Separated Processes,	1930	$Y = 67.6 \times S - 2.56 \times A - 5.5$
Each with Multiplicative Feedback From Structure	Pooled 1965 1970 1975	$Y = 43.9 \times S - 1.10 \times A + .0027 \times 0 + 36.$
See Figure 5b	1975	$Y = 52.8S - 1.24 \times A + 106.$
Multiplicative Single	1930	$Y = -168.8 \times LnA + 90.17 \times LnW + 209.1 \times LnM + 585.9 \times LnR - 2191$

Table D-2. Continued

Model	Sample	Results[a]
Process Interaction Without Feedback From Structure	Pooled 1965 1970 1975	$Y = -967.2 \times \ln A + 402.5 \times \ln W + 3418 \times \ln R + 608 \times \ln M - 9172$
See Figure 6a	1975	$Y = -1179.8 \times \ln A + 484.7 \times \ln W + 4769$

[a] Y = Rate of change of urban structure x 10^9 CE/Acre·Year
U = Urban structure x 10^{12} CE/Acre
S = Sunlight x 10^6 CE/Acre·Year
R = Rain x 10^6 CE/Acre·Year
W = Wave x 10^6 CE/Acre·Year
A = Aquifer water storage x 10^6 CE/Acre
N = Natural gross primary productivity x 10^6 CE/Acre·Year
M = Mineral Soil x 10^6 CE/Acre
O = Organic Soil x 10^6 CE/Acre

[b] Equation used for logistic model of urban growth constraints in Table 13 derived from betas of equation given above divided by appropriate energy cost quality factor.

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