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Ecological energetics, hierarchy, and urban form: a system modelling approach to the evolution of urban zonation

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Abstract. Cities are hierarchical centers of consumption and have had sharp pulses of growth and decline over history. Viewing regional development from an energy perspective is appealing in its analogy to natural systems, though the theory itself as applied to social systems remains undeveloped. The evolutionary changes of an urban system are strongly determined by exogenous energetic inputs and internally self-organized behaviors. Energy from life-support and production systems transformed and is converged spatially to urban centers. The energy-systems language method has kinetic and energetic definitions to represent open thermodynamics and the equations for simulation. This method is applied to study the evolution of urban ecosystems. Ideas of systems ecology and energetic hierarchy emerging from general system theory are adapted to formulate a macro evolutionary model of urban zonal systems. Five consecutive zones are proposed to represent Taipei metropolis: undeveloped; agricultural; residential; industrial; and urban. Each zone includes variables of area, asset, and population, and pathways interconnecting system components. Left – right positions of each zone indicate places in energy hierarchy with power circuits from left to right linking different zones, and control circuits from right to left. A model of urban zonation formulated as a set of differential equations is developed. The model is run to assess the evolution of urban zones in relation to energetic flows. Over time each zone within the urban system of Taipei metropolis evolves as a result of energy convergence and is forced to adapt its internal structure in response to external changes. Similar to care in ecosystems, it is concluded that urban systems exhibit in the long run a certain morphogenesis, a qualitative change in dynamics which moves an urban system toward different stages of spatial organization.

1 Introduction

Cities are hierarchical centers of consumption and have had sharp pulses of growth and decline in history. In urban studies, Berry (1964) showed how cities and groups of cities may be regarded as systems, and Wilson (1970) used entropy to develop models of urban and regional structure. Urbanization is well established as a focus of study in the social sciences but it is rarely a focus of study in disciplines related to ecology. Modern cities are characterized by marked evolutionary change, in which the energetic flows to and in a city exert a profound effect. Earlier research on the hierarchically organized urban system used an entropy-maximizing paradigm, which assumes the society to be a closed system (Batten, 1982). Planners have also investigated the relationship between energy and urban form by examining the relative energy efficiency of alternative spatial configurations of urban forms. In most of these studies (for example, see Owens, 1987) it is assumed initially that energy constraints are a powerful determinant of urban form.

Cities thrive on the energy and materials supplied by the countryside in the form of food and other renewable resources. The evolutionary changes of an urban system depend strongly on the exogenous energetic inputs and the internally self-organized behavior. Cottrell (1955) addressed the link between energy surplus and urban civilization. In his best-known book, *Cities in Evolution*, Geddes (1915) criticized that coal-based industrialization and the consequent conurbation were really Kakotopias; the cities of organic balance with nature would create utopias. Martinez-Alier (1987) addressed the merit of Geddes's idea of carefully tracing out energy flows for the analysis of the evolution of cities, which is closer to true human ecology than the misnamed 'human ecology' of the school of urban sociology of Chicago in the 1920s.

It has been hypothesized that the spatial configuration of human activities depends largely on energy production and consumption conditions. Odum (1971; 1983; 1988b) has dealt extensively with the interaction between humans and nature in attempting to create a unified theory for all systems based on energy flows and energy laws. Over the past decades, Odum and coworkers have extended their work from natural ecosystems to include the system of humans and their interaction with natural systems. Energy analysis has also been applied to study urban systems. Zucchetto (1975) used the city of Miami as a case study and developed a simulation model of urban growth based on energy flows. He concluded that the decline in the importance of the city was due to the decreasing net energy flows in the city. The inability of the city to capture energy and, in turn, maximize power led to its decline. Brown (1981) also examined energy flows through the urban hierarchy in Florida. Huang and Liao (1991) applied ecological energetic analysis to study the ecological economic status of the Taipei metropolitan region; the energy hierarchy of the city of Taipei was also assessed. However, an integrated theory of the interdependence of energetic flows and urban development in the spatial context remains to be established.

This paper is focused on the spatial structure of urban zonation and we examine the dynamics of the evolution of zonal patterns. The underlying theme throughout is the hypothetical effect of energetic flows on urban zonation, and how different zones organize hierarchically in the spatial context. Viewing regional development from an energy perspective is appealing in its analogy to natural systems though the theory itself as applied to social systems remains undeveloped. Computer simulation of city models has a long history. Earlier reviews (Batty, 1976; Mohan, 1979) describe most models built up from relationships between population trends, employment, and land use. Aggregated urban models, such as that of Forrester (1969), were criticized for ignoring the spatial organization. Cellular automata have recently received a lot of attention to investigate principles of urban evolution in the spatial context by setting 'states' and 'rules of change' (for example, see Batty and Xie, 1994; White and Engelen, 1993). The evolution of the urban form depends not only on its previous state but on exogenous conditions and driving forces which affect the carrying capacity of a city. If a city is the hierarchical center of a landscape system, it is best described by a model which relates the city and its zones to the entire landscape resources. In this paper we begin by expanding some concepts emerging from the general system theory (GST) of ecological energetics. The laws describing growth, depreciation, and interaction of biological systems and social systems are analogous. One can explore the evolution of urban systems by developing a dynamic simulation model, with energy circuit language and ideas underlying the theory of systems ecology. In section 3 the system model and the methods of dynamic analysis to be used for simulating urban zonation are outlined. The term 'urban' refers, in this paper, to a functionally interwoven agglomeration, comprising central city and surrounding areas which provide life-support services to the city in that context. After formulating a macro model of a self-organizing urban system, we used Taipei metropolis to interpret the evolution of urban zonation. The results of the simulation are presented and discussed in section 4. The conclusions are given in section 5.

2 Energy, hierarchy, and urban evolution

Social and economic evolution includes progress of learning mechanisms, innovations, and inventions as a result of adapting to environments (Batten, 1982). For urban evolution, symbiotic relationships between human settlements and the environment bring about innovation. Development of urban areas is similar around the world. The early cities were small settlements surrounded by agricultural lands. As the population and resource use expanded, the cities grew and surrounding agricultural lands were converted to urban uses. The existence and maintenance of an urban region, and of its internal structure (urban center, residential area, agricultural district, etc), depend on the flow of goods and services in, out, and throughout the city. Systems approach can be used to aid the conceptualization of the phenomenon of urban regions such that the interrelationship of the objects and attributes of the system of interest lie on one side and the study of subsystems of interest within an interacting whole lie on the other. Once a city or region is viewed as a system, it is possible to introduce such ideas as 'energy' into the conceptualization of an urban system. For an ecosystem, there are storage of biomass or energy at each level, with various inflows and outflows of imports, feeding, maintenance, exports, etc. For the economic system, there can be storage of money, labor, land, etc, and flows of energy, goods, and services. In order to thread together the human economy and natural systems, energy was used as a common denominator. In this way, we should be at the threshold of utilizing a well-developed body of ideas and techniques in analyzing and understanding combined systems of humans and nature in general and urban systems in particular.

Friedman (1973, pages 66–67) sees urbanization as consisting of two opposite yet related forces: first, urbanization as "the geographic concentration of population and non-agricultural activities in urban environments of varying size and form"; and second, urbanization as "the geographic diffusion of urban values, behavior, organizations, and institutions". The spatial organization of cities in the landscape is often represented as a hierarchy. Energy flow is a basic functional characteristic of the ecosystem; it can also serve as a measure for understanding humans and their environment. The study of ecosystems suggests principles by which energy flows generate hierarchies in all systems. One reason for hierarchical organization of cities in the landscape is for distribution of goods and services as described by Friedmann. Another reason for this hierarchy of cities in the landscape is the convergence of energy (Odum, 1988a). Not only are cities organized in hierarchies, but each city is in itself arranged in a spatial hierarchy. The city center is the most concentrated, containing the largest buildings, the highest density of people, and the greatest energy flows. Figure 1 (over) shows the hypothetical arrangement of the spatial hierarchy of a region, in order to represent the region as a system with energetic hierarchy. Surrounding the central city are rings of gradually less concentrated activity radiating away from the center. The hypothesis of energy transformation in self-organizing open systems, proposed by Odum (1988b), involves concepts of self-development (such as evolution) in energy terms which are quite beyond classical energetics. All living systems organize into characteristic designs with hierarchical energy transfer, recycling of material, feedback control, and autocatalysis. At each transformation, most of the available energy is degraded and dispersed as a necessary process of the second law of thermodynamics in order to generate a smaller amount of energy of another type for the next hierarchy. Viewing urbanization as a change in the source and amount of energy flow from the rural to the urban core provides a workable conceptual link between urbanization and natural environments.

In extending the laws of energetics, Odum has made extensive use of Lotka's (1925) maximum power principle, which states that the systems which maximize power and use this power effectively will survive in competition with other systems. Urban ecosystems are organized in hierarchies because this design maximizes useful energy processing. The urban and information center is the highest in the hierarchy. Production and consumption are symbiotic. The urban area is in some sense a heterotrophic system that has to rely on surrounding landscapes for life-support services. The energy

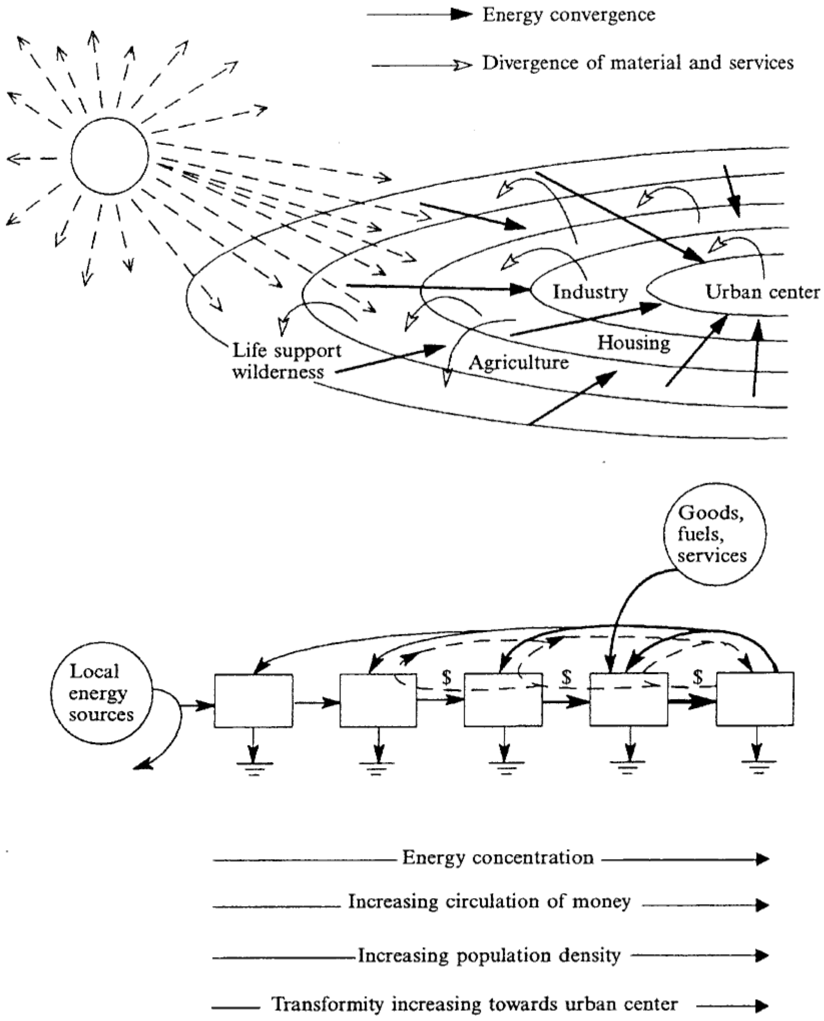

Figure 1. Conceptual view of urban zones and energy convergence.

from life-support and production systems transforms and converges spatially toward urban centers. Services (for example, labor and management) and valuable products (for example, machinery, fertilizer, and so on) diverge from urban centers as they are recycled, stimulating production of food and other physiological necessities at the lower hierarchy. In this view, urbanization is the process of change in the type of energy sources, which tend to increase the intensity of energy convergence from surrounding landscapes. The spatially converging pattern of energy flow brings highly concentrated flows of high energy into the centers.

All symbols used in the model diagrams were designed by Odum in the development of his energy language, which has been used for synthesis, analysis, and simulation of ecological systems since 1967. Odum's energy symbols have rigorous kinetic and energetic definitions so that they represent, at the same time, open-system thermodynamics and the equations for its simulation. A description, explanation, and mathematical representation of these symbols can be found in Odum (1971; 1983). The symbols used in this paper are summarized in figure 2.

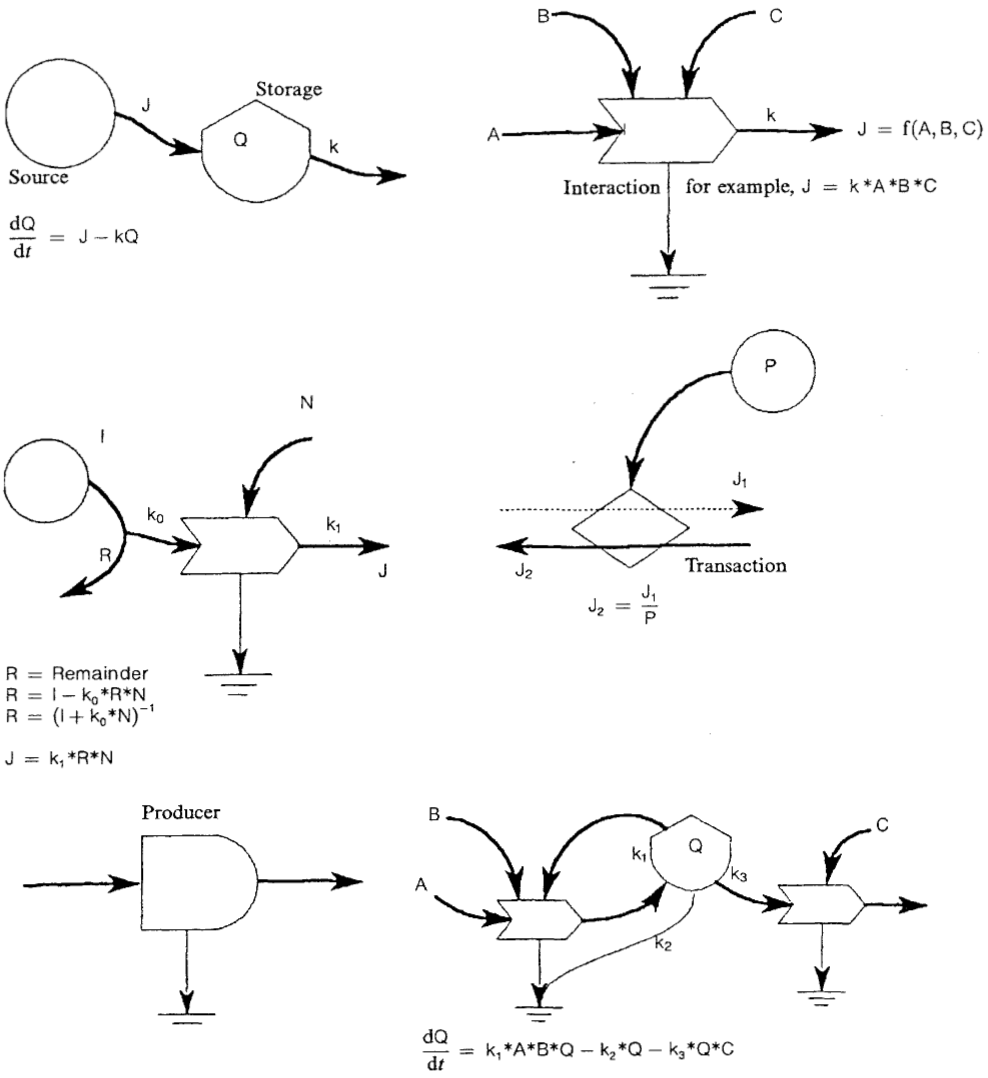

Figure 2. Symbols and mathematical representation of the energy circuit language used.

3 System model of urban zonation

To employ ideas of GST and techniques of energetic analysis for the study of urban zonation, one needs to categorize a region into various zones and to identify the major components of the urban system. In this section I present a macro model of an urban system for describing system components and interactions of flows and storage for the simulation of the evolution of urban zones. Urban system components can be categorized into objects, activities or processes, and forces (table 1, see over). The 'objects' comprise the population, land, and assets; 'activities or processes' include those of land conversion, growth and depreciation of assets, production, etc; and 'forces' refer to energetic inflows, such as renewable energy and import of goods and services, which drive the processes of the system. The zones of an urban system may be represented as a cross section from the supporting rural areas to the concentrated urban center. To provide a basis for numerical experiments, a hypothetical concentric zonation is

Table 1. Components, processes, and forces of urban systems.

Object	Activity or process	Force
Land	Land conversion	Renewable energies
Population	Population growth	Population immigration
Asset	Migration	Imports of goods and services
Information	Production	Information inflow
	Depreciation of assets	
	Exports of goods and services	

employed in this paper. The urban system is divided into five zones, namely, undeveloped areas and parks, agriculture and resource production, suburban residence, town and industrial district, and urban and information center. Figure 3 represents an overview macro model, with Odum's energy language, of the hypothetical urban zonation. For simplified policy thinking, the zones are aggregated into a chain of blocks. The zones are arranged according to the energetic hierarchy so that energy from the life-support and production system is transformed successively and converged spatially, from left to right, to the urban center. The main means of storage which have been chosen to represent each zone within the urban system are population (Pe, Pa, Pr, Pt, Pu), area (Ae, Aa, Ar, At, Au), and asset (B, Ag, Hr, Ht, St). The urban and information center further includes the asset of information center (INF). In addition to the flow-limited renewable energies (Env), regional biodiversity (BD) provides species inflow to the production of biomass in the undeveloped areas and parks; goods and services (a function of transaction between assets and the external system) are imported to zones of agriculture and resource production, the town and industrial district, and the urban and information center. Another inflow to the city that has profound effects is the immigration of people, resulting from the attraction of the urban asset. Population in the urban center (Pu) is also reduced because of crowding. Similarly, the higher the information asset, the greater the inflow of information (IINF) to the urban center. Population may also migrate between adjacent zones (Pe – Pa – Pr – Pt – Pu). Depreciation on all assets is also included to represent decay of structures. Each zone block draws resources from larger areas in the next zone outward. Each zone block can pull land from the zones on either side, depending on the assets in each zone.

Viewing the urban region as a zonation system also involves the definition of interactions, as these are responsible for its socioeconomic and spatial structure. The interactions that determine the socioeconomic structure are the natural and social increase of population, production of assets, and monetary transaction. The essential power that maintains the flow, and thereby the urban center and its internal structure, is that of the economic exchange with the outside world. The model is spatially hierarchical, as the outer zones are bigger than the central zones. The spatial structure is dependent on spatial interaction between neighboring zones, such as competitive behavior of land conversion, energy convergence, and material divergence. The concept of energetic flows is particularly useful when spatial interactions are viewed as processes that generate the zonation pattern of an urban region.

To set up the appropriate rate equations describing dynamic processes in any open system, we must consider the interactions between: (1) the components of the system of interest, and (2) the system and its external environment. The completed diagram of the urban zonation system is a rigorous representation of the differential equations and these may be written automatically, translated without further thought, because each symbol has its mathematical equivalent with one term for each pathway (see table 2).

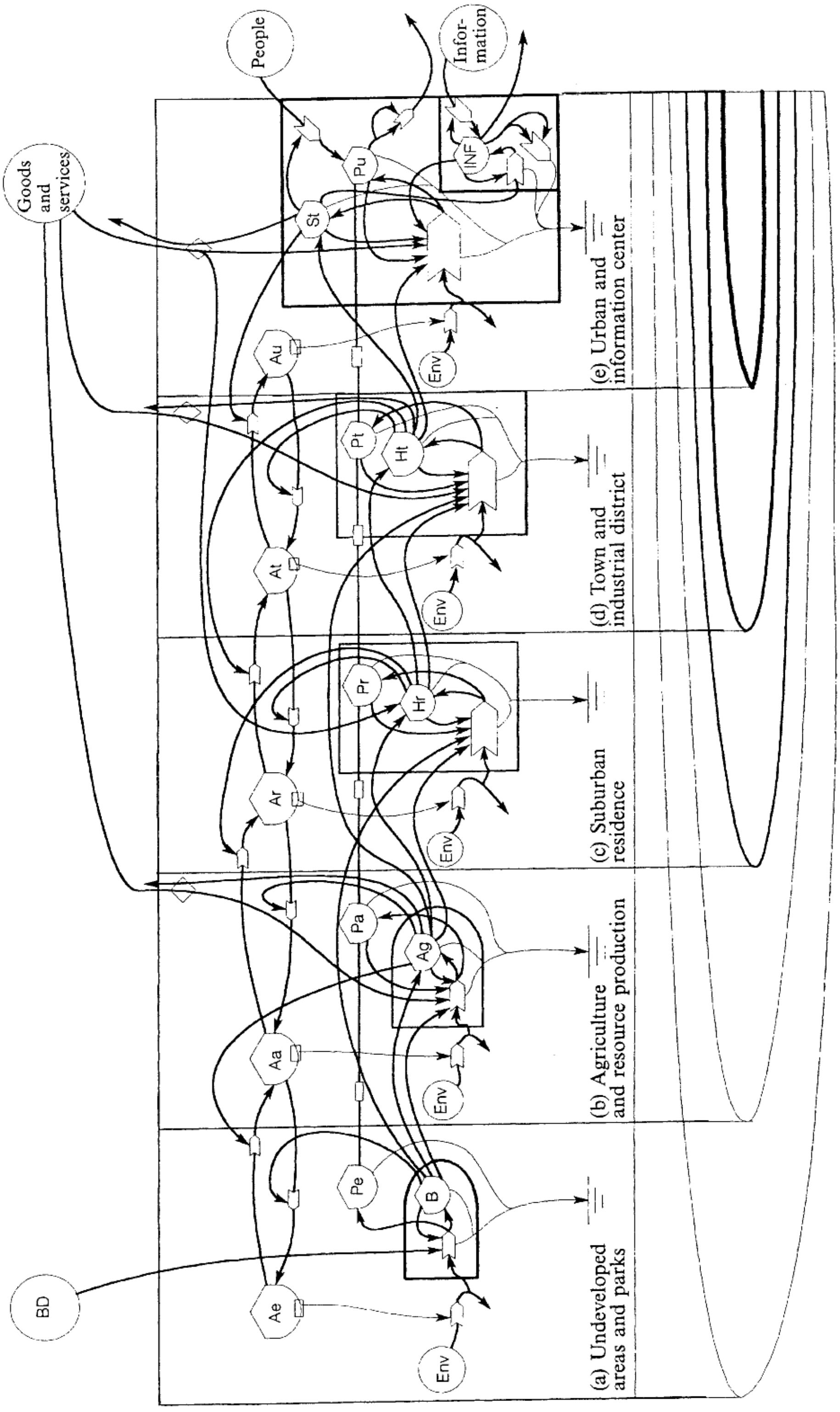

Figure 3. Energy diagram of urban zones.

Table 2. System equations of the urban zonation model.

Undeveloped area and parks

Re: remainder of environmental resources,
$$Re = E * Ae/(1 + k_{100} * BD * B)$$
PRE: production,
$$PRE = Re * BD * B$$
B: biomass,
$$dB/dt = k_{101} * PRE - k_{102} * B - k_{104} * PRA - k_{105} * PRR - k_{106} * B * Aa - k_{113} * B$$
Pe: population,
$$dPe/dt = k_{103} * PRE - k_{112} * Pe - k_{114} * (Pe - Pa)$$
Ae: natural area,
$$Ae = A - Aa - Ar - At - Au$$

Agriculture and resource production

Ra: remainder of environmental resources,
$$Ra = E * Aa/(1 + k_{200} * B * Ga * Ag * Pa)$$
Ga: inflow from economic system,
$$Ga = Ja * RPa, \quad Ja = K_{205} * Ag$$
PRA: production,
$$PRA = Ra * B * Ag * Ga * Pa$$
Ag: agricultural asset,
$$\begin{aligned} dAg/dt = {} & k_{113} * B + k_{201} * PRA - k_{202} * AG - k_{203} * PRR - k_{204} * PRT - k_{205} * Ag \\ & - k_{206} * Ag * Ae - k_{207} * Ar * Ar - k_{215} * Ag \end{aligned}$$
Pa: population,
$$dPa/dt = k_{114} * (Pe - Pa) + k_{209} * PRA - k_{210} * Pa - k_{216} * (Pa - Pr)$$
Aa: agricultural area,
$$dAa/dt = k_{108} * Ae * Ag - k_{110} * B * Aa - k_{212} * Aa * Hr + k_{213} * Ag * Ar$$

Suburban residence

Rr: remainder of environmental resources,
$$Rr = E * Ar/(1 + k_{300} * B * Ag * Pr * Hr)$$
PRR: production,
$$PRR = Rr * B * Ag * Pr * Hr$$
Hr: residential asset,
$$\begin{aligned} dHr/dt = {} & k_{215} * Ag + k_{301} * PRR - k_{302} * Hr - k_{303} * PRU - k_{304} * PRT - k_{305} * Hr * At \\ & - k_{307} * Hr * Aa + k_{312} * Gu - k_{313} * Hr \end{aligned}$$
Pr: population,
$$dPr/dt = k_{216} * (Pa - Pr) + k_{308} * PRR - k_{309} * Pr - k_{314} * (Pr - Pt)$$
Ar: residential area,
$$dAr/dt = k_{212} * Aa * Hr - k_{213} * Ar * Ag + k_{310} * At * Hr - k_{311} * Ar * Ht$$

Town and industrial district

Rt: remainder of environmental resources,
$$Rt = E * At/(1 + k_{400} * Ag * Hr * Gt * Pt * Ht)$$
Gt: inflow from economic system,
$$Gt = Jt * RPt, \quad Jt = k_{404} * Ht$$
PRT: production,
$$PRT = Rt * Ag * Hr * Gt * Pt * Ht$$
Ht: asset of town and industrial district,
$$\begin{aligned} dHt/dt = {} & k_{313} * Hr + k_{401} * PRT - k_{402} * Ht - k_{403} * PRU - k_{404} * Ht - k_{405} * Ht * Ar \\ & - k_{407} * Ht * Au - k_{412} * Ht \end{aligned}$$
Pt: population,
$$dPt/dt = k_{314} * (Pr - Pt) + k_{408} * PRT - k_{409} * Pt - k_{413} * (Pt - Pu)$$
At: town and industrial area,
$$dAt/dt = k_{310} * At * Hr + k_{311} * Ar * Ht - k_{410} * At * St + k_{411} * Au * Ht$$

Table 2 (continued).

Urban and information center

Ru: remainder of environmental resources,
$\mathrm{Ru} = \mathrm{E} * \mathrm{Au}/(1 + k_{500} * \mathrm{Hr} * \mathrm{Ht} * \mathrm{St} * \mathrm{Pu} * \mathrm{Gu} * \mathrm{INF})$

Gu: inflow from economic system,
$\mathrm{Gu} = \mathrm{RPu} * \mathrm{Ju}, \quad \mathrm{Ju} = k_{504} * \mathrm{St}$

PRU: production of urban center

PRI: production of information asset,
$\mathrm{PRU} = \mathrm{Ru} * \mathrm{Hr} * \mathrm{Ht} * \mathrm{St} * \mathrm{Pu} * \mathrm{Gu} * \mathrm{INF}, \quad \mathrm{PRI} = \mathrm{St} * \mathrm{INF}$

St: urban asset,
$\mathrm{dSt}/\mathrm{d}t = k_{412} * \mathrm{Ht} + k_{501} * \mathrm{PRU} - k_{502} * \mathrm{St} - k_{503} * \mathrm{IP} * \mathrm{St} - k_{504} * \mathrm{St} - k_{505} * \mathrm{St} * \mathrm{At} - k_{509} * \mathrm{PRI}$

Pu: population,
$\mathrm{dPu}/\mathrm{d}t = k_{413} * (\mathrm{Pt} - \mathrm{Pu}) + k_{506} * \mathrm{PRU} - k_{507} * \mathrm{Pu} - k_{508} * \mathrm{Pu} * \mathrm{Pu} + \mathrm{IP} * \mathrm{St}$

INF: information asset,
$\mathrm{dINF}/\mathrm{d}t = k_{510} * \mathrm{PRI} - k_{511} * \mathrm{INF} * \mathrm{INF} - k_{512} * \mathrm{INF} - k_{513} * \mathrm{PRU} + \mathrm{INF} * \mathrm{IINF}$

Au: area of urban center,
$\mathrm{dAu}/\mathrm{d}t = k_{410} * \mathrm{At} * \mathrm{St} - k_{411} * \mathrm{Au} * \mathrm{Ht}$

The energetic flows and interrelationships between storage of each zone are somewhat identical. With agriculture and resource production zone as an example (see figure 4, over), it can be seen that production of agricultural assets (Ag) is generated by an autocatalytic interaction (PRA). Population (Pa) is another means of storage within the zone generated by autocatalytic production. The death rate is described as a proportion of agricultural population (k_{210}*Pa). Migration of population also occurs between adjacent zones represented by k_{114}*(Pe − Pa) and k_{216}*(Pa − Pr). In addition to Ag and Pa, this interaction also depends on three sources of inflow: (1) renewable sources necessary for survival and for providing work services for humans (Ra); (2) energy contributed from the lower hierarchy, that is, biomass energy (B) of natural areas to agricultural production; and (3) goods and services exchanged from the economic system (Ga). The finite inflow of renewable sources is represented by an equation of the Michaelis–Menten type,

$$\mathrm{Ra} = \frac{\mathrm{E}*\mathrm{Aa}}{1 + k_{200}*\mathrm{B}*\mathrm{Ga}*\mathrm{Ag}*\mathrm{Pa}},$$

which imposes a limit on growth. Changes in agricultural area affect the amount of renewable energy (E * Aa) captured by this zone. The accumulated storage in asset Ag connects other zones through various energetic flows: (a) feedback for maintaining the asset (k_{201} * PRA); (b) contribution to the production of a higher hierarchy, that is, residential, and town and industrial areas (k_{203}*PRR, k_{204}*PRT); (c) exports in exchange of goods and services (k_{205}*Ag); and (d) contribution to the conversion of adjacent lands into agriculture (k_{206}*Ag*Ae, k_{207}*Ag*Ar). The heat sink at the bottom of figure 4 (over) represents the dispersion of potential energy into heat, as described by the second law of thermodynamics, which accompanies all real transformation processes and depreciation of storage (for example, k_{202}*Ag).

Using Odum's energy circuit language, I describe the hierarchy of urban zonation, within the framework of GST by using equations expressing the interactions of the different components of the system. The equations of the system express the interdependence of the various components across different zones, and these intrinsic nonlinearities result in the self-organization of the urban region, so that its structures, articulations, and hierarchies are the result of energy convergence and material divergence. The thermodynamic view is that the zones, areas, population, and assets will

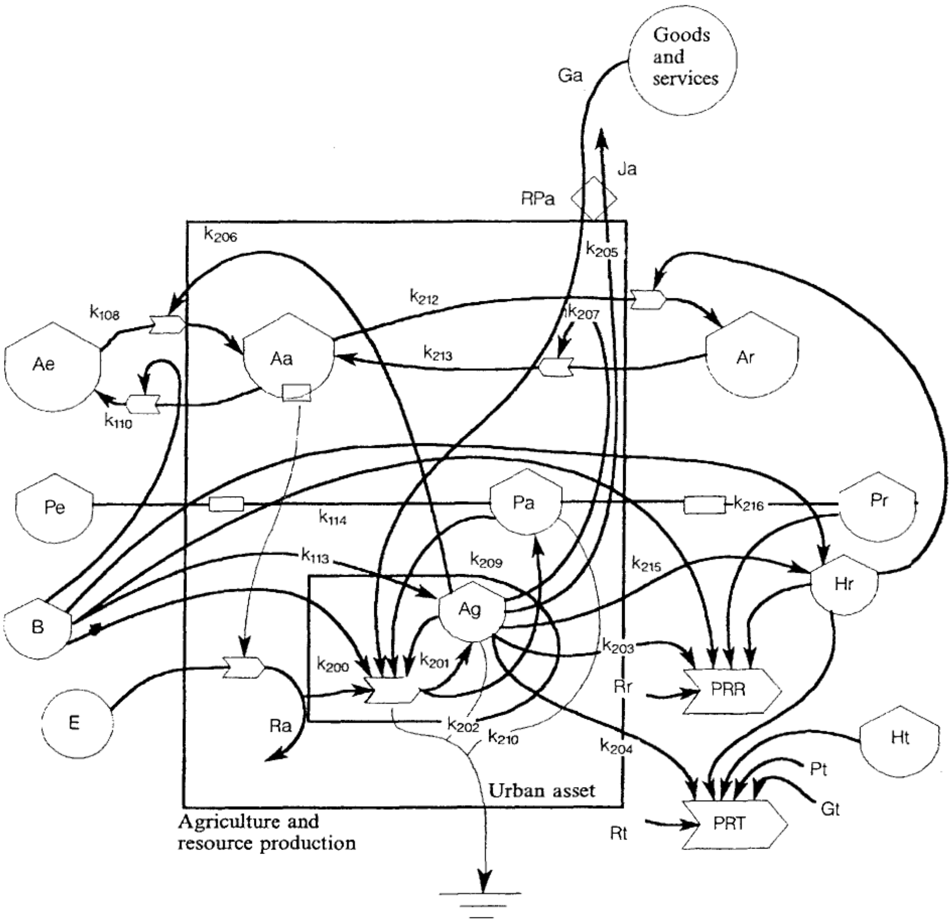

Figure 4. Energy diagram and system equations of the agriculture and resource production zone.

self-organize in the series of autocatalytic models, as in the real world, with people changing their culture as needed to fit the performance of the models.

In all, the mechanisms of the model of urban zonation can be summarized as follows:
(1) Large flows of energy from the production system converge spatially and are transformed into smaller volumes of energy of higher quality, for example, an urban asset;
(2) The products and services from agricultural, industrial, and urban zones are exported in exchange for goods and services from the external economic system;
(3) Each zone competes with its adjacent zones through land conversion;
(4) Higher assets in the urban center attract inflow of population and information assets from the external system;
(5) People migrate between zones as a result of density effects.

4 Simulation results

Located at strategic places in the landscape for the convergence of goods, services, and energy, present-day cities are where a large part of the world population now resides. In this section, the evolution of the urban zonation pattern is described through simulation runs. In order to provide a basis for the numerical experiment, Taipei metropolis is used as an example to run this idealized simple, concentric, urban system model. Figure 5 represents the current spatial pattern of Taipei's urban zonation.

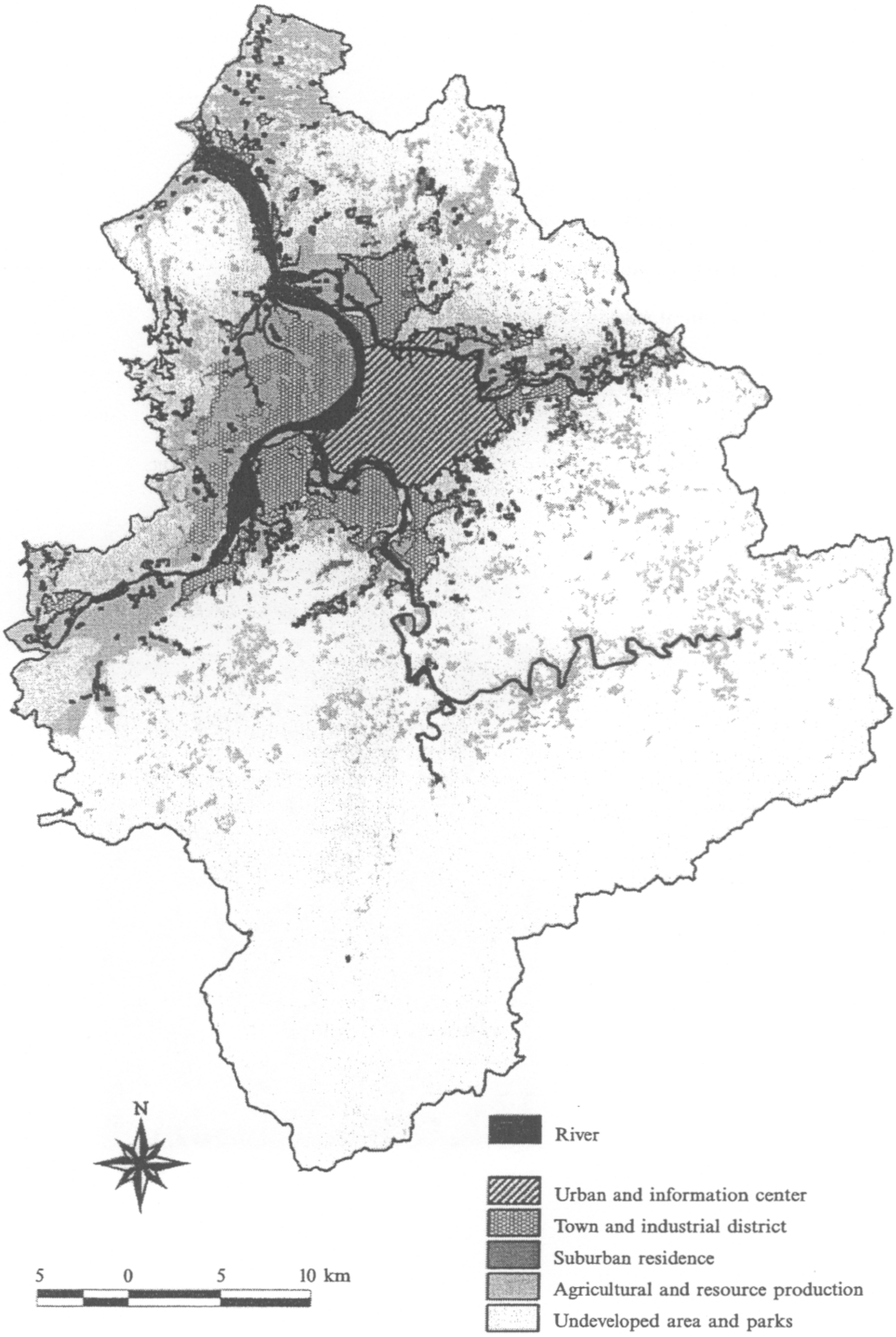

Figure 5. Spatial zonal pattern of Taipei metropolis.

Table 3. Storage values for calibrating coefficients.

Storage	Name	Value and basis
A	Total area	1.71×10^3 km^2
Ae	Natural area	5.97×10^2 km^2
Aa	Agricultural area	2.56×10^2 km^2
Ar	Residential area	3.41×10^2 km^2
At	Town and industrial area	2.56×10^2 km^2
Au	Area of urban center	2.56×10^2 km^2
B	Biomass of natural area	5.97×10^{12} g (natural area $\times$ 1×10^{10} g km^{-2})
Ag	Agricultural assets	2.56 km^2 (floor area of agricultural buildings = 1% of agricultural area)
Hr	Residential assets	1.02×10^2 km^2 (floor area of housing = 30% of residential area)
Ht	Assets of town and industrial district	2.05×10^2 km^2 (floor area of industrial buildings = 80% of town and industrial area)
St	Urban assets	3.84×10^2 km^2 (floor area of urban structure = 150% of urban center)
INF	Information assets	12.8 km^2 (floor area of public buildings = 5% of urban center)
Pe	Population of natural area	5.97×10^4 people (natural area $\times$ 100 people km^{-2})
Pa	Population of agricultural area	7.68×10^4 people (agricultural area $\times$ 300 people km^{-2})
Pr	Population of residential area	6.82×10^5 people (residential area $\times$ 2000 people km^{-2})
Pt	Population of town and industrial district	1.28×10^6 people (town and industrial area $\times$ 5000 people km^{-2})
Pu	Population of urban center	3.84×10^6 people (urban center $\times$ 15 000 people km^{-2})

Like most early cities, Taipei is located at the mouth of a river, the Tansui, where port facilities could be developed. In addition, fertile soils resulting from sedimentation of upstream areas provided a resource basis for agricultural activities in the past. The present-day landscape of rural lands, roads, and land uses is a result of the past patterns of growth of population and energy use. After preliminary collection and estimation of data, one can readily visualize and adjust the time constants for each pathway and can estimate missing data from steady state assumptions. Tables 3 and 4 summarize the values of storage of the model and values of assumed flows of agriculture and the resource production zone. The assumed flows are consistent with known turnover times when inflows and outflows are equal and storage is maximum. Coefficients of equations of the system can be calibrated from the assumed flows.

4.1 A macro view of urban evolution

Prior to running the simulation model to study the evolutionary process of urban zonation, two conditions were adjusted to fit the current model for the situation of Taipei. First, Taipei metropolis did not have five zones at its origin. New energy pathways might evolve as a result of fluctuation to form additional zones. In order to introduce these structural fluctuations into the system description, two explicit criteria for evolution are included in the program.

Table 4. Flow values of agriculture and resource production zone.

Flow name	Mathematical expression	Value and basis
Env inflow	E	$3 \times 10^6\ \mathrm{m}^3\ \mathrm{km}^{-2}\ \mathrm{yr}^{-1}$ (rain $= 3000\ \mathrm{mm\ yr}^{-1} \times 10^{-3}\ \mathrm{m\ mm}^{-1} \times 10^6\ \mathrm{m}^2\ \mathrm{km}^{-2}$)
Env use by agr assets	$k_{200} * B * Ra * Ag * Ga * Pa$	$5.38 \times 10^8\ \mathrm{m}^3\ \mathrm{yr}^{-1}$ (70% of env inflow $= 0.7 \times 3 \times 10^6\ \mathrm{m}^3\ \mathrm{km}^{-2}\ \mathrm{yr}^{-1} \times 2.56 \times 10^2\ \mathrm{km}^2$)
Env remainder	$Ra = E * Aa - k_{200} * B * Ra * Ag * Ga * Pa$	$2.3 \times 10^8\ \mathrm{m}^3\ \mathrm{yr}^{-1}$ ($3 \times 10^6\ \mathrm{m}^3\ \mathrm{km}^{-2}\ \mathrm{yr}^{-1} \times 2.56 \times 10^2\ \mathrm{km}^2 \times 0.3$)
Production of agr assets	$k_{210} * PRA$	$0.149\mathrm{km}^2\ \mathrm{yr}^{-1}$ (based on a growth rate of 5.8%)
Depreciation of agr assets	$k_{202} * Ag$	$0.0256\ \mathrm{km}^2\ \mathrm{yr}^{-1}$ (based on a turnover period of 100 years)
Agr use by suburban residences	$k_{203} * PRA$	$0.0128\ \mathrm{km}^2\ \mathrm{yr}^{-1}$ (assumed to be 0.5% of agr assets)
Agr use by town and industrial district	$k_{204} * PRA$	$0.0128\ \mathrm{km}^2\ \mathrm{yr}^{-1}$ (assumed to be 0.5% of agr assets)
Export of agr product	$Ja = k_{205} * Ag$	$0.0512\ \mathrm{km}^2\ \mathrm{yr}^{-1}$ (assumed to be 2% of agr assets)
Agr use to convert natural area into agr area	$k_{206} * Ag * Ae$	$0.84 \times 10^{-2}\ \mathrm{km}^2\ \mathrm{yr}^{-1}$
Agr use to convert res area into agr area	$k_{207} * Ag * Ar$	$0.84 \times 10^{-2}\ \mathrm{km}^2\ \mathrm{yr}^{-1}$
Agr use to convert ind area into agr area	$k_{208} * Ag * At$	$0.84 \times 10^{-2}\ \mathrm{km}^2\ \mathrm{yr}^{-1}$
Growth of agr population	$k_{209} * PRA$	1535 people yr^{-1} (based on a 2% growth rate)
Decrease of agr population	$k_{210} * Pa$	1535 people yr^{-1} (based on a 2% death rate)
Change of agr land to ind use	$k_{211} * Ag * At$	$2.56\ \mathrm{km}^2\ \mathrm{yr}^{-1}$
Change of agr land to res area	$k_{212} * Aa * Hr$	$1.28\ \mathrm{km}^2\ \mathrm{yr}^{-1}$
Change of res area to agr land	$k_{213} * Ag * Ar$	$1.28\ \mathrm{km}^2\ \mathrm{yr}^{-1}$
Change of ind use to agr land	$k_{214} * Ag * At$	$2.56\ \mathrm{km}^2\ \mathrm{yr}^{-1}$
Conversion of agr assets into res assets	$k_{215} * Ag$	$0.0256\ \mathrm{km}^2\ \mathrm{yr}^{-1}$ (based on a 1% conversion rate)
Migration between natural area and agr area	$k_{114} * (Pe - Pa)$	assumed to be 0.01% of population difference
Migration between agr area and res area	$k_{216} * (Pa - Pr)$	assumed to be 0.5% of population difference

Notes: $PRA = Ra * B * Ag * Ga * Pa$; env, environmental; agr, agricultural; res, residential; ind, industrial.

(1) The energy flows to urban and information centers do not occur until the floor area of the town and industrial district exceeds 200 km^2.

(2) The energy flows to suburban residences do not occur until the population density in the urban center exceeds 3000 person per km^2.

Second, the land conversion in Taipei metropolis deviates from the simplified pattern shown in figure 3. Agricultural lands were converted to town and industrial areas prior to the existence of suburban residences. Because most of the suburban residences in Taipei metropolis lie on hillslopes, the lands were converted from natural undeveloped areas rather than from agriculture.

Figure 6 shows the simulation result of the evolution of Taipei metropolis's urban zonation. Over time each zone within the urban system is evolved and forced to adapt its internal structure in response to external changes. There were only three zones in the Taipei area in the early stage of urban development. As assets accumulated, the urban center evolved in the 1930s and the appearance of suburban residences on hillslopes in the late 1960s is a consequence of high population density in the urban center. As shown in figure 7, growth of an asset at one level is followed by growth of an asset at the next hierarchy. The simulated results have illustrated that zones of higher order developed successively as a result of energy convergence over time. In ecology, the process of ecosystem growth and development is called 'succession' and the term for the mature state is 'climax'. Owing to the spatial segregation of different zones in

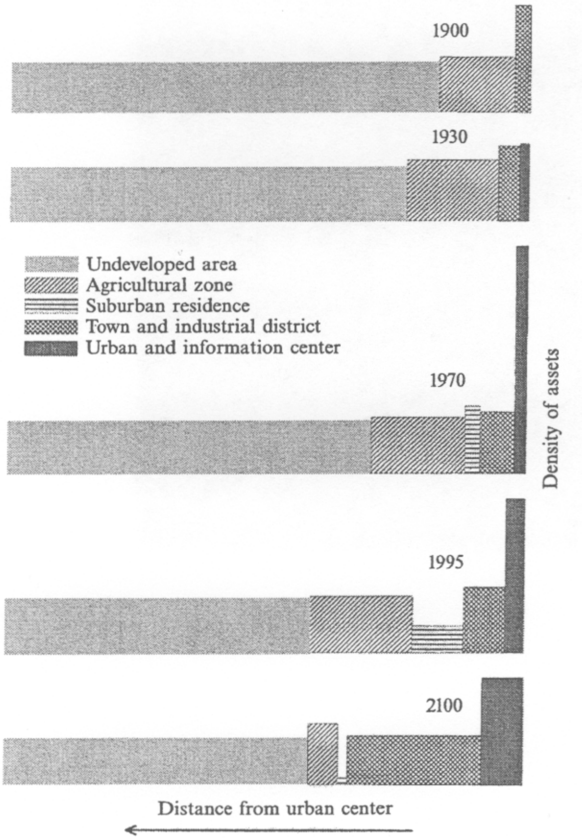

Figure 6. Simulation results of urban zonal change of Taipei metropolis.

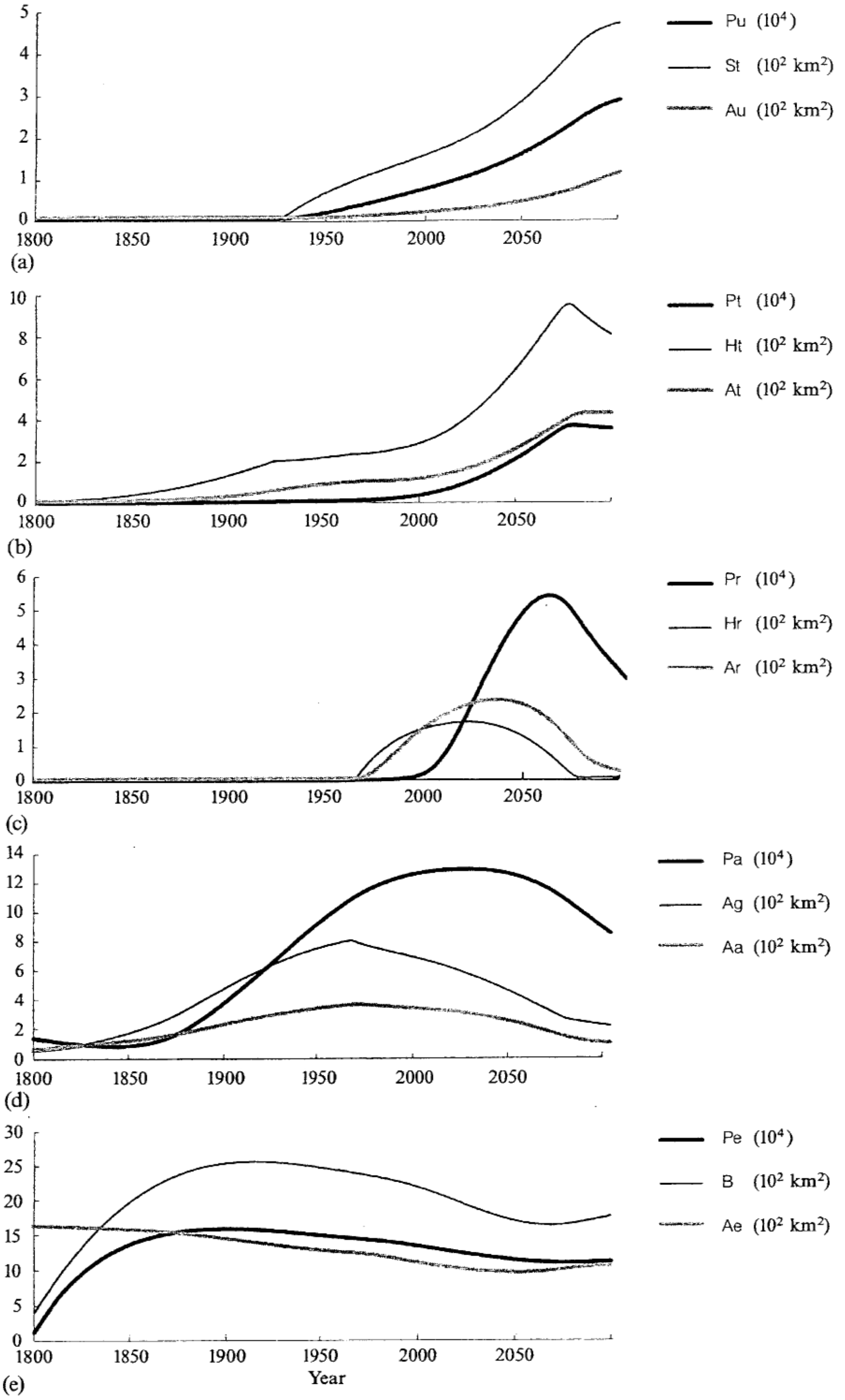

Figure 7. Simulation results of the urban evolution of Taipei metropolis: (a) urban and information center; (b) town and industrial area; (c) suburban residence; (d) agriculture and resource production; (e) undeveloped area.

Table 5. Effects of change of flow rates on agriculture and the resource production zone.

Flow	Storage		
	area	asset	population
Increase inflow of goods and services, Ga	+	+	+
Increase production rate of agricultural assets, k_{201}	+	+	+
Increase growth rate of agricultural population, k_{209}	+	+	++
Increase rate of change of agr land to industrial use, k_{211}	−/+	−/+	−/+
Increase rate of change of agr land to residential area, k_{212}	−	−	−
Increase rate of change of natural area to agr area, k_{108}	++	++	++
Increase agr use to convert natural area into agr area, k_{206}	−	−	−

Notes: agr, agricultural; ++, significant increase; +, increase; −, decrease; −/+, decrease first then increase.

the urban setting, the assets and population of each zone oscillate and the areas shift between neighboring zones. The urban center of Taipei did not exist until the 1930s and suburban residences started to appear around the mid-1960s, which coincides with the historical development of Taipei.

In order to understand further the effect of change of a specific flow rate on the system as a whole, sensitivity analysis is performed to simulate the change of coefficients (k) on system storage. Table 5 summarizes the effects of change of flow rates on the behavior of the agriculture and resource production zone. As a result, the increase of inflow of goods and services (Ga), production rate of agricultural assets (k_{201}*Ra*B*Ag*Ga*Pa), and growth rate of agricultural population (k_{209}*Ra*B*Ag*Ga*Pa) will increase the area, assets, and population of the agricultural zone. The increase of the rate of change of agricultural area into industrial area will result in the decrease of agricultural area, assets, and population in the beginning. However, owing to the prosperity of the industrial zone and its pulling effect of converting residential area into town and industrial districts, the agricultural zone outcompeted its neighboring zone, suburban residential districts, and began to grow. Increasing the contribution of agricultural assets to convert natural area into agricultural area (k_{206}*Ag*Ae) will first decrease the storage of asset (Ag) and then result in the decrease of both agricultural area and population.

Based on the findings of the sensitivity analysis, scenarios can be proposed to analyze the possible outcomes of the interacting urban zones. Figure 8 represents one of the scenarios and its simulated results. It was desired to estimate the consequence of the effect of lower energetic inflows on the spatial pattern of urban zonation. To determine this the model was programmed with a step input for decreasing inflows of goods and services for agriculture and resource production zone (Ga), town and industrial district (Gt), and urban and information center (Gu). It was assumed that the inflows of goods and services will start to decrease gradually from 10% in year 2001 to 90% by the year 3000. Figure 8 presents the results of the simulation and compares them with the base simulation previously displayed in figure 7. Owing to the decrease of inflows of goods and services to both Gt and Gu, the areas, assets, and populations in both zones will continue to decrease significantly. Because of the

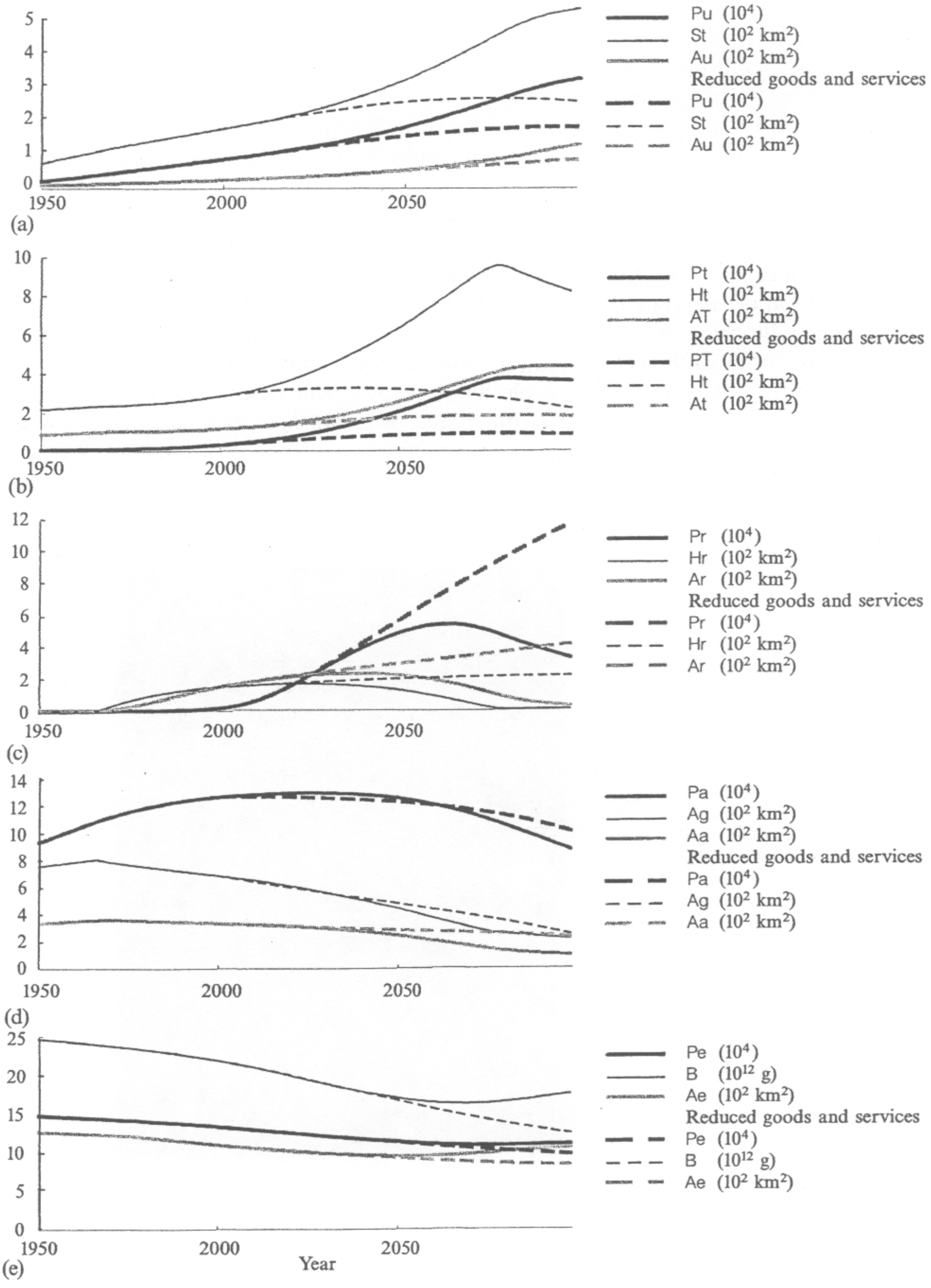

Figure 8. Simulation results of Taipei metropolis under low-energy conditions: (a) urban and information center; (b) town and industrial area; (c) suburban residence; (d) agriculture and resource production; (e) undeveloped area.

reduction in pulling effect from town and industrial district, the suburban residential district grows considerably. Although the inflow of goods and services to the agriculture and resource production zone decrease, the pulling effect to convert agriculture into industrial zone is less and the agricultural activity can rely on inflow of renewable environmental resources; therefore the agricultural zone continues to grow. The growth of agricultural and residential zones then results in the decrease of natural area.

5 Further thoughts and concluding remarks

In this paper I have presented a mixture of quantitative and theoretical results for understanding the evolution of hierarchical zonation of the urban system through consideration of energetic flows. The urban economic system in this paper is perceived as a nonequilibrium system governed by certain nonlinear processes. In this dynamic world, nonlinear differential equations are the basic building blocks. Owing to the macro perspective of the urban evolution, the increment of time for simulation is on a yearly basis. Therefore the daily difference of urban activities such as commuting patterns and energy consumption is not included. As a result of energy convergence and material divergence, a region can be divided into various competing and symbiotic zones; each zone comprises population, economic assets, and natural capital. Five consecutive zones are proposed to represent Taipei metropolis; each zone includes components of area, asset, and population, and pathways interconnecting components within and between each zone. After calibration of the coefficients, the model is run with initial values of year 1800. Over time, each zone within the urban system of Taipei metropolis evolves as a result of energy convergence. Similar to ecosystems, urban systems exhibit in the long run a certain morphogenesis, a qualitative change in dynamics which moves an urban system toward a different level of organization. The survival of urban zones depends on a view of them not as independent units, but rather on an understanding of them as the integration of the web of life. This viewpoint leads towards the conceptual world of hierarchy and order through fluctuations. The mutual nonlinear interactions between population, area, and assets of each zone result in a self-organizing spatial system, from which an urban hierarchy evolves.

An understanding of the interactions between urbanization and natural environment is a prerequisite for an ecologically sensitive and economically rational accommodation of urbanization. The approach adopted here advocates models capable of generating complexity in the phenomena of interest, while retaining simplicity in model structure. This is a key feature of the general system theory of dynamic models. The universality of phenomena like self-organization and hierarchical order through fluctuations heralds their impeding emergence as fundamental paradigms of science. Evolution of this type is a natural course of events in a world that is far from equilibrium.

To study evolution, we must consider three factors: (1) reproduction; (2) selection through competition; and (3) variation through innovations (Nicolis and Prigogine, 1977). The first two factors are incorporated in the system model developed in this study. Innovation, the third factor, is excluded from the deterministic equations, which describe the average behavior of a large number of elements. Social and economic evolution includes learning mechanisms, innovations, and inventions by various individuals and groups, who are trying to adapt to their environments. In the case of urban evolution, the sources of innovation are not directly genetic but refer generally to various changes in incoming information and technical behavior of a system. In addition to urban innovation, new development pathways may evolve and result in the structural fluctuations of an urban system. For example, at the beginning of the 1800s, there were only three zones in the Taipei metropolis. The development of residential communities on hillslope land had increased not only energetic pathways but also complexity of zonal relations.

Good policy for planning a landscape includes arranging converging and diverging materials in complete cycles. Expenditures on diverging and dispersing wastes back to the rural systems are as important as those on bringing products into the centers of an economy. Land-use activities on zones with mismatching hierarchy (for example, industry in natural area, agriculture in urban center, etc) will require higher energy investment to maintain its viability. Urban and regional planning, and especially national planning and a national urban policy, must be directed to channel urbanization along evolutionary paths that are as little environmentally exploitative as possible. Many 'what if' questions can be simulated by use of the system model developed in this paper. For example, protection of hillslopes is critical to ensure the dependable supply of water resources. By changing the parameters of the model, we can address the likely consequence of the effect of prohibiting the conversion of natural reserves into suburban residence on the urban zonation of the entire metropolitan region. Protection of farmland has always been a controversial issue between urban economists and environmental protection groups. Will agricultural assets continue to grow if we prohibit developments on agricultural land? Simulating the behavior of the model can provide useful thought for policymakers and urban planners.

Although this paper has restricted the discussion to use of the system model there is every reason to believe that this is just one example of a wide range of models that demonstrates similar behavior. The next logical progression is the application of a GIS-based model for the representation of zonal changes spatially. In this way, policy for locating developments in the future can be aided by maps of concentration of energy use and energy hierarchy so that suitable areas for matching economic activities with existing energetic flows can be found. It is hoped that this paper and the concepts contained in it may further our understanding of the energy basis of urban evolution and stimulate further ideas and theories for studying the hierarchical organization of the urban system spatially.

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