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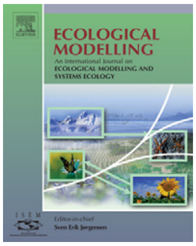

Energetic mechanisms and development of an urban landscape system

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ABSTRACT

Viewing urbanization as a change in the source and amount of energy flows from rural background to urban core provides a biophysical perspective of urban development. In this paper we begin by applying energetic principles to an urban setting and relating them to spatial hierarchy. Based on past research in urban energy theory and system modeling, we developed a spatial model to simulate the evolving spatial hierarchy of an urban system due to changing energy flows. Using an energy systems diagram, the spatial unit model consists of three interacting subsystems – natural area, agricultural area and urban area – representing a simplified entity or unit model of each grid element within a city-region. The Taipei metropolitan region is used as an example and is divided into grids of 1 km × 1 km to reveal the spatial heterogeneity of the urban landscape system. The spatial simulation was performed using geographical information system (GIS) and the model results show an increase in the urban energy hierarchy and reveal a pattern of spatial convergence. The energetic mechanisms of the evolving spatial hierarchy of the urban landscape system are discussed.

1. Introduction

The land surface is organized in river basins, and human trade and settlement patterns are organized as cities and their hinterlands. Development of urban areas is similar around the world. Cities often develop where streams and rivers converge and spread fertile soils transported from up stream. The physical energy of water running downhill spreads water out into floodplains and agricultural lands, where it stimulates productivity and provides essential life-support sources to human beings. Early cities were small settlements surrounded by agricultural lands. As the population and resource use increased, the urban areas expanded and surrounding agricultural lands were converted to urban uses. The existence and maintenance of an urban region, and of its internal structure depend on the flows of goods and services into, out of, and throughout the city. Past efforts to study the development of spatial organization of urban systems have been centered on socio-economic viewpoints, and the biophysical perspectives of the evolving urban spatial system were frequently ignored. Complex urban ecological systems are the product of an evolutionary process; the implications of the process of evolution on the form and function of the components of urban landscapes are yet to be completely understood. A systems approach can be used to conceptualize the urban region as an entity with interacting objects and attributes. When studying the urban landscape system, the question we have is: what is the reason for the spatial distribution of different zones (e.g. the natural area, agriculture, residential area, urban center, etc.), and how will they change with time?

The development of urban landscape systems, interactions between cities and their surrounding life-support environ-

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ments, and diffusion in urban hierarchies are also part of the larger process of urbanization. It has been hypothesized that the spatial configurations of urban landscapes depend largely on energy production and consumption conditions (Huang, 1998b; Huang et al., 2001). Using emergy as a common unit for combining the energy flows from natural environment and economic system, Huang (1998a) indicated that in less than half a century, Taiwan has changed from a rural country with an economy based on raw commodity production to one that is highly industrialized with a low self-sufficiency of emergy use. Furthermore, using indices of ecological energetic flows, Taiwan is classified into four urban ecological economic systems: agricultural settlement; suburban industry; urban metropolis; resource production. The energy hierarchy of the city of Taipei was also assessed. Huang (1998b) developed a system model to examine the evolution of urban zones in relation to energy flows using a simulation model; the underlying theme was the hypothetical effect of energetic flows on urban zonation, and how different zones organize hierarchically in space. Five consecutive zones were hypothesized to represent the Taipei metropolis' spatial configuration, but the spatial data were not incorporated for the analysis. In order to study the effect of energy flows on the spatial organization of urban zonation, Huang et al. (2001) employed the emergy concept and GIS to classify the Taipei metropolitan region into six energetic zones to reveal its spatial hierarchies. For the purpose of developing a theory of urban energetics, Huang and Chen (2005) proposed and tested six hypotheses of urban energetics, including the changes in the diversity of emergy sources, changes in urban metabolism, energy hierarchy, the relation between emergy and money flows, spatial hierarchy of emergy use from urban center toward rural areas and the relationship between urban fragmentation and emergy flows. An urban ecosystem model was also developed by Huang and Chen (2005) to investigate the relationships between energy flows and urban development.

Aggregated urban system models have been criticized for ignoring spatial organization and the development of GIS has provided the capability to integrate spatial processes in the modeling efforts (Alberti, 1999). The increasing awareness of the need for spatially explicit land use models within the land-use and land-cover change (LUCC) research community has led to the development of a wide range of land use change models. Recent progress in computer modeling capability and the development of GIS have made it possible to link human and ecological systems and to provide the capability to integrate spatial processes. Spatial models of land use change can analyze the causes and consequences of land use dynamics to understand the functioning of the land use system. Numerous land use models developed from different disciplines such as empirical statistical models (Verburg et al., 1999, 2002; Serneels and Lambin, 2001), ecological models (Voinov et al., 1999; Boumans et al., 2001; Costanza and Voinov, 2004), agent-based models and cellular automata (Batty, 2001; Parker et al., 2003; Loibl and Toetzer, 2003; Matthews, 2006) have been applied extensively to simulate land use change. The combination of cellular automata and agent-based models has recently received considerable attention as a tool to investigate principles of urban evolution in a spatial context by calculating the state of a pixel based on its initial state, the conditions in the surrounding pixels, and a set of transition rules, and actions models of agent cognition (for example, see Batty and Xie, 1994; Parker et al., 2003; Matthews, 2006). From a bottom-up perspective, the integration of cellular automata and agent-based models obviously becomes one of the most effective methods to explore the evolution of the urban landscape from microscale. However, the evolution of the urban landscape system depends not only on its previous and surrounding states but also on exogenous conditions and driving forces such as renewable energy flows and imported goods and services, which affect the change of land use in a city-region. Another type of land use model is needed, one that can incorporate the biophysical perspective to quantify neighboring effects.

As compared to other modeling efforts, the top-down approach of ecological modelling, which is based on general system theory, can analyze patterns of urban landscape system by emphasizing on the interactions between system components from macroscopic viewpoints (Odum and Odum, 2000; Costanza and Voinov, 2004). Furthermore, ecological models frequently take into account energy flows as driving force of the system, which is often ignored by other modeling efforts (Odum, 1983; Huang and Chen, 2005). Ecological models are important in environmental research and decision making. There are numerous tools available for doing dynamic or spatial modeling, but very little for supporting both. System dynamics software has limited or non-existent capabilities for spatial modeling. Conversely, GIS has become a very powerful tool for spatial modeling. Incorporating system dynamics into GIS is generally difficult and typically demands the linkage of GIS to external simulation software through data files or embedding programmed modules within the GIS. Costanza et al. (1995) developed a spatially explicit general ecosystem model which integrated human and environmental systems for simulating the effects of land use scenarios on ecosystem processes. Alberti (1999) developed an urban ecosystem model for simulating the environmental pressures associated with human activities under alternative socioeconomic and environmental scenarios. The spatial heterogeneity in land uses, human activities and management practices was taken into consideration in this modeling effort. However, the greatest challenge for integrating urban and environmental modeling is still in interfacing the various disciplines involved. The difficulty in integrating the natural and social sciences has limited the progress of urban ecological modeling (Alberti, 1999).

In this paper, we begin by expanding energetic principles to an urban setting and then relating them to spatial hierarchy (Section 2). The hypotheses developed from the spatial energetic hierarchy of the urban landscape system are supported by data from the metropolis of Taipei. In order to reveal the spatial evolution of an urban landscape due to energy flows, a spatially dynamic energy system model was developed (see Section 3). After formulating a macroscopic minimodel of a self-organizing urban landscape system, we used data from the Taipei metropolis to interpret the evolution of spatial hierarchy due to energy flows through the application of a GIS-based simulation model. The results of the simulation are presented and discussed in Section 4. Conclusions are given in Section 5.

2. Urban energetics and spatial hierarchy

The evolution of self-organizing cities maintains a long period of steady state, followed by a short period of strong fluctuation or chaos, from which the system re-emerge to a new level of steady state and structural stability. The spatial organization of cities can be described as a hierarchy. There are many small towns scattered throughout the region, fewer medium cities, and only one or two very large urban centers. One reason for the hierarchical organization of cities in the landscape is for distribution of goods and services as described by Friedman (1973). Another reason for this hierarchical organization is the convergence of energy (Odum, 1988a). Not only are cities in the landscape organized in hierarchies, but each city and its hinterlands are themselves arranged in a spatial hierarchy.

The urban landscape system is more than the sum of its parts; it reflects a far-from equilibrium situation in which the spatial hierarchical order among the central places is developed, maintained and then transformed by means of interaction, fluctuation and dissipation of incoming energy sources. The fact that a system self-organizes its internal structure is a fundamental property of open and complex systems. Self-organized systems are complex in two respects. First, their parts are often too numerous to establish their causal relations. Second, their parts and components are interconnected in a non-linear network of feedback loops and can be described by a set of non-linear differential equations. The notion of self-organization was fascinated because of the implied property of non-causality inherent in such systems. In other words, external forces acting on the system do not exclusively determine its behavior, but instead trigger an internal and independent process by which the system spontaneously self-organizes itself (Portugali, 1997). Haken's synergestics and Prigogine's dissipative structures are the most influential ideas in the domain of self-organization of cities and urbanism (Portugali, 1997). Although the concept of "dissipative structures" was first studied in non-living systems, it is also involved in living systems. The self-organization of a physical system for maintaining far-from equilibrium structure offers us an opportunity to extend our understanding from non-living to living systems.

Renewable energy enters the ecosystem evenly spread out on a broad landscape surface. Solar energy is captured by plants and either radiated as heat or transformed into biomass. Dilute solar energy captured by plants is concentrated into plant biomass and converged spatially towards consumer centers. The energy reaching the consumers is much less than the original energy, according to the second law of thermodynamics, but it has higher quality. As energy is transformed, the products flow toward concentrated centers and materials and services circulate between the centers and the sparse areas (Odum and Odum, 2001). This converging and diverging design can be observed in an urban landscape system. For example, urban areas receive food supply and other life-support services from rural areas and provide labor and equipment to manage their life-supporting environments and return the waste materials released during the consumption process. In an attempt to define the theory of biophysical value that is applicable with equal facility to ecological and economic systems, Odum proposed two terms – *emergy* and *transformity* – to take into account the varied qualities of energy inherent in the hierarchy of system components (Odum, 1988b, 1996). Emergy is *all the available energy that was used directly and indirectly in the work of making a product and expressed in units of one type*. Transformity is *the emergy of one type required to make a unit of energy of another type*. Transformity measures the relative position along a gradient of increasing quality of energy and can be regarded as index of energy hierarchy.

In an effort to develop a theory of urban energetics, Huang and Chen (2005) proposed the following hypothesis the organization of emergy flows in urban systems is arranged in a spatial hierarchy with the highest emergy use close to urban center. The spatial characteristics of energy hierarchy in an urban landscape system can be shown by the example of the Taipei metropolitan region (Fig. 1). The urban center in the Taipei area has the highest empower density of fuel use and the lowest environmental emergy. Fossil fuels are the concentrated energy sources, which can be easily transported in huge amounts, and are a primary driving force behind urban areas. In contrast, the spatially diffuse renewable energy sources such as solar insolation, rain and wind, provide essential life-support services for cities both directly and indirectly. The diversity of emergy flow is also highest in the urban center. Due to the higher emergy intensity in urban centers, the empower density, transformity and emergy investment ratio of Taipei decrease with distance from the urban center (Huang, 2003).

The urban system is far-from thermodynamic equilibrium, which involves non-linear interactions between system components; the new states of which have been called "dissipative structures" to emphasize their dependence on the flows of energy and matter from their surroundings (Allen, 1982). According to Odum (1995), during self-organization, system designs develop and prevail that maximize power intake, energy transformation and those uses that reinforce production and efficiency. The basic idea of the maximum power principle is that a system that can draw more resources and use them appropriately to maintain and enhance its structure will outcompete systems that have fewer resources to drive their activities or make less adaptive use of those resources that are available.

A chain of coupled autocatalytic urban zones, as in Fig. 2, represents the hierarchy of self-organization; each section from left to right has a lower energy flux, but has a larger territory and turnover time than the one before. The transformity representing the hierarchy of urban systems increases from natural areas toward urban areas. Each zone shown in Fig. 2 has three directions of pathways for contributing to the system. One feedback to the left to reinforce the supporting zone; a second reinforces its own autocatalysis; a third interacts with higher levels of the larger systems and is controlled and amplified by their feedbacks. Odum (1995) points out that for a chained hierarchical system similar to Fig. 2, maximum empower requires equal priority in assignment of a unit's resources to the lower transformity supporters, to itself, and to support higher transformity levels. With the convergence of energy from rural areas to urban center units are formed with

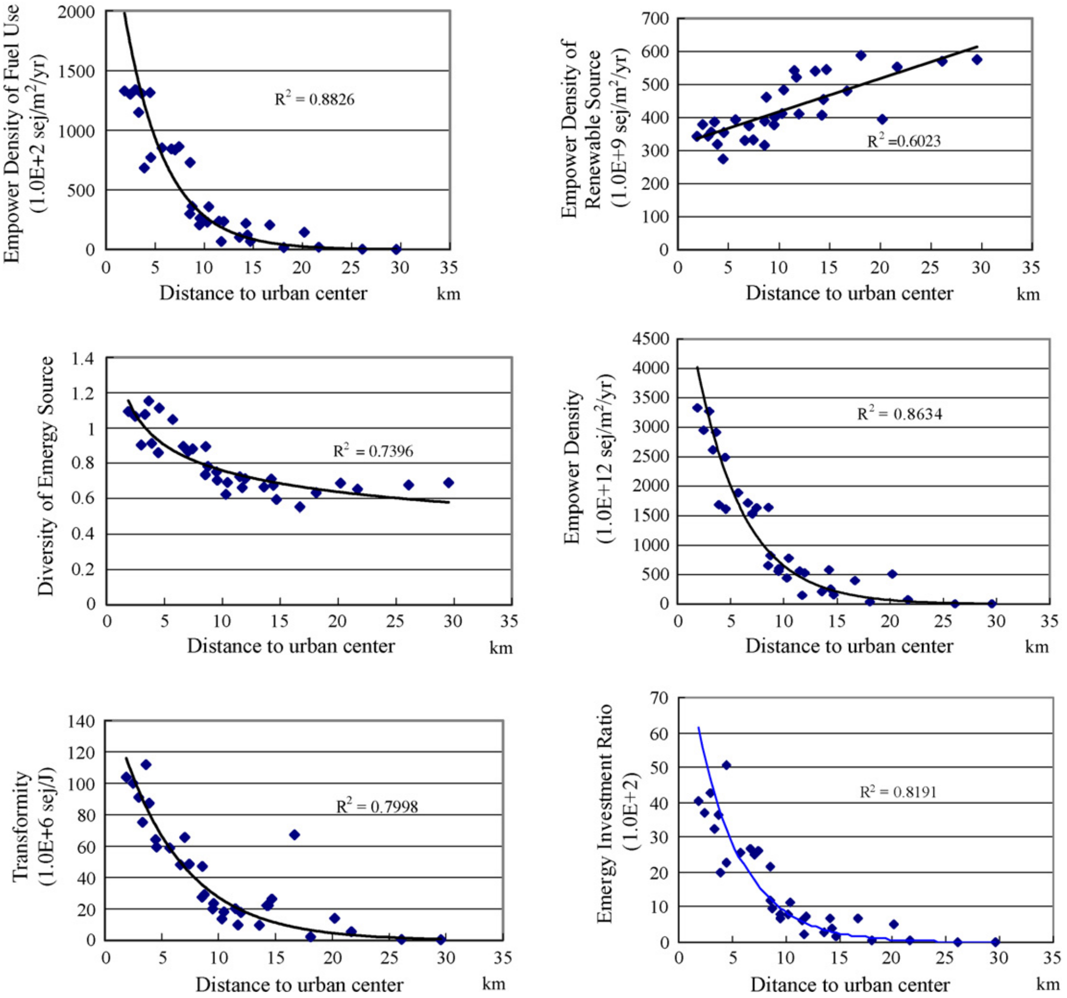

Fig. 1 – Spatial energy hierarchy of Taipei area.

higher transformity, territorial influence and turnover time. The units with higher hierarchy on the right control and reinforce the units on the left by feeding back high transformity interactions. The optimal balance between the development of city and its surrounding countryside varies. To maximize performance, the consumer center must return services to reinforce the rural system to maintain their symbiotic relationship.

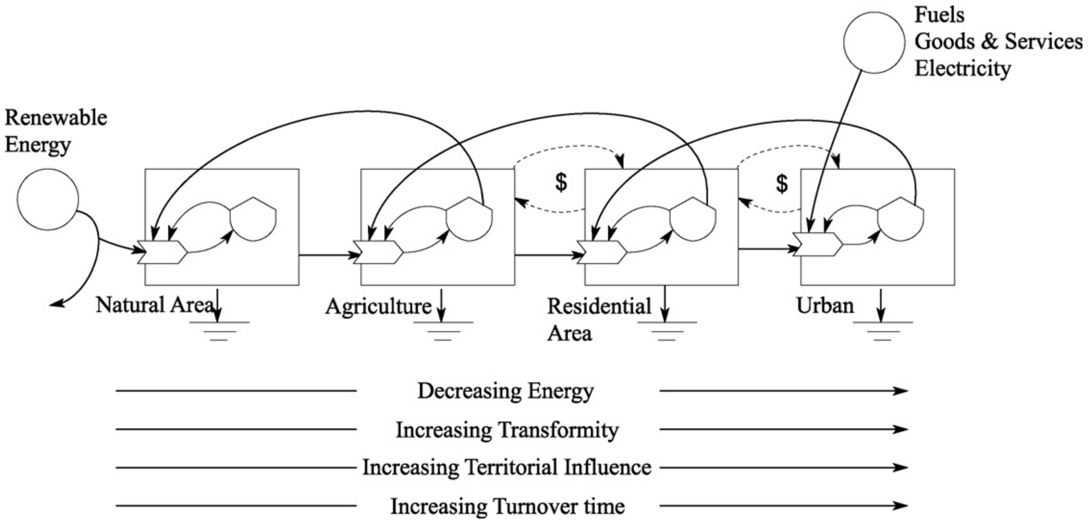

Fig. 2 – Energy hierarchy of urban system (Huang and Chen, 2005).

3. Spatial model of urban energetics

Viewing urbanization as a change in the source and amount of energy flows from the rural to urban core (see Fig. 1) provides a conceptual link between urbanization and the natural environment. Land use change is often modelled as a function of socio-economic and biophysical variables that act as the so-called driving forces of land use change. In this paper energy convergence is considered the driving force of land use change. This section presents a macroscopic minimodel of an urban system for describing system components and interactions of flows and storages for simulation of the spatial dynamics of urban land uses. To employ ideas of general system theory (von Bertalanffy, 1968) and techniques of energetic analysis (Odum, 1983) for the study of spatial urban evolution, one needs to divide a region into small areas and to identify the major components of the urban system. Urban landscape systems are groups of interacting, interdependent parts linked together by exchange of energy, matter and information. Landscape systems are therefore characterized by interactions between components and complex feedback loops. The urban landscape system model developed in this paper consists of three interlinked subsystems – natural, agricultural and urban – each representing a simplified entity of its own and interacting with the others through energy flows. Fig. 3 represents

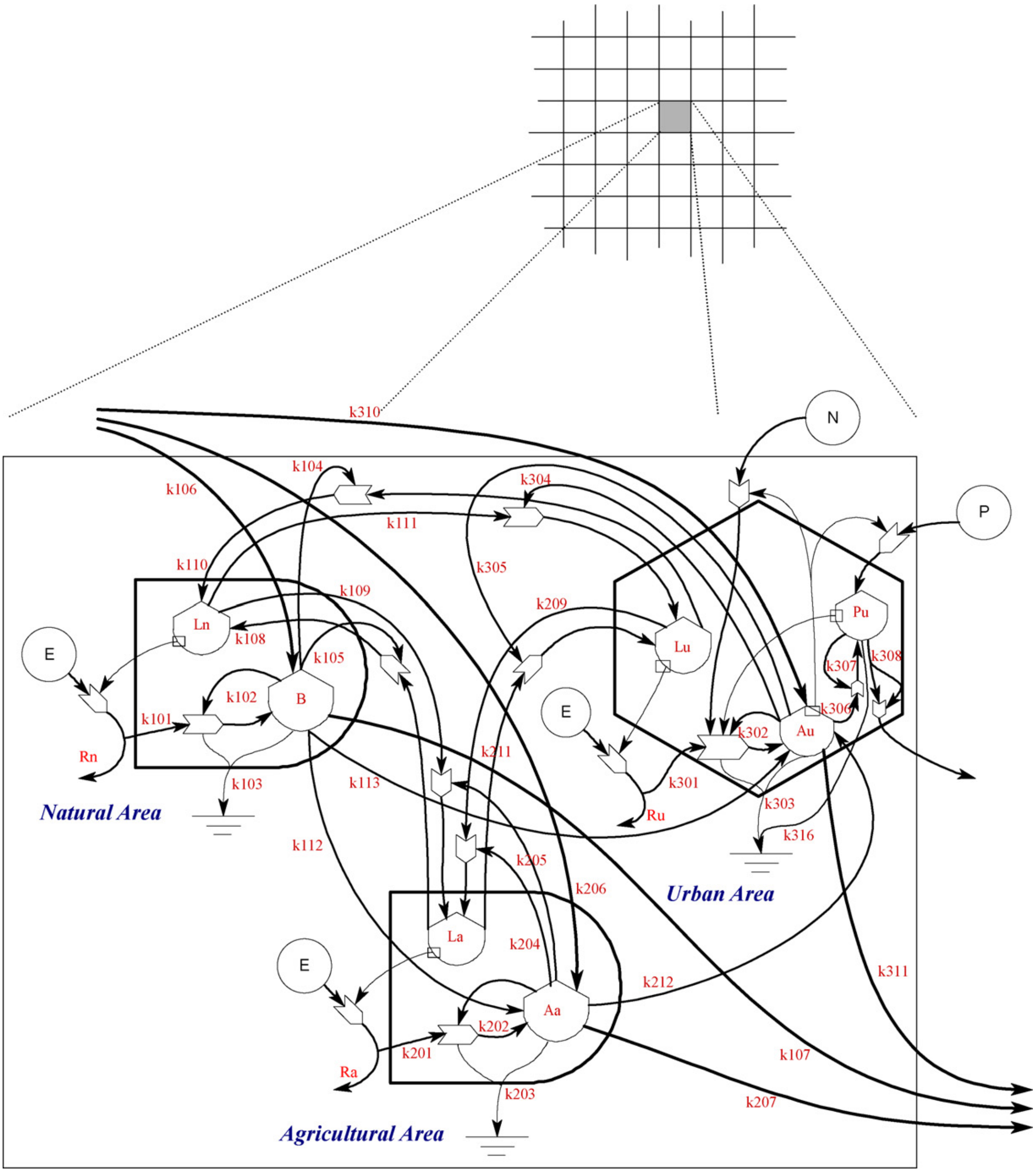

Fig. 3 – Energy diagram of urban landscape system.

an overview diagram of the macroscopic minimodel, using Odum's energy systems diagram; it shows the ecological economic system of an individual grid within a city-region. The energy system diagram can be translated into a set of first order differential equations to describe the energy balance and cycling of materials in urban system. A description, explanation and mathematical representation of these energy symbols can be found in Odum (1983) and Odum and Odum (2000).

The storages that have been chosen to represent each subsystem are: area (Ln, La and Lu) and assets (B, Aa and Au). The urban area subsystem further includes population (Pu). The system components are inter-connected by energy flows marked with coefficients ($k101, \ldots, k316$). The natural area provides the nutrient base for the agricultural area and important life-support services to the human population in urban areas. Most urban models simply ignore these forces and treat biophysical processes as exogenous variables. Urban areas can be seen as heterotrophic systems that are highly dependent on vast inputs of energy and materials from outside the system. The supply lines of food for cities frequently extend across city boundaries. As with food, the water needs of large cities often exceed nearby supplies, forcing municipalities to pump and convey water over great distances. In the model developed in this section, in addition to flow-limited renewable energies (E), non-renewable energies (N) and population (P) are two major inflows to urban areas. The convergence of energy from rural areas and inflows of non-renewable energies and population combine to affect the spatial distribution of activities and ultimately the spatial heterogeneity of natural processes and land uses. The completed diagram of the urban landscape system is a rigorous representation of the differential equations and they can be translated without further thought because each symbol has its mathematical equivalent with one term for each pathway. Using difference equations, Table 1 describes the urban hierarchy by expressing the interacting behaviors of different components of the system.

Table 1 – System equations of the urban landscape model

Natural area

R: environmental remainder of natural area

$$\mathrm{Rn} = E \times \mathrm{Ln}/(1 + k101 \times B)$$

B: biomass

$$dB/dt = k102 \times \mathrm{Rn} \times B - k103 \times B - k104 \times B \times \mathrm{Lu} - k105 \times B \times \mathrm{La} - k112 \times B - k113 \times B + (k106–k107) \times B$$

Ln: natural area

$$d\mathrm{Ln}/dt = k108 \times \mathrm{La} \times B - k109 \times \mathrm{Ln} \times \mathrm{Aa} + k110 \times \mathrm{Lu} \times B - k111 \times \mathrm{Ln} \times \mathrm{Au}$$

Agricultural area

Ra: environmental remainder of agricultural area

$$\mathrm{Ra} = E \times \mathrm{La}/(1 + k201 \times \mathrm{Aa})$$

Aa: agricultural asset

$$d\mathrm{Aa}/dt = k112 \times B + k202 \times \mathrm{Ra} \times \mathrm{Aa} - k203 \times \mathrm{Aa} - k204 \times \mathrm{Aa} \times \mathrm{Lu} - k205 \times \mathrm{Aa} \times \mathrm{Ln} + (k206–k207) \times \mathrm{Aa} - k212 \times \mathrm{Aa}$$

La: agricultural area

$$d\mathrm{La}/dt = k109 \times \mathrm{Ln} \times \mathrm{Aa} + k209 \times \mathrm{Lu} \times \mathrm{Aa} - k108 \times \mathrm{La} \times B - k211 \times \mathrm{La} \times \mathrm{Au}$$

Urban area

Ru: environmental remainder of urban area

$$\mathrm{Ru} = E \times \mathrm{Lu}/(1 + k301 \times \mathrm{Ru} \times \mathrm{Au} \times \mathrm{Pu} \times (N \times \mathrm{Au}))$$

Au: urban asset

$$d\mathrm{Au}/dt = k302 \times \mathrm{Ru} \times \mathrm{Au} \times \mathrm{Pu} \times (N \times \mathrm{Au}) + k212 \times \mathrm{Au} + k113 \times B - k303 \times \mathrm{Au} - k304 \times \mathrm{Au} \times \mathrm{Ln} - k305 \times \mathrm{Au} \times \mathrm{La} - k306 \times \mathrm{Au} \times \mathrm{Pu} + (k310–k311) \times \mathrm{Au}$$

Lu: urban area

$$d\mathrm{Lu}/dt = k111 \times \mathrm{Ln} \times \mathrm{Au} + k211 \times \mathrm{La} \times \mathrm{Au} - k110 \times \mathrm{Lu} \times B - k209 \times \mathrm{Lu} \times \mathrm{Aa}$$

Pu: urban population

$$d\mathrm{Pu}/dt = k307 \times \mathrm{Au} \times \mathrm{Pu} + P \times \mathrm{Au} - k308 \times \mathrm{Pu} \times \mathrm{Pu} - k316 \times \mathrm{Pu}$$

The formulations of the system equations for the three subsystems are basically identical. Using the natural area subsystem as an example, the production of biomass (B) in the natural area relies mainly on the flow-limited renewable energies (E). The finite inflow of renewable sources is represented by a Michaelis–Menten type equation, $\mathrm{Rn} = E \times \mathrm{Ln}/(1 + k101 \times B)$, which imposes a limit to growth. The accumulated storage in biomass B will feedback to produce biomass ($k102 \times \mathrm{Rn} \times B$) and converge to support the storages of higher hierarchical units ($k112 \times B$; $k113 \times B$). In addition, the accumulated storage of biomass B will contribute to affect the conversion of agricultural land and urban area into natural area, which are expressed mathematically as $k105 \times B \times \mathrm{La}$ and $k104 \times B \times \mathrm{Lu}$, respectively. Similarly, the accumulation of agricultural assets (Aa) and urban assets (Au) will also contribute to convert natural area into agricultural area ($k205 \times \mathrm{Aa} \times \mathrm{Ln}$) and urban area ($k304 \times \mathrm{Au} \times \mathrm{Ln}$). Changes in areas will affect the amount of renewable energies ($E \times \mathrm{Ln}$; $E \times \mathrm{LA}$; $E \times \mathrm{Lu}$) captured by natural, agricultural and urban subsystems. The production of urban assets (Au) is generated by an autocatalytic interaction, which is expressed as $\mathrm{PRU} = \mathrm{Ru} \times \mathrm{Au} \times \mathrm{Pu} \times (N \times \mathrm{Au})$. The accumulated urban assets (Au) will affect the inflows of non-renewable energies (N) and population (P). Population in urban area (Pu) is also an autocatalytic production. The natural increase of population is a function of urban assets and population and is described as $k307 \times \mathrm{Au} \times \mathrm{Pu}$; the death rate is assumed proportional to the population ($k316 \times \mathrm{Pu}$). Migration also occur as a crowding effect ($k308 \times \mathrm{Pu} \times \mathrm{Pu}$). For representing spatial dynamics of the urban landscape system, the energy transfers of biomass (B), agricultural asset (Aa) and urban assets (Au) across each cell boundary are included in the model. Storage of biomass in each grid area will receive biomass from upstream grids ($k106 \times B$) and drain to grids downstream ($k107 \times B$). The accumulation of agricultural assets and urban assets will attract from ($k206 \times \mathrm{Aa}$; $k310 \times \mathrm{Au}$) and lose to ($k207 \times \mathrm{Aa}$; $k311 \times \mathrm{Au}$) neighboring cells depending on the storage difference between any given cell and the neighboring grids.

Using Odum's energy circuit language, I described the overview aspect of an urban landscape system spatially within the framework of GST by using equations expressing the interactions within and between natural, agricultural and urban subsystems. The model explicitly addressed the hierarchical organization of landscape systems. The non-linearities of the system equations will result in hierarchical system self-organization. The spatial dynamics of an urban landscape system depend strongly on the internally self-organized behavior of each individual grid and the interactions with neighboring grids. The model provides a basis for develop-

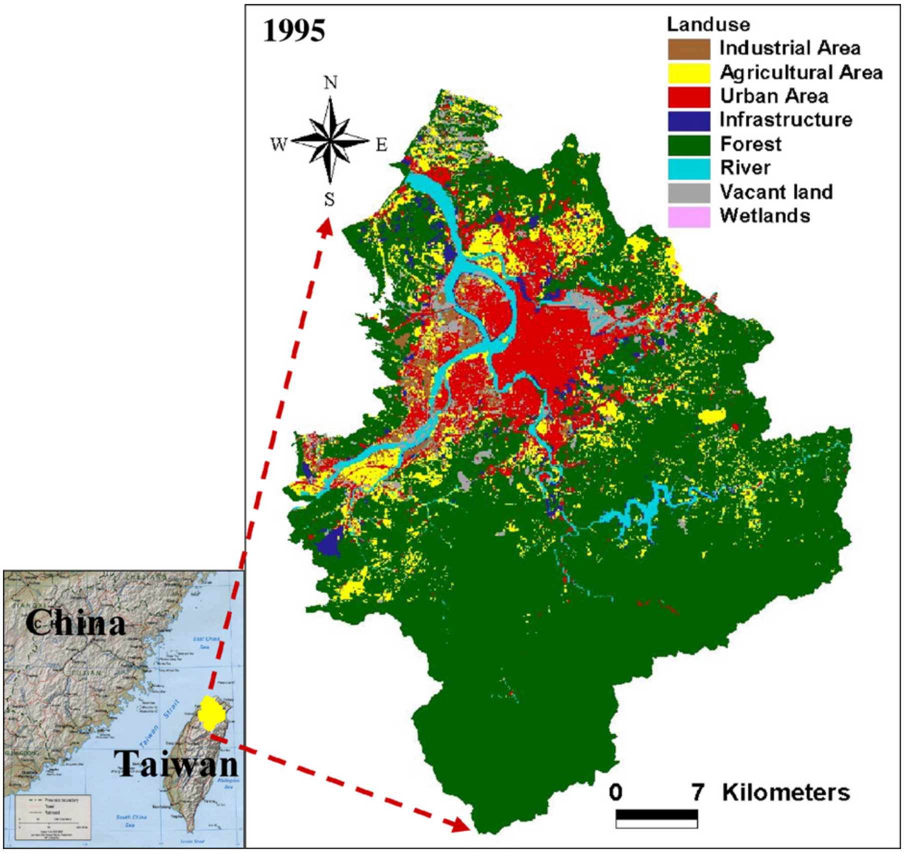

Fig. 4 – Land use map of Taipei metropolitan region.

ing integrated knowledge of the process and mechanisms that govern system dynamics of urban spatial development patterns.

4. Simulation results

4.1. *A macroview of the development of urban landscape system*

In this section, the evolving urban landscape system is described through simulation runs. Taipei metropolitan region, encompassing 1724 km^2, is used as a case study to provide numerical data to run the simulation model. Like most early cities, Taipei is located at the mouth of a river (in this case the Tamsui River—Fig. 4), which was used as a major route for transporting goods to and from overseas. In addition, the physical energy of water running downhill was used to spread water and nutrients out in the low-lying basin where it historically stimulated agricultural productivity of the land. The present-day landscape of land uses in the Taipei metropolitan region is a result of the past pattern of natural processes, population growth, urbanization and energy use (Fig. 4).

To reveal and model the spatial heterogeneity of the urban landscape system, the Taipei metropolitan region is divided into grids of 1 km × 1 km; the urban landscape system of each grid can be represented by the model diagram shown in Fig. 3. After collection and estimation of data, the coefficients for each pathway in the model diagram (see Fig. 3) can be estimated. Table 2 summarizes the assumed values of storages and flows in the urban landscape model. The most recent land use map of 1995 was used as a basis for estimating the values of areas and assets in each grid cell. The assumed flows in each cell are consistent with known turnover times when inflows and outflows are equal and storage is maximum. Coefficients in the system model can be calibrated from the assumed flows. To simulate the spatial pattern of the urban ecological economic system, the spatial analysis capability of the raster-based geographic information system, Idrisi (Eastman, 1999), was used as a modeling tool to simulate the spatial dynamics of Taipei's urban landscape system (Fig. 5).

Because the study area is of relatively small spatial extent, we base our land use data on land use maps that denote land use types, respectively, by homogeneous polygons. For study areas within the Taipei metropolis the spatial resolution of the analysis was coarse. Land use is defined by the area within each grid. Models that rely on geographic data often use a regular grid to represent data and processes. Geographical information system (GIS) was used to process all spatial data and convert them into grids. The land use data from 1960 was used as the initial values for simulation. Fig. 6 summarizes the simulation results for natural area, agricultural area and urban area of the Taipei metropolitan region from 1960 to 2010. The simulated spatial patterns of land uses are identical to land use maps for 1981 and 1995. The natural area in the low-lying basin where streams converge was first converted

Table 2 – Values of storages and flows of Taipei's urban landscape system

Name	Mathematical expression	Value and basis
Natural area	Ln	$0.4\,\mathrm{km}^2$ (assumed 40% of the $1\,\mathrm{km} \times 1\,\mathrm{km}$ grid)
Agricultural area	La	$0.1\,\mathrm{km}^2$ (assumed 10% of the $1\,\mathrm{km} \times 1\,\mathrm{km}$ grid)
Urban area	Lu	$0.5\,\mathrm{km}^2$ (assumed 50% of the $1\,\mathrm{km} \times 1\,\mathrm{km}$ grid)
Biomass of natural area	B	$0.4 \times 10^{10}\,\mathrm{g}$ (natural area $0.4\,\mathrm{km}^2 \times 1.0 \times 10^{10}\,\mathrm{g\,km^{-2}}$)
Agricultural asset	Aa	$1 \times 10^{-3}\,\mathrm{km}^2$ (agricultural area $0.1\,\mathrm{km}^2 \times 1\%$)
Urban asset	Au	$0.15\,\mathrm{km}^2$ (floor area of urban structure = 150% of urban area)
Urban population	Pu	3.62×10^3 population km^{-2} (maximum population)
Environmental input	E	$3 \times 10^6\,\mathrm{m^3\,km^{-2}\,year^{-1}}$ (rain = $3000\,\mathrm{mm\,year^{-1}} \times 10^{-3}\,\mathrm{m\,mm^{-1}} \times 10^6\,\mathrm{m^2\,km^{-2}}$)
Environmental remainder of natural area	$\mathrm{Rn} = E \times \mathrm{Ln} - k101 \times \mathrm{Rn} \times B$	$0.12 \times 10^6\,\mathrm{m^3\,km^{-2}\,year^{-1}}$ (10% of environmental input on natural area = $0.1 \times 3 \times 10^6\,\mathrm{m^3\,km^{-2}\,year^{-1}} \times \mathrm{Ln}$; Ln assumed to be 40% of total area)
Environmental remainder of agricultural area	$\mathrm{Ra} = E \times \mathrm{Lu} - k201 \times \mathrm{Ra} \times \mathrm{Aa}$	$0.09 \times 10^6\,\mathrm{m^3\,km^{-2}\,year^{-1}}$ (30% of environmental input on agricultural area = $0.3 \times 3 \times 10^6\,\mathrm{m^3\,km^{-2}\,year^{-1}} \times \mathrm{La}$; La assumed to be 10% of total area)
Environmental remainder of urban area	$\mathrm{Ru} = E \times \mathrm{Lu} - k301 \times \mathrm{Ru} \times \mathrm{Au} \times \mathrm{Pu} \times (N \times \mathrm{Au})$	$0.9 \times 10^6\,\mathrm{m^3\,km^{-2}\,year^{-1}}$ (60% of environmental input on urban area = $0.6 \times 3 \times 10^6\,\mathrm{m^3\,km^{-2}\,year^{-1}} \times \mathrm{Lu}$; Lu assumed to be 50% of total area)
Population immigration	P	0.241×10^3 population $\mathrm{km^{-2}\,year^{-1}}$ (assumed $P \times \mathrm{Au}$ to be 1% of Pu)
Non-renewable emergy	N	$2.13 \times 10^{20}\,\mathrm{sej\,km^{-2}\,year^{-1}}$ (Huang et al., 2001)
Environmental use by natural area	$k101 \times \mathrm{Rn} \times B$	$1.08 \times 10^6\,\mathrm{m^3\,km^{-2}\,year^{-1}}$ (90% of environmental input on natural area = $0.9 \times 3 \times 10^6\,\mathrm{m^3\,km^{-2}} \times 0.4\,\mathrm{km}^2$)
Biomass production	$k102 \times \mathrm{Rn} \times B$	$2.8 \times 10^8\,\mathrm{g\,year^{-1}}$ (assumed growth rate of 7%)
Biomass depreciation	$k103 \times B$	$1.6 \times 10^8\,\mathrm{g\,year^{-1}}$ (assumed 4% depreciation rate)
Biomass use to convert urban area into natural area	$k104 \times B \times \mathrm{Lu}$	$0.5 \times 10^8\,\mathrm{g\,km^{-2}\,year^{-1}}$ (assumed to be 1.25% of biomass)
Biomass use to convert agricultural area into natural area	$k105 \times B \times \mathrm{La}$	$0.1 \times 10^8\,\mathrm{g\,km^{-2}\,year^{-1}}$ (assumed to be 0.25% of biomass)
Spatial flow of biomass	$(k106–k107) \times B$	Coefficient is calculated based on elevation difference with neighboring grids
Change of agricultural area to natural area	$k108 \times \mathrm{La} \times B$	$1 \times 10^{-3}\,\mathrm{km^2\,km^{-2}\,year^{-1}}$ (assumed to be 1% of agricultural area)
Change of natural area to agricultural area	$k109 \times \mathrm{Ln} \times \mathrm{Aa}$	$1 \times 10^{-3}\,\mathrm{km^2\,km^{-2}\,year^{-1}}$ (assumed to be 0.25% of natural area)
Change of urban area to natural area	$k110 \times \mathrm{Lu} \times B$	$8 \times 10^{-3}\,\mathrm{km^2\,km^{-2}\,year^{-1}}$ (assumed to be 1.6% of urban area)
Change of natural area to urban area	$k111 \times \mathrm{Ln} \times \mathrm{Au}$	$8 \times 10^{-3}\,\mathrm{km^2\,km^{-2}\,year^{-1}}$ (assumed to be 2% of natural area)
Conversion of biomass to agricultural asset	$k112 \times B$	$0.5 \times 10^8\,\mathrm{g\,km^{-2}\,year^{-1}}$ (assumed to be 1.25% of biomass)
Conversion of biomass to urban asset	$k113 \times B$	$0.1 \times 10^8\,\mathrm{g\,km^{-2}\,year^{-1}}$ (assumed to be 0.25% of biomass)
Environmental use by agricultural area	$k201 \times \mathrm{Ra} \times \mathrm{Aa}$	$0.21 \times 10^6\,\mathrm{m^3\,km^{-2}\,year^{-1}}$ (70% of environmental input on agricultural area = $0.7 \times 3 \times 10^6\,\mathrm{m^3\,km^{-2}} \times 0.1\,\mathrm{km}^2$)
Production of agricultural asset	$k202 \times \mathrm{Ra} \times \mathrm{Aa}$	$1 \times 10^{-4}\,\mathrm{km^2\,km^{-2}\,year^{-1}}$ (based on a growth rate of 10%)
Depreciation of agricultural asset	$k203 \times \mathrm{Aa}$	$2 \times 10^{-5}\,\mathrm{km^2\,km^{-2}\,year^{-1}}$ (based on a turnover period of 50 years)
Agricultural use to convert urban area into agricultural area	$k204 \times \mathrm{Aa} \times \mathrm{Lu}$	$1 \times 10^{-5}\,\mathrm{km^2\,km^{-2}\,year^{-1}}$ (assumed to be 1% of agricultural asset)
Agricultural use to convert natural area into agricultural area	$k205 \times \mathrm{Aa} \times \mathrm{Ln}$	$1 \times 10^{-5}\,\mathrm{km^2 km^{-2}\,year^{-1}}$ (assumed to be 1% of agricultural asset)
Spatial convergence of agricultural asset	$(k206–k207) \times \mathrm{Aa}$	Coefficient is calculated based on the difference of asset with neighboring grids
Change of urban area to agricultural area	$k209 \times \mathrm{Lu} \times \mathrm{Aa}$	$5 \times 10^{-4}\,\mathrm{km^2\,km^{-2}\,year^{-1}}$ (assumed to be 0.1% of urban area)
Change of agricultural area to urban area	$k211 \times \mathrm{La} \times \mathrm{Au}$	$5 \times 10^{-4}\,\mathrm{km^2\,km^{-2}\,year^{-1}}$ (assumed to be 0.5% of agricultural area)
Conversion of agricultural asset to urban asset	$k212 \times \mathrm{Aa}$	$1 \times 10^{-4}\,\mathrm{km^2\,km^{-2}\,year^{-1}}$ (assumed to be 10% of agricultural asset)
Environmental use by urban area	$k301 \times \mathrm{Ru} \times \mathrm{Au} \times \mathrm{Pu} \times (N \times \mathrm{Au})$	$0.6 \times 10^6\,\mathrm{m^3\,km^{-2}\,year^{-1}}$ (40% of environmental input on urban area = $0.4 \times 3 \times 10^6\,\mathrm{m^3\,km^{-2}} \times 0.5\,\mathrm{km}^2$)
Production of urban asset	$k302 \times \mathrm{Ru} \times \mathrm{Au} \times \mathrm{Pu} \times (N \times \mathrm{Au})$	$2 \times 10^{-3}\,\mathrm{km^2\,km^{-2}\,year^{-1}}$ (assumed growth rate of 2%)

Table 2 (*Continued*)

Name	Mathematical expression	Value and basis
Depreciation of urban asset	$k303 \times Au$	8×10^{-4} km^2 km^{-2} year^{-1} (assumed turnover period of 200 years)
Urban asset use to convert natural area into urban area	$k304 \times Au \times Ln$	4.75×10^{-4} km^2 km^{-2} year^{-1} (assumed to be 0.32% of urban asset)
Urban asset use to convert agricultural area into urban area	$k305 \times Au \times La$	1.25×10^{-4} km^2 km^{-2} year^{-1} (assumed to be 0.08% of urban asset)
Urban asset consumed by people	$k306 \times Au \times Pu$	1×10^{-3} km^2 km^{-2} year^{-1} (assumed to be 0.67 of urban asset)
Population growth	$k307 \times Au \times Pu$	54.3 population km^{-2} year^{-1} (based on 1.5% growth rate)
Population emigration	$k308 \times Pu \times Pu$	36.2 population km^{-2} year^{-1} (assumed to be 1% of population)
Spatial convergence of urban asset	$(k310–k311) \times Au$	Coefficient is calculated based on the difference of asset with neighboring grids
Death of population	$k316 \times Pu$	54.3 population km^{-2} year^{-1} (based on 1.5% death rate)

to agricultural use, and then developed into urban area. The present urban area in the Taipei metropolitan region is surrounded by hilly slopes and forest with scattered agricultural lands in between urban area and natural area. Over time, the energy converged from rural biomass to agricultural assets then to urban assets in the hierarchical center of the Taipei metropolitan region. With the accumulation of agricultural and urban assets, the natural areas in the center basin were converted to agricultural land and urban area (Fig. 7). The growth of urban assets accelerated the inflows of non-renewable energies and population into the urban area. It is expected that this growth will continue in the Taipei metropolitan region and eventually, the central basin will be fully developed with higher population density.

4.2. *Energetic mechanisms and spatial hierarchy of the urban landscape system*

According to the simulation results of the urban landscape system, the energetic mechanisms for the evolving spatial hierarchy of urban landscape systems can be summarized as follows:

(1) Spatial convergence of energy
The distribution of natural energy is characterized with spatial heterogeneity in landscape systems. The geopotential energy carries water and nutrients downhill and spreads out these materials in the river mouth and flood plains and stimulates agricultural productivity for human settlements. For the case of the Taipei metropolitan region, the low-lying basin in the central portion is the center of energy convergence. The accumulation of natural energy in the basin stimulated agricultural productivity in the past and became the current city of Taipei—the hierarchical center of the urban ecological economic system. Due to its hierarchical position and high intensity of energy flows, both natural and economic energy flows from surrounding areas are converged spatially toward the city of Taipei.

(2) Energy transformation and urban development
Within each grid of the urban landscape system, the stored biomass energy and agricultural assets also converge towards the urban center through hierarchical energy transformation. Together with inflows of non-renewable energies, goods and services and immigration of population, urban assets accumulate. In order to accommodate growth, urban assets feedback energy to convert natural and agricultural areas into urban area in the local neighborhood.

(3) Urban sprawl and the constraint of environmental resources
As natural and agricultural areas are converted to urban use, urbanization extends outward from the urban center to rural areas. The accumulation of urban assets tends to attract more inflows of non-renewable energies, goods and services and population from outside the system and this

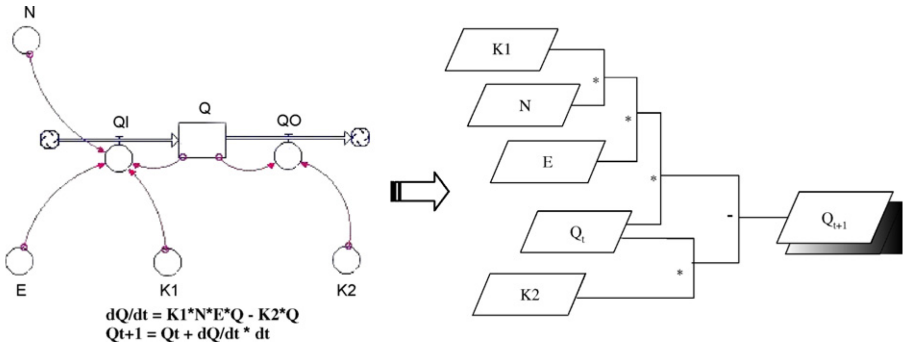

Fig. 5 – Spatial simulation using GIS.

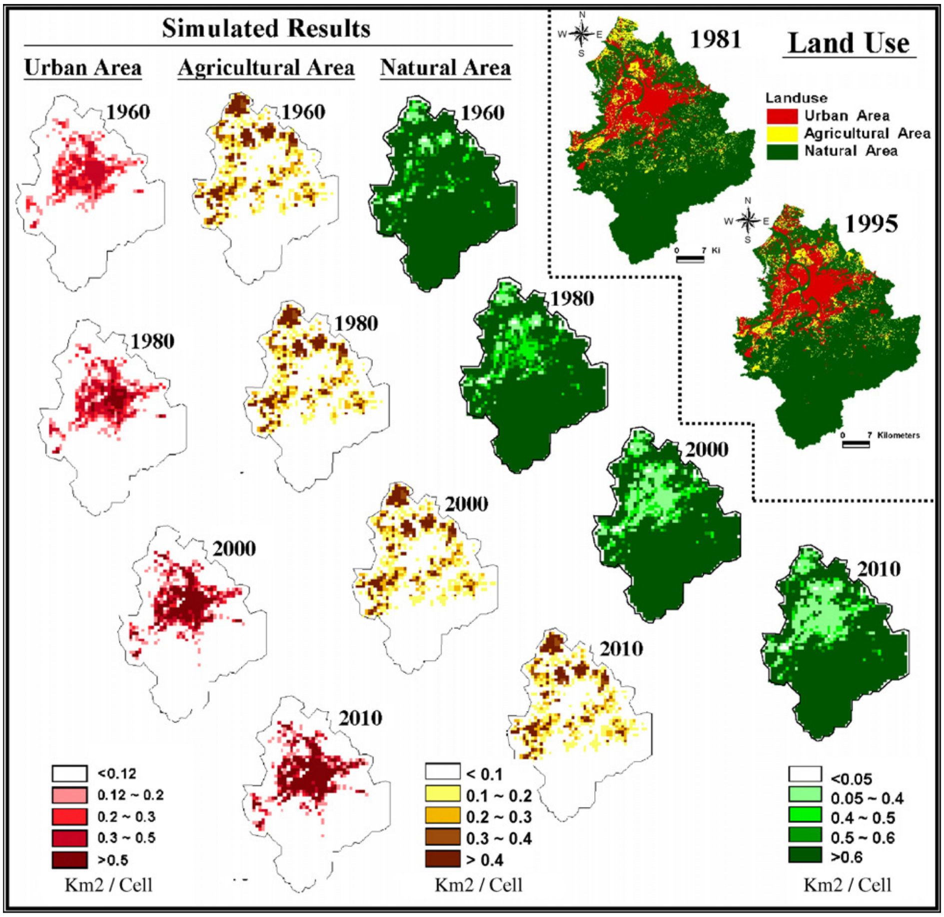

Fig. 6 – Simulated results of land use in Taipei metropolitan region.

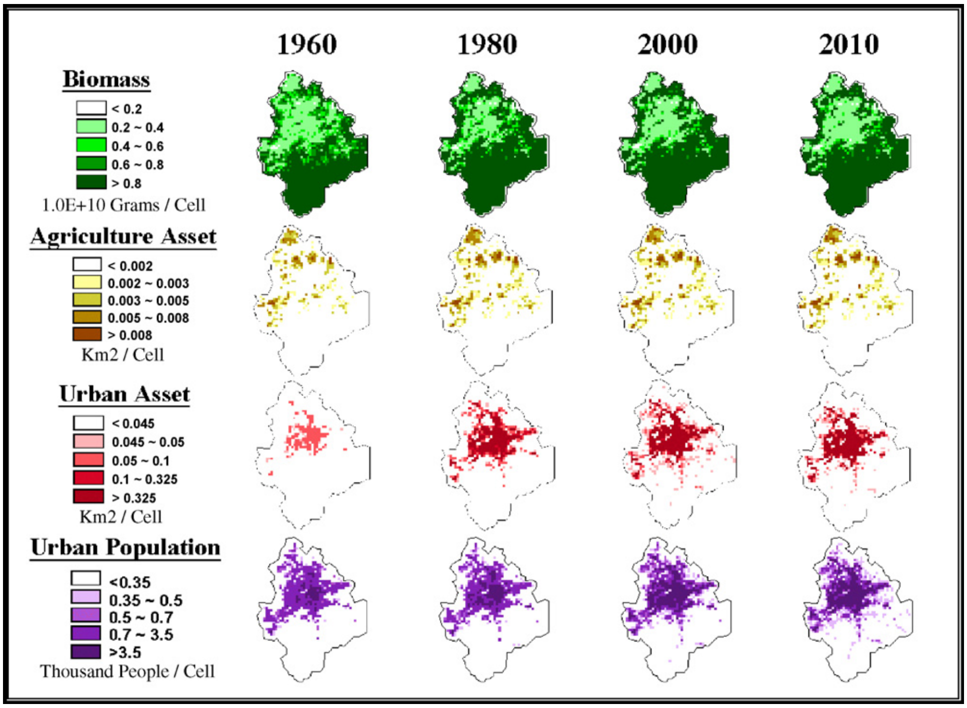

Fig. 7 – Simulated results of storages of Taipei's urban landscape system.

results in the continuing growth of the urban system. However, urban sprawl is not without limitations. The urban area has to rely on its surrounding rural system for life-support services and due to the phenomenon of urban sprawl, rural areas have been converted to urban use, resulting in decreased life-support capability. Although the urban population and urban assets are likely to continue to grow, the area of urban land use is now somewhat stabilized.

5. Concluding remarks

The relationship between spatial organization and energy hierarchy of city-regions, and its implications for urban planning has been addressed by Huang (1998b), Huang et al. (2001) and Odum and Odum (2001). Although important progress has been made in spatial modeling, the modeling of urban systems is still primitive in terms of efforts to include ecological principles. In this paper, we build on past research on urban energetics and urban system modeling to develop a model to simulate the evolving urban spatial pattern as a consequence of energy flows and convergence. The spatial model developed in this paper uses the Taipei metropolitan region as an example of urban landscape change for discussion of underlying energetics. The pattern of land use reveals the spatial organization of land use in relation to underlying biophysical and socioeconomic conditions. The simulation results not only describe the evolving urban landscape system in Taipei, but also reveal its underlying energetic mechanisms and energy flows.

The self-organization of an urban landscape system corresponds to the elaboration of a stable pattern of coexisting zones. The flow of energy and matter through the boundaries of each cell allows the urban system not only to spontaneously self-organize itself, attain a certain structure and maintain it far from equilibrium conditions; the spatial order also appears spontaneously. This structure is manifested as the distribution of different land use activities in space, including the relative abundance or assets of different types of land uses. Furthermore, the urban landscape system develops hierarchical spatial patterns to organize the urban economy and its surrounding natural environment and agricultural land geographically. Self-organized systems are thus said to be creative.

The evolving urban landscape system exhibits dynamic self-organization, which planners must take into account. This paper is not concerned with the debate on the actual mechanisms of the spatial dynamic process of urban landscape systems, but rather with the way in which system level responses can be explained by the interactions and feedback of components in an evolutionary dynamic. The scope of the model developed in this paper is not without limitation; the model is not a general purpose model for predicting land use change or for studying the impact of land use change on ecosystem processes. The simulation approach adopted in this paper advocates models capable of generating complexity in the phenomena of interest, while retaining simplicity in model structure—the key feature of general system theory models. Energy systems models emphasize the general principles of system behavior and simplify the micro interactions of urban and environmental systems by reducing human behaviors into several differential equations. Instead of linking the system modeling software and GIS software for spatial simulation, the approach used in this paper takes advantage of the arithmetic operation capability of GIS to simulate the evolving land use patterns.

Urban planners and decision makers were skeptical about the usefulness of energy system modeling. The purpose of developing the spatial simulation model in this paper is neither for predicting future land use change nor for analyzing the impacts of urban development on ecosystems. The intention is to explore the hypothesis of a spatial energetic hierarchy in urban landscape systems. Although energy system modeling has never been used to develop an operational urban simulation model, the concept has laid out the basis for urban ecological research and made important progress with respect to understanding how urban ecosystems operate and how they differ from natural ecosystems (Alberti, 1999).

This paper has restricted the discussion to use of a system model and GIS for spatial simulation. There is every reason to believe that this is just one example of a wide range of approaches that demonstrates similar behavior. We envisage several directions the continuing application of energy theory and spatial simulation in studying urban landscape systems:

(1) The spatial model of the urban landscape system can be further expanded to include the flows of life-support services and materials flows between grid cells to study the relations between different zones: competing, mutually cooperative or symbiotic?
(2) Emergy or other energy approach such as exergy, can be included in the spatial simulation, e.g. see Jørgensen and Fath (2004), Laganis and Debeljak (2006) and Tilley and Brown (2006), if the material and energy flows can be calculated appropriately. In addition, the spatial pattern of urban energetic evolution and the difference of urban energetics between urban sprawl and a compact city could be analyzed by including indices such as empower density, land use transformity, emergy investment ratio, net emergy yield ratio, etc., in the simulation model.
(3) Compare the differences of energetic mechanisms between city-regions with different natural features (e.g. coastal region versus continental region) or between cities with different hierarchical position (e.g. economic center versus agricultural town).

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