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Emergy-based evaluation of peri-urban ecosystem services

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ABSTRACT

Peri-urban areas are often characterized by valuable natural environments that provide essential life-support functions and ecosystem services for urban residents. Global environmental change has raised concerns over how urbanization and land use and land cover change affect ecosystem services. This study applied systems ecology theory and ecological energetic analysis to value the worth of natural environment and ecosystem services to a socioeconomic system. We begin with a general discussion of peri-urban areas and their ecosystem services. An emergy approach is applied to establish a framework for evaluating the ecosystem services by identifying systemic roles of each system components. The two-part framework includes: (1) an emergy evaluation of energetic flows of ecosystem services; and (2) an impact matrix to analyze systemic roles of services in the analyzed system. On the basis of the proposed valuation framework and land cover types in the greater Taipei area, this study analyzed ten ecosystems to determine how they interact, via energy flows, to contribute services to human society. By converting all stocks and flows into common emergy units, an impact matrix is constructed to analyze the systemic role of ecosystem components by classifying their status of being active, reactive, critical or indifferent. The analytical results indicate that the soil component of forest ecosystems, upstream rivers and agricultural productivity play critical role of ecosystem services in the study region. The effect of land cover change during 1971–2006 in the study region on ecosystem services is also analyzed. Finally, the implications of biophysical valuation of ecosystem service for spatial planning as related to adapting to global environmental change are discussed.

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1. Introduction

Global environmental change has prompted new concerns about the role of urban areas in global systems (Sanchez-Rodriguez et al., 2005). The consequences of increased urbanization and urban sprawl are apparent in many regions worldwide (Vitousek et al., 1997; Antrop, 2000; Seto and Fragkias, 2005; Jantz et al., 2005; Martinuzzi et al., 2007). Urbanization can also be considered a process of spatial expansion of urban areas by transforming rural land use into urban land use, which changes the spatial patterns and ecological functions of landscapes (Antrop, 2000). Of the many impacts of global environmental change, land use change has been highlighted as a key human-induced effect on ecosystems (Dolman and Verhagen, 2003). Sprawl not only consumes natural and productive lands by converting forests and agricultural land into built environments but also fragments, degrades and isolates remaining natural areas (Robinson et al., 2005).

The transition zones between urban and rural areas, generally known as peri-urban areas, are vulnerable to increased urban pressures. Peri-urban areas are not only transition zones, but also interaction zones between urban and rural activities; the landscape features of peri-urban areas are subject to rapid modification by human-induced activities (Douglas, 2006). Notably, peri-urban areas should be considered an extension of a city rather than an entirely separate area. Their ecological functions and economic and demographic processes are more or less integrated with the city. From the perspective of an environmental planner, peri-urban areas are valuable protected areas, forested hills, preserved woodlands, prime agricultural lands, important wetlands, etc. which can provide essential life support services for urban residents. Globalization-driven changes in peri-urban areas have directly and indirectly affected the vulnerability of metropolitan regions. Adverse environmental conditions also affect both economic growth and urbanization in peri-urban area resulting from the rapid spatial expansion of urban land use. After the pioneering Peri-Urban Environmental Change (PU-ECH) project, implemented by SCOPE, Douglas (2006) summarized areas perspective for the scientific understanding of key issues of peri-urban environments. Land cover and land use change in peri-urban areas were placed emphasis for the understanding of socioeconomic needs in peri-urban areas and their environmental consequences.

Natural and social science researchers have documented the effects of conversion of rural to urban land on ecosystem

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functioning and the subsequent effects and on feedback related ecosystem services. Land use and land cover change in peri-urban areas often change ecosystem services by modifying energy and material flows. Peri-urban sprawl often impairs the ecological functions needed for providing environmental services. The sprawl landscape is characterized by increased fragmentation, increasing substitution of ecological functions with human functions and highly reduced capacity of ecological functions to support human functions (Alberti et al., 2006).

Cities must depend on the natural services provided by ecosystems beyond city limits. Peri-urban ecosystems are essential for regulating and maintaining ecological processes and life-support services for urban residents. Ecosystem services refer to the benefits that human populations derive, directly or indirectly, from ecosystem functions (Costanza et al., 1997). Ecosystem services and their values have received increased public attention in recent years. Many classifications of ecosystem functions and services have been described in the literature (e.g. Costanza et al., 1997; Daily, 1997; de Groot et al., 2002). The Millennium Ecosystem Assessment (2005) categorized ecosystem services into provisioning, regulating, cultural, and supporting services. The complex causal chains linking urban land use to environmental change, which in turn affects socioeconomic systems, emphasizes the importance of understanding the dynamics of peri-urban ecosystems and the services they provide to cities.

Adaptation to global environmental change is a great challenge for spatial planners in Taiwan. The rapid economic growth of Taiwan during 1970–1980 transformed Taiwan from a rural-based economy to an industrialized society. Many previously rural areas now have croplands interspersed with small manufacturing factories and large industrial districts, which are all essential components of the urban economy. On the western coastal plains of Taiwan, peri-urbanization is an increasing pressure on the environment as well as on the ability of planning agencies to counter the problems associated with intensified land use. The existing practice of land management in Taiwan fails to meet the increasing demand for usable knowledge between global environmental change and land use. Adequate spatial planning and land use controls to alleviate negative effects and loss of ecosystem services due to global environmental change are only now beginning to receive attention in Taiwan. In land use planning and review of development projects in Taiwan peri-urban areas, the benefits of human society from ecosystem services are often not fully taken into account; as a result, productive and valuable landscapes continue to be converted into built-up areas. de Groot (2006) suggested that one reason for the continued unsustainable use of productive landscapes is the under-valuation of the benefits of landscapes and their ecosystem functions. Therefore, before developing strategies and policies for planning and managing peri-urban areas in Taiwan, the roles and ecosystem functions of peri-urban areas must be clarified from a regional perspective.

The valuation of ecosystem services must encompass a full appreciation of the value of natural and semi-natural environments in terms of their contribution to societal well being. The contributory value of ecosystem services to urban economic activity cannot be properly assessed solely by market prices. Money paid for ecosystem services from urban systems largely goes to human extractors rather than to compensate for the free work of the environmental system. Ecosystem services are generated by the complex natural cycles, driven by solar energy and operate on many temporal and spatial scales (Daily, 1997). How can we explain the biophysical values of ecosystem services in peri-urban areas? How have ecosystems and their services changed been affected by peri-urbanization? Finally, how can these services and their changes due to peri-urbanization be evaluated?

To effectively address these issues, this study establishes a framework for a biophysical approach to ecosystem assessment in peri-urban areas using emergy synthesis to evaluate how ecosystem services impact human society (see Section 2). The emergy approach used evaluates the energetic flows of ecosystem services of ten land cover types in peri-urban areas of Taipei (Section 3). Section 4 presents an impact matrix for analyzing the systemic roles of each service by synthesizing the energetic flows of the ten land cover types assessed. Section 5 further analyzes and discusses changes in the ecosystem services of Taipei peri-urban area due to land cover change. Conclusions are presented in Section 6 along with recommendations for future research.

2. Framework for evaluating ecosystem services

This section establishes a framework for the biophysical valuation of ecosystem services in peri-urban areas. As Fig. 1 shows, the framework consists of five steps: (1) delineation of the ecosystems to be valued; (2) identification of the services provided by ecosystems; (3) emergy evaluation of ecosystem services; (4) an impact matrix for analyzing systemic roles of services; (5) synthesis of ecosystem services.

2.1. Delineation of the ecosystems to be valued

Valuation requires that the object to be evaluated be clearly specified. In addition to socio-economic values for industrial and housing development or public facilities such as freeways and land fills. Peri-urban areas could be sites considered valuable protected areas, forested hills, important ecosystems or prime agricultural lands (Douglas, 2006). A systemic analysis initially involves clarifying the geographic, biophysical and socioeconomic characteristics of the study region. The ecosystems of the analyzed area may contain many different sub-ecosystems. This study emphasizes the need for spatial delineation to describe the sub-ecosystems to be evaluated. Satellite images and aerial photos can be used to interpret the spatial distribution of land cover to delineate the boundaries of natural and semi-natural ecosystems. Varying land cover may be related to different ecosystem services. For example, a forest ecosystem is associated with timber and water supply; paddy rice field can provide food and recharge ground water. Further, the inventory of natural processes and their land use consequences are useful for projecting urbanization trends and for evaluating changes in ecosystem service due to urbanization.

2.2. Identification of the services provided by ecosystems

Ecosystem services refer to the goods and services provided by the ecosystem to human society. This study classifies the ecosystem services into four categories based on the categories presented in the Millennium Ecosystem Assessment (2005): provisioning services (e.g. food, water, timber, and fiber); regulating services (e.g. climate regulating, flood regulation, disease regulation and water purification); cultural services (e.g. recreational, aesthetic, educational, and spiritual benefits); and supporting services (e.g. nutrient cycling, soil formation and photosynthesis). Although ecosystem functions and services in peri-urban areas can be identified and itemized, the function and use of one service may influence the availability of other ecosystem functions and services. Therefore, the analysis and assessment of ecosystem services must be approached from a systemic viewpoint.

To elucidate how a sub-ecosystem, identified in step 1, generates services to human society, the first task is to diagram the stocks-flows and interactions between system components of

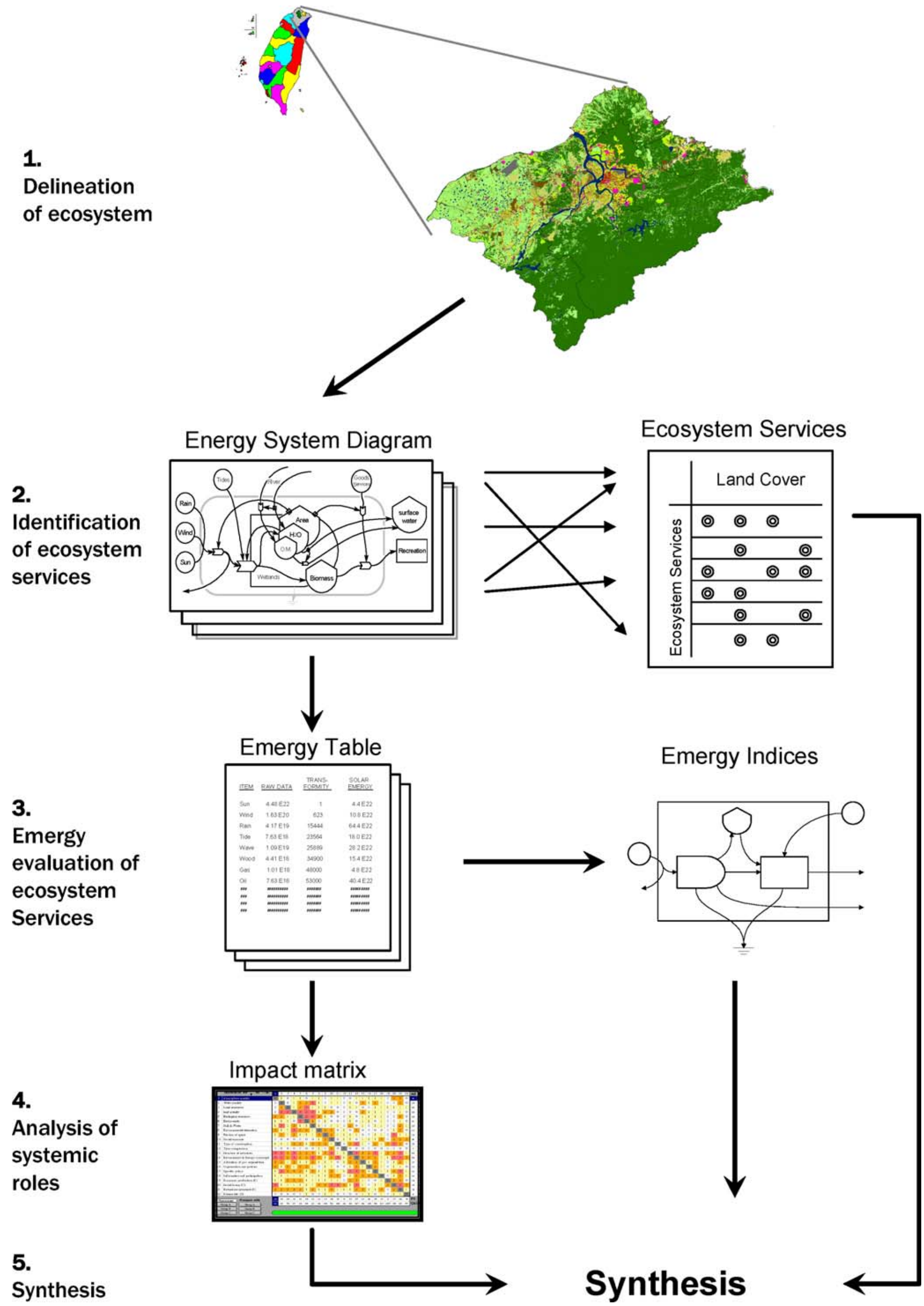

Fig. 1. Framework of ecosystem valuation.

each landscape sub-ecosystems. The subsystems and components within each subsystem are defined by the system characteristics of the study region. These subsystems represent the main ecological and socioeconomic aspects of the region. Ecological energetic diagrams developed by Odum (1971, 1983, 1996) were used to trace energy flows between system components to identify ecosystem functions and services that are valuable to the urban system. Each energetic flow can be categorized as supporting, provisioning, regulating or cultural ecosystem services. Among the ecosystem services, provision services and regulating services have the closest linkage between ecosystem services and human well-being (Millennium Ecosystem Assessment, 2005). Inter- and intra-subsystem linkages can be determined via energetic and material flows between system components. Intra-linkages between subsystem components can be regarded as supporting services, which are processes for maintaining system viability. Inter-linkages between ecosystems and urban systems can be considered the other three ecosystem services (provisioning, regulating and cultural) which support the physiological requirements of urban systems.

2.3. Emergy evaluation of ecosystem services

Before valuing the ecosystem services identified in the previous steps, they must be assessed in biophysical terms. Determining the intrinsic value of the natural environment in providing ecosystem services requires a new accounting system that can assess the contribution of non-market environmental services to the economic system. Emergy synthesis combines principles of General System Theory, thermodynamics and systems ecology to account for the total environmental resources contributed for the generation of a product or a service (Odum, 1988). Emergy is defined as *all the available energy that is used, directly and indirectly, in making a product, expressed in units of one type of energy*; transformity is *the emergy of one type required to make a unit of energy of another type* (Odum, 1996). If a product is expressed in mass units the term "specific emergy" can be used instead of transformity. Since solar energy units (solar equivalent joules, sej) are the most commonly applied, the terms solar emergy and solar transformity (sej/J) can be defined. Solar transformities have been calculated for a wide variety of energies, resources and commodities (e.g. Brown and Bardi, 2001; Brandt-Williams, 2002; Campbell et al., 2005; Kangas, 2002; Odum, 1996, 2000; Odum et al., 2000).

After drawing a system diagram, an emergy evaluation table can be developed to quantify the energy content (e.g. joule) or mass of the identified flows. The energy content or mass can then be multiplied by its solar transformity or specific emergy to obtain its emergy in solar emjoules (sej). By converting all energy flows and physical resources to solar emergy, these values can be used for direct numerical comparison and summing for totaling. Emergy indices, such as the emergy yield ratio, can be calculated by aggregating resource flows to evaluate process performance and to measure sustainability.

Odum (1988, 1996), and Brown and Ulgiati (2004) provide further details on the concept and procedure of emergy synthesis. Theoretical developments in emergy methodologies, as well as, illustrations of the application of emergy evaluation in the assessment of the economic value of resources can be found in publications from the biennial emergy conferences (see Brown et al., 2000, 2003, 2005, 2007).

2.4. Impact matrix for analyzing systemic roles of services

The systemic role of each system component can be identified using an impact matrix. This methodology is contained in the sensitivity model (SM), a widely applied biophysical approach, described by Vester and Hesler (1982). The cross impact analysis represents a system with a set of components, the so-called impact factors, and their mutual interactions. This approach has been used in a variety of applications, including corporate management and rural development (see Lang et al., 2006). With the involvement of local residents, planners, and interest groups, Chan and Huang (2004) applied a sensitivity model to analyze the sustainability of a local community. In this work, an impact matrix was also applied for pattern recognition of the systemic roles of identified variables.

According to Vester (1988), the impact matrix can reveal linkages between system components. Each component defines a row and column of the impact matrix. The assessments in a single row indicate the flows from a component X to the other components, whereas the assessments in a single column indicate the flows from other components to component X (see Fig. 2). By aggregating the emergy flows to and from each component, the systemic role of each component within the entire system can be classified depending on its "system impact": active, passive, critical (ambivalent) or indifferent (buffer) (Wiek and Binder, 2005).

The sums of all flows to all other components (sum of rows = active sum) and sum of inflows from other components (sum of columns = passive sum) of the impact matrix reveal two systemic characteristics for each component, the "active vs. reactive" and "critical vs. buffer". The sum of rows indicates the activeness of a component, which indicates its influences on the other components and thus the whole system. The sum of the columns indicates the passiveness of each component, which indicates how strongly it is influenced by other components. Because the flows between components are all in emergy units, the "critical vs. indifferent" can be calculated by summing the active and passive sums of a component to reveal how strongly the component is interconnected with other system components. The higher the total sum (TS) of flows to and from the component, the more critical it is to the system. The "active vs. reactive" is calculated by dividing the active sum (AS) by the passive sum (PS) for each component, which reveals whether the component strongly influences other components or is prone to external influence. If the ratio of "active sum" to "passive sum" (Q) is >1, the component has an active role in the system; if it is <1, the component is strongly influenced by other components. The

From ⇩ to ⇨	**Component 1**	**Component 2**	**Component 3**	**Component 4**	…	**AS**
Component 1						
Component 2						
Component 3						
Component 4						
….						
PS						
TS						
Q						

Active-sum (AS): The active sum represents the ability of an individual component to influence all other components in the system
Passive-sum (PS): The passive sum is a corresponding value for the passiveness of the component due to changes of other components in the system
Total Sum (TS): The total sum (AS+PS) indicates how strongly the component is interlinked with the system
Quotient (Q): The quotient AS/PS can indicate whether its character is more active or reactive

Fig. 2. Impact matrix showing interaction between components and indices measuring systemic roles of components.

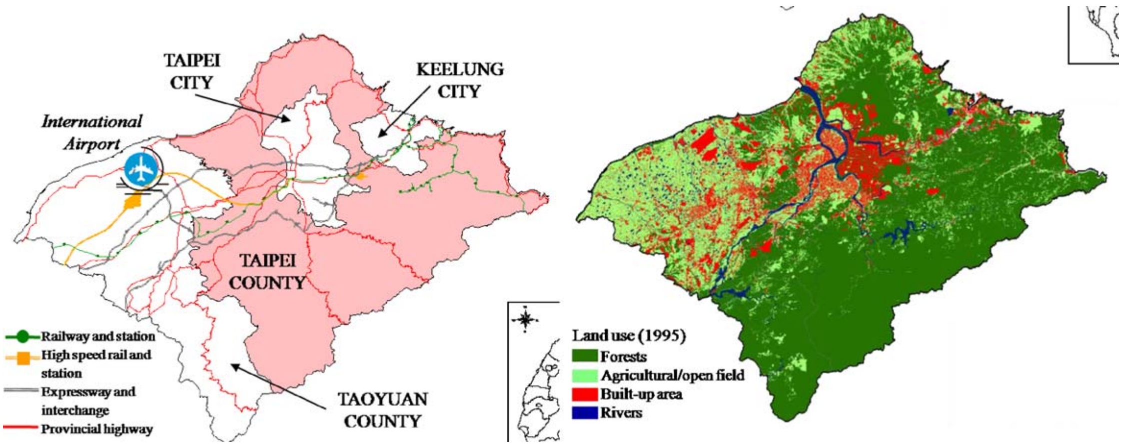

Fig. 3. Regional context and land use of the greater Taipei area.

system components can be represented on a system grid (see Fig. 9) to indicate the relative impact of each component and to classify the components by their systemic roles in the system (active, reactive, critical, or indifferent).

2.5. Synthesis of ecosystem services

After calculating emergy flows for the identified ecosystem services and the systemic roles for system components of each sub-ecosystem, overall peri-urban ecosystem services can be synthesized. For example, the change in ecosystem services due to land cover change can be discussed.

3. Emergy evaluation of ecosystem services in Taipei-peri-urban areas

In Taiwan, urbanization driven by rapid economic growth since the 1970s has imposed great stress on natural resources and environmental quality, especially in peri-urban areas. Although many areas have been affected by urban sprawl, this study focused on the greater Taipei area, the most populated and fast growing area of northern Taiwan. The greater Taipei area ranges in altitude from sea level along the west coast to over 2000 m in the southern tip of Taiwan (Fig. 3). The Taipei Basin, which is situated in the central part of the study area, is surrounded by hill areas where rivers intersect. The North–South Expressways connect major cities and extend toward southern Taiwan along the west coast. Urban land use dominates the Taipei Basin, with urban density decreasing as one moves toward the hill areas. Currently, the City of Taipei has about 2.6 million inhabitants. The populations of Taipei County and Taoyuan County are growing rapidly and are becoming more urban. In just 35 yr (1971–2006), the population of the greater Taipei area increased 106%, from 4.2 million to 8.7 million.

The study area spans a gradient of landscape types, from urban centers in the Taipei Basin to rural/agricultural lands to forested hill slope lands. The Taipei peri-urban area also includes a water protection area and water supply facilities, such as the Fei-tsui

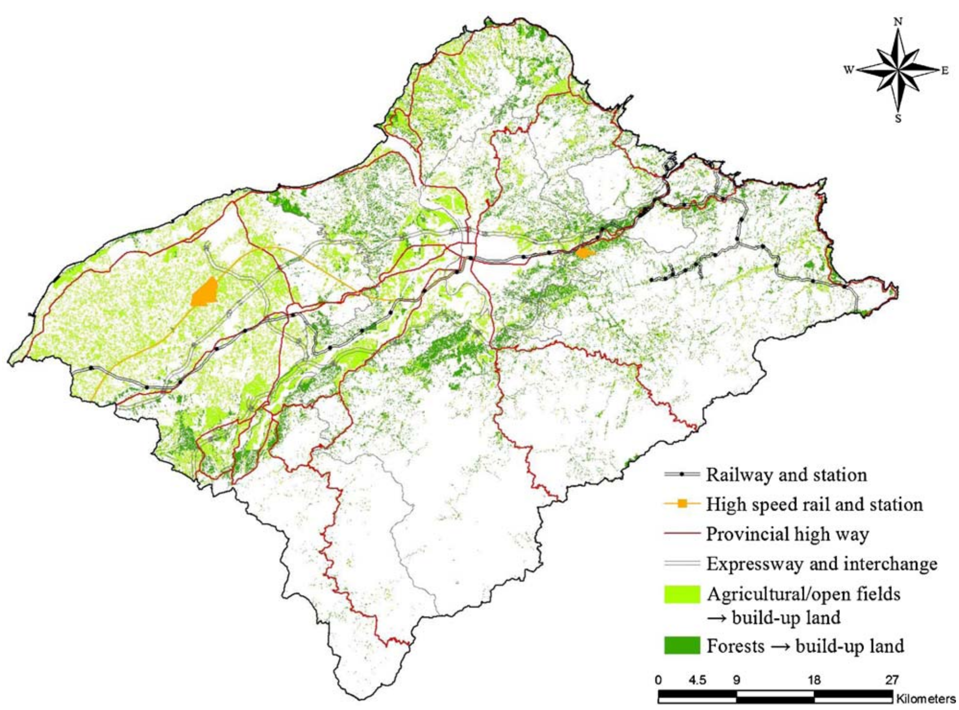

Fig. 4. Land cover change during 1971–2006.

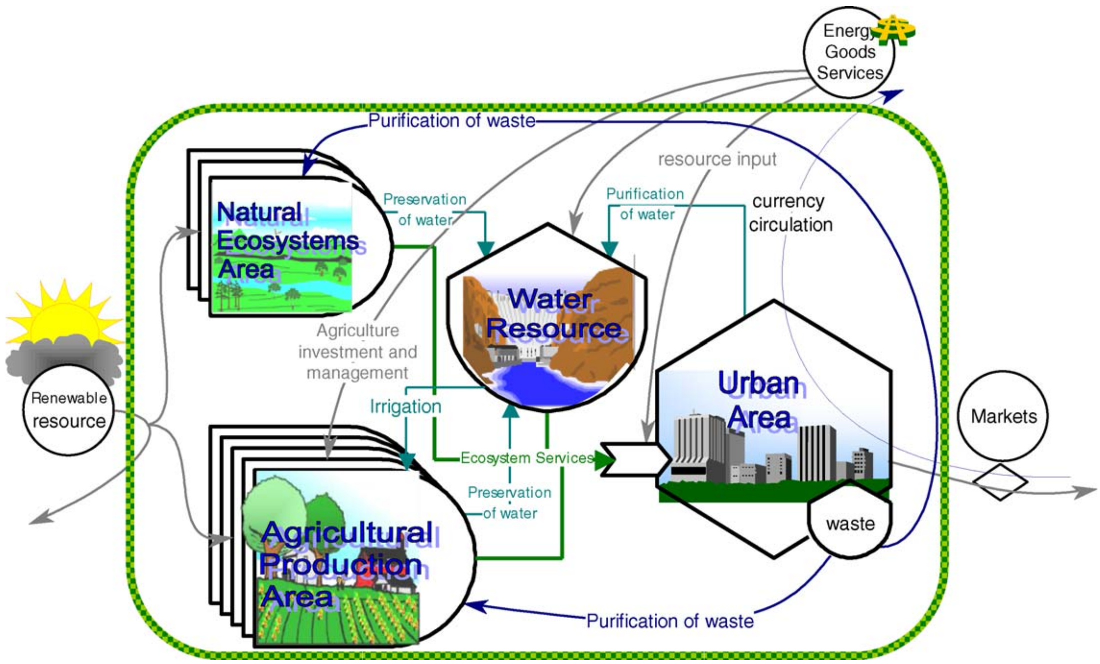

Fig. 5. Ecological economic system of the greater Taipei area.

reservoir and Shihmen reservoir. Recently urban srawl has been most pronounced in the greater Taipei area, as indicated by urban diffusion and competition for low-priced land. For example, urban areas have increased by more than 27,634 ha (147%) whereas agricultural areas have decreased 29,942 ha (28%) during 1971–2006. A SPOT image was analyzed to develop a digital record of land cover for comparison with a 1971 map of land cover (Huang et al., 2009). Urban development has increased at lower elevations close to major transportation corridors and urbanized areas (Fig. 4). The built-up lands in the study region have spread into previously rural and peri-urban lands to create complex zones with varying rural landscapes, land use, access to public facilities and environmental interfaces with urban areas. The major consequences of urban sprawl on these landscapes include the loss of forest land and agricultural land, fragmentation of agricultural fields and loss of the rural character of the landscape.

Taipei and its peri-urban areas have widely varying environmental characteristics. Using an Odum energy diagram (Fig. 5) a conceptual urban ecological economic system can be presented. In this representation, locally available renewable energy sources power natural ecosystems and human-subsidized agricultural production systems to provide important life-support services to the urban system. Goods and services must be imported from economic system to transform and extract indigenous resources needed for life-support in the urban areas. Based on land use and land cover maps, this study identified ten major peri-urban ecosystems which can generate ecosystem services for urban areas. The natural ecosystem includes forest and riparian wetland. The agricultural production system includes paddy rice fields, crop lands, orchards, and range farms. Water resources are another important system for generating various ecosystem services for urban areas. Table 1 summarizes the services that each of these ecosystems might provide. The following section describes the results of our emergy synthesis for evaluating ecosystems services.

3.1. Natural ecosystem areas

The biophysical evaluation of ecosystem services begins with an analysis of energy flows within the examined system. The conceptual energy system diagram of forests is shown in Fig. 6. The

Table 1
Ecosystem services of the greater Taipei areas.

Services	Ecosystem									
	Natural ecosystem area		Agricultural production area						Water resource	
	Forest	Riparian Wetland	Paddy rice field	Crop land	Orchard	Range farm	Fallow	Aquaculture	Upstream	Downstream
Provisioning services										
Food			•	•	•	•		•		
Fresh water	•								•	
Regulating services										
Water regulation	•	•								
Erosion regulation	•			•	•					
Water purification and waste treatment		•								•
Cultural services										
Recreation and ecotourism	•	•		•	•	•		•	•	•
Supporting services										
Soil formation	•						•			
Primary production	•		•	•	•					
Nutrient cycling	•	•		•			•			

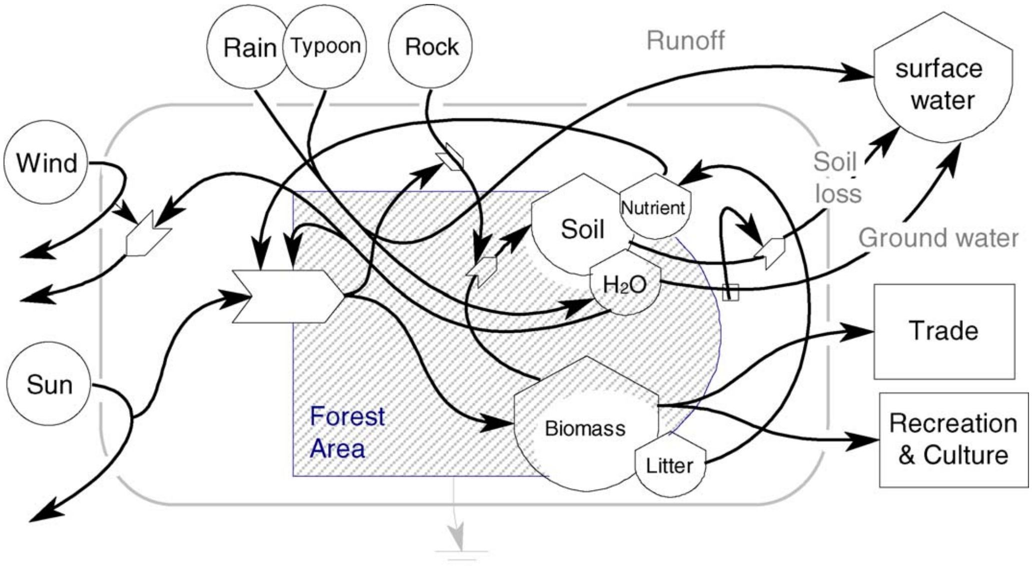

Fig. 6. Energy diagram of forest ecosystem.

land cover of undeveloped areas in the study region is dominated by mountainous forests, lands which are vital for conserving water resources. Renewable energies in this subsystem include the sun, wind and rain, power associated with the production of forest biomass. Soil nutrients are regenerated from the weathering of rocks and forest debris. Rain water infiltrating the soil is later discharged as surface water. The forest ecosystem thereby provides the essential services of purifying and conserving water resources. Timber harvesting represents a direct provision of ecosystem service from forest ecosystems. Due to the large and undeveloped characteristics of forest areas, the aesthetic value of forests provides important cultural services to urban residents as well.

The flows of energy sources, outflows and internal processes of forest areas (Fig. 6) were used to calculate emergy values for 2006 (Table 2). The chemical energy of rain (6.36 E20 sej/yr) is the major source of renewable emergy in forest areas. A portion of the chemical emergy of rain is absorbed by plants and transpired (1.94 E20 sej/yr) via photosynthesis. Rather than being consumed directly by humans, some energetic flows are needed to sustain ecosystems; such indirect services, or supporting services (Millennium Ecosystem Assessment, 2005) include water purification, nutrient recycling, soil generation, etc. The emergy evaluation of internal processes includes net primary productivity of forest (1.94 E20 sej/yr), litter fall, soil formation (3.72 E18 sej/yr) and water infiltration (6.44 E20 sej/yr). Water infiltration has the highest emergy value of all internal processes and generates a ground water discharge of 5.45 E20 sej/yr to surface waters. Since timber harvesting is prohibited, no flows were recorded. Ecosystems also provide aesthetic and cultural values to urban areas, and other than recreational services, are perhaps the most highly valued ecosystem services for cities. Without them, cities would be more stressful environments for urban inhabitants. The forest areas in the study region provide excellent opportunities for recreation such as hiking and biking. The emergy value of cultural services in forest areas is the total emergy inflows to the system (6.36 E20 sej/yr).

Another important natural ecosystem in the study region is riparian wetlands. These areas help purify water by absorbing organic matter and associated contaminants. However, wetlands in the study area are relatively small making the emergy flows to and from riparian wetlands significantly smaller than that of other natural ecosystems.

Table 2
Emergy evaluation of forest ecosystem in 2006.

Items	Raw data (unit/yr)		Transformity (sej/unit)	Source	Solar emergy (sej/yr)
Inflow energy					
1. Sun	8.97E+18	J	1		8.97E+18
2. Wind	3.02E+17	J	1496	Odum (1996)	4.51E+20
3. Typhoon	1.16E+16	J	3868	Odum (2000), Odum (1996)	4.51E+19
4. Rain (geopotential)	1.07E+13	J	10,488	Odum (1996)	1.12E+17
5. Rain (chemical)	3.49E+16	J	18,200	Odum (1996)	6.36E+20
6. Rain (chemical-absorbed)	1.07E+16	J	18,200	Odum (1996)	1.94E+20
7. Rock weathering	3.44E+09	G	74,000	Odum (1996)	2.55E+14
Internal processes					
8. NPP, total live biomass	1.08E+16	J	18,020		1.94E+20
9. Litterfall	1.04E+16	J	18,619		1.94E+20
10. Soil formation	3.72E+09	G	1.00E+09	Odum (1996)	3.72E+18
11. Infiltration	2.32E+16	J	27,764	Odum (1996)	6.44E+20
Outflow energy					
12. Surface runoff	1.11E+16	J	27,764	Odum (1996)	3.07E+20
13. Ground water discharge	1.96E+16	J	27,764	Odum (1996)	5.45E+20
14. Soil loss	6.54E+13	J	74,000	Odum (1996)	4.84E+18
15. Harvested timber	0.00E+00	J	70,035	Tilley (1999)	0.00E+00
16. Recreation					6.36E+20

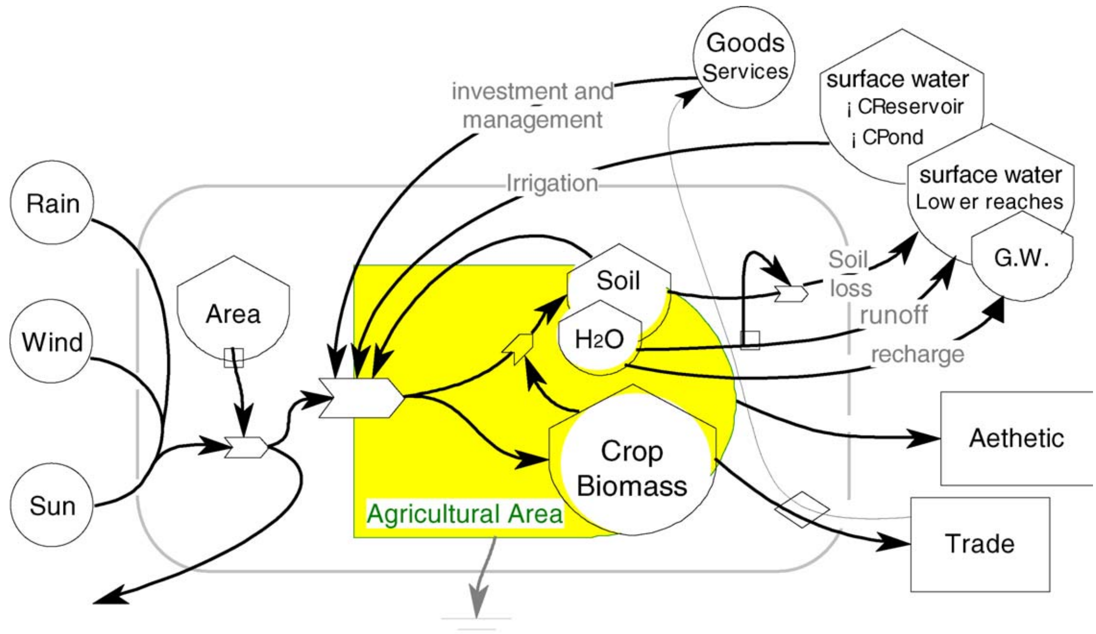

Fig. 7. Energy diagram of agricultural ecosystem.

3.2. Agricultural production area

The agricultural areas in the greater Taipei area include paddy rice fields, crop lands, orchards, range farms and fallow lands. Fig. 7 presents the energy flows of a typical agricultural production system, which explicitly incorporates renewable energy, agricultural land, crop biomass, soils, inflows of irrigated water and goods and services. The amount of renewable energies used by the agricultural production area depends on the size of agricultural fields. In addition to renewable energy, this human-subsidized production system must use energy and materials (e.g. fertilizer, irrigation water, and labor) to enhance crop production. Food provision is the major ecosystem service offered by agricultural production areas. Since large volumes of irrigated water are required to grow rice, the water contained in the soil can also be used to recharge ground water. Agricultural production in peri-urban areas can also provide an aesthetic value to nearby urban dwellers.

The major crops in the study area are rice and vegetables. Due to excess agricultural production in Taiwan, approximately 50% of the agricultural lands in the study area are currently fallow and receive government subsidizes. Table 3 summarizes the emergy value of flows in 2006 for each of the agricultural production systems in the greater Taipei area. Using emergy as an enumerative, rice paddy fields, crop lands and fallow lands capture most renewable energies. Although the size of range farms is smaller than that of other agricultural fields, the emergy value of live stock production (1.21 E21 sej/yr) is higher than that of all crops due to the higher levels of goods and services from the economic system used in livestock production. The emergy values of rice production and vegetable crops are 1.31 E20 sej/yr and 1.24 E20 sej/yr, respectively. Paddy rice fields require more

Table 3
Emergy value of agricultural production in 2006.

Items	Paddy rice field (sej/yr)	Cropland (sej/yr)	Fallow (sej/yr)	Orchard (sej/yr)	Range farm (sej/yr)	Aquaculture (sej/yr)	Total (sej/yr)
Inflow energy							
1. Sun	2.98E+17	5.99E+17	1.82E+18	1.40E+17	1.46E+16	1.17E+17	2.99E+18
2. Wind	1.50E+19	3.02E+19	9.15E+19	7.07E+18	7.36E+17	5.89E+18	1.50E+20
3. Rain (geopotential)	2.34E+15	4.69E+15	1.42E+16	1.10E+15	1.15E+14	4.58E+14	2.30E+16
4. Rain (chemical)	2.11E+19	4.25E+19	1.29E+20	9.96E+18	1.04E+18	8.30E+18	2.12E+20
5. Rain (chemical-absorbed)	6.09E+18	1.22E+19	3.72E+19	3.05E+18	3.17E+17	2.39E+18	6.13E+19
6. Goods and services	4.25E+18	1.30E+20	–	2.16E+19	1.20E+19	4.26E+20	5.94E+20
7. Fertilizer							1.89E+16
N	2.65E+15	4.03E+15	–	1.89E+15	–	–	8.56E+15
P	1.52E+15	5.51E+15	–	2.30E+15	–	–	9.33E+15
K	1.20E+14	5.67E+14	–	2.85E+14	–	–	9.72E+14
8. Irrigation	2.05E+20	2.84E+19	–	6.65E+18	1.19E+18	8.89E+18	2.50E+20
9. Irrigation (ground water)	7.74E+17	1.05E+17	–	2.47E+16	–	2.48E+18	3.39E+18
Internal processes							
10. Infiltration	1.18E+20	–	–	–	–	–	1.18E+20
11. Green manure biomass	–	–	2.24E+13	–	–	–	2.24E+13
Outflow energy							
12. Surface runoff	2.04E+19	4.10E+19	1.24E+20	9.61E+18	1.00E+18	–	1.96E+20
13. Soil loss	7.72E+17	1.55E+18	4.71E+18	3.64E+17	3.79E+16	–	7.43E+18
14. Production	1.31E+20	1.24E+20	–	4.40E+19	1.21E+21	5.47E+19	1.56E+21
15. Recreation	2.54E+19	1.73E+20	1.29E+20	3.16E+19	1.31E+19	4.34E+20	8.06E+20

irrigated water (2.05 E20 sej/yr) than other crops and also function as a source of groundwater recharge (1.18 E20 sej/yr). The emergy determination of the aesthetic value (cultural service) from agricultural production areas is calculated by summing all emergy inflows to the system, which accounts to 8.06 E20 sej/yr.

3.3. Water resource

The Tansui River is the major stream network in northern Taiwan. The river flows approximately 158.7 km from its headwaters in Hsin-Chu County and passing through Taoyuan County, Taipei County and Taipei City before draining into the Taiwan Straits. In the study region, headwater streams are typically small with high velocity due to the steeper gradient of topography. While flowing downhill, these smaller streams merge to become a larger and slower moving body of water with a slope lower gradient. Although down stream channels have higher stream runoff then upstream channels, the geo-potential energy at each stream confluence declines (Huang et al., 2007). The Feitsui reservoir and Shihmen reservoir are the major water bodies constructed to ensure a reliable water supply for urban residents. Shihmen reservoir also provides irrigated water for agricultural use in Taoyuan County. To evaluate ecosystem services of surface waters in the study region, this study used the locations of reservoirs as divides marking upstream from downstream watersheds (Fig. 8). In addition to surface runoff, upstream channels also receive inflows from ground water. The impoundment of reservoirs not only provides public water supply, but also generates hydroelectricity. In addition to surface runoff and upstream flows, downstream channels also receive waste water inflow from nearby urban areas. Many smaller ponds in downstream areas can store water for irrigation or be used for fish production.

Data for various natural processes in the Tansui River Basin (e.g. precipitation and topography) were collected from various statistical and geographical sources to calculate the emergy of stream runoff. Table 4 shows the results of the emergy synthesis of surface water in the study region. Ground water discharge from upstream watersheds accounts for 5.45 E20 sej/yr, while the emergy value of reservoir inflows is approximately 4.77 E20 sej/yr. Provision of water supply (1.89 E21 sej/yr) is the major contribution to emergy outflow of surface water. Hydroelectricity generation (3.03 E20 sej/yr) is also an important contributor of emergy to urban areas.

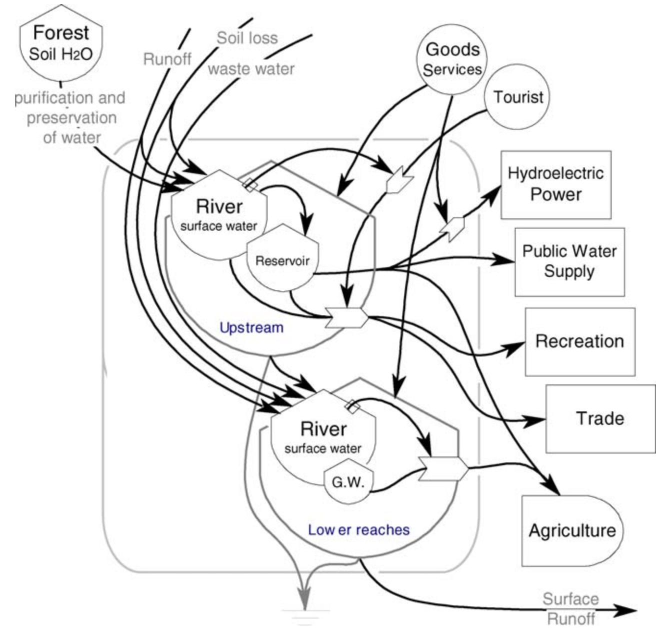

Fig. 8. Energy diagram of water resources in the greater Taipei area.

4. Impact matrix for identifying systemic roles of ecosystems

This study analyzed the role of each component in providing ecosystem services to urban areas. The previous sections list the services from each ecosystem and their respective emergy flows. It is apparent that each ecosystem is interconnected by energy flows to and from each system component. This can be visualized using a symmetrical impact matrix (Table 5). Assessments in each row indicate how one component influences other components, whereas assessments in each column indicate the influence of the other components on it. The components with a high active sum (AS) include upstream rivers, soil nutrients and crop biomass of agricultural production areas, and soil water in forest ecosystems. The upstream rivers, crop biomass and soil water in forest ecosystems also have high passive sums (PS), leading to the highest value for a total sum (TS = AS + PS), which indicates the critical influence of these components in the entire system.

Table 4
Emergy evaluation of water resources in 2006.

	Raw data (unit/yr)		Transformity (sej/unit)	Source	Solar emergy (sej/yr)
Inflow energy					
1. Ground water	1.96E+16	J	27,764	Odum (1996)	5.45E+20
2. Runoff (upstream)	1.11E+16	J	27,764	Odum (1996)	3.07E+20
3. Runoff (downstream)	7.08E+15	J	27,764	Odum (1996)	1.96E+20
4. Soil loss (upstream)	6.54E+13	J	74,000	Odum (1996)	4.84E+18
5. Soil loss (downstream)	1.00E+14	J	74,000	Odum (1996)	7.43E+18
6. Waste water	4.37E+12	J	676,409	Huang (1992)	2.95E+18
7. Goods and services	9.76E+07	US$	1.87E+12	Huang and Chen (2005)	1.82E+20
8. Tourist	3.01E+07	US$	1.87E+12	Huang and Chen (2005)	5.63E+19
Internal processes					
9. Reservoir inflows	1.72E+16	J	27,764	Odum (1996)	4.77E+20
10. Upstream flow (geopotential)	2.74E+16	J	27,764	Odum (1996)	7.60E+20
11. Upstream flow (chemical)	8.93E+10	J	48,459	Odum (1996)	4.33E+15
Outflow energy					
12. Hydroelectricity	2.47E+15	J	123,000	Odum (1996)	3.03E+20
13. Water supply	9.74E+15	J	194,108	Huang (1992)	1.89E+21
14. Recreation					1.23E+21
15. Fish production	1.29E+10	J	2.00E+06	Odum (1998)	2.59E+16
16. Irrigation	5.16E+15	J	48,459	Odum (1996)	2.50E+20
17. Irrigation (ground water)	1.22E+14	J	27,764	Odum (1996)	3.39E+18
18. River (O.M.)	9.14E+05	J	48,459	Odum (1996)	4.43E+10

Table 5
Impact matrix of ecosystem services – 2006.

From↓ to →	Forest ecosystem			Riparian wetland			Agricultural production system			Water resource			Urban system	Active sum (AS)
	Soil water	Soil nutrient	Biomass	Soil	Water	Biomass	Soil water	Soil nutrient	Biomass	Upstream	Down stream	Ground water		
Renewable energies	6.36E+20				1.22E+18		2.12E+20							
Forest ecosystem														
Soil water										8.52E+20		6.44E+20		1.496E+21
Soil nutrient			1.94E+20							4.84E+18				1.993E+20
Biomass		2.55E+14											0.00E+00	2.549E+14
Riparian wetland														
Soil						5.99E+17								5.991E+17
Water											1.97E+17			1.975E+17
Biomass														0
Agricultural production system														
Soil water											1.96E+20	1.18E+20		3.143E+20
Soil nutrient									1.56E+21		7.43E+18			1.572E+21
Biomass													1.56E+21	1.564E+21
Water resource														
Upstream				6.99E+12	1.97E+17		2.50E+20				7.60E+20		2.19E+21	3.204E+21
Down stream														1.975E+17
Ground water							3.39E+18							3.385E+18
Urban system								1.89E+16	5.94E+20	2.39E+20	2.20E+07			8.327E+20
Passive sum (PS)	6.36E+20	2.55E+14	1.94E+20	6.99E+12	1.41E+18	5.99E+17	4.65E+20	1.89E+16	2.16E+21	1.10E+21	9.64E+20	7.62E+20	3.76E+21	
Total sum (TS)	2.13E+21	1.99E+20	1.94E+20	5.99E+17	1.61E+18	5.99E+17	7.80E+20	1.57E+21	3.72E+21	4.30E+21	9.64E+20	7.65E+20	4.59E+21	
Quotient (AS/PS)	2.3530	781965.1	1.31E-06	85673.6	0.139	0	0.6755	83330.873	0.7248	2.925	0.000205	0.004445	0.222	

By calculating the activeness and passiveness of each system component, and placing them into a system grid (Fig. 9) we can examine the significance of each component within the system. In Fig. 9, the horizontal lines represent the arithmetic sum of passiveness while the vertical lines represent the arithmetic sum of activeness. Separating the diagram into four sectors allow examination of the specific significance of each component (i.e., passive, reactive, critical, or indifferent). The benefit of this visualization of the system analysis results is that the relative roles of each component are revealed (Wiek and Binder, 2005).

The *forest ecosystem* can conserve water resources by storing excess runoff and discharging ground water to surface water. The soil water component (A) thus provides a regulating service on water flow and plays a critical role in the entire system. The soil nutrients in the forest ecosystem (B) are an active component because they support biomass production. However, since harvesting timber is prohibited, no provisioning service is available from forest biomass (C), and its role is less active. *Riparian wetlands*, however, tend to fall in the indifferent sector of the system grid due to their smaller area relative to the other ecosystems. The high active sum and passive sum values of agricultural production system components (G, I) reveal the critical role they play in the provision of ecosystem services. Given the topographic characteristics of the study region, reservoirs are used to designate *water resources* as upstream and downstream. The upstream rivers (J) provide surface water and hydroelectricity. These rivers are considered the most critical components and have an active role in the entire system. The downstream portion of the surface water (K) tends to receive runoff and discharge from other system and consequently its role is less than that of upstream components.

5. Discussion – change in ecosystem services caused by land cover change

Some ecosystem changes result from activities related to the human use of ecosystem services, such as food and water. However, most ecosystem changes in the greater Taipei area are the indirect result of land use and land cover changes. The global drivers of industrial transformation in Taiwan have resulted in land use and land cover change in peri-urban areas. Rapid capital accumulation and the high cost of urban land have led to increased investment in peri-urban areas, but because developers focus on short-returns, environmental degradation is common. The rapid industrial development and urbanization along the highway and expressway corridors of the west coast of Taiwan resulted in the loss and degradation of prime agricultural lands and subsequent environmental impacts, such as water pollution. Changes in land use, utilization of natural resources, and environmental services of peri-urban areas are clearly being driven by a number of factors. Competition for land for urban expansion, the promotion of the national industrialization strategy, and the impacts of imported crops on local markets all have played a role in land use change in this region.

Comparing the 2006 SPOT image classification with the 1971 land cover in the greater Taipei areas clearly shows that urban sprawl has extended from the region's urban centers to nearby agricultural areas, particularly along major roads (Fig. 4) (Huang et al., 2009). Urban planners and decision makers must become aware of the regional changes in ecosystem services that take place as urban areas expand. In particular, the links between socioeconomic driving forces, land cover changes, and their environmental impacts must be clearly understood. Land cover change in greater Taipei area has resulted not only from urban sprawl but also from the loss of agricultural land in rural areas. The considerable expansion of built-land between 1971 and 2006 has a direct impact on energy and material flows in peri-urban areas and thus

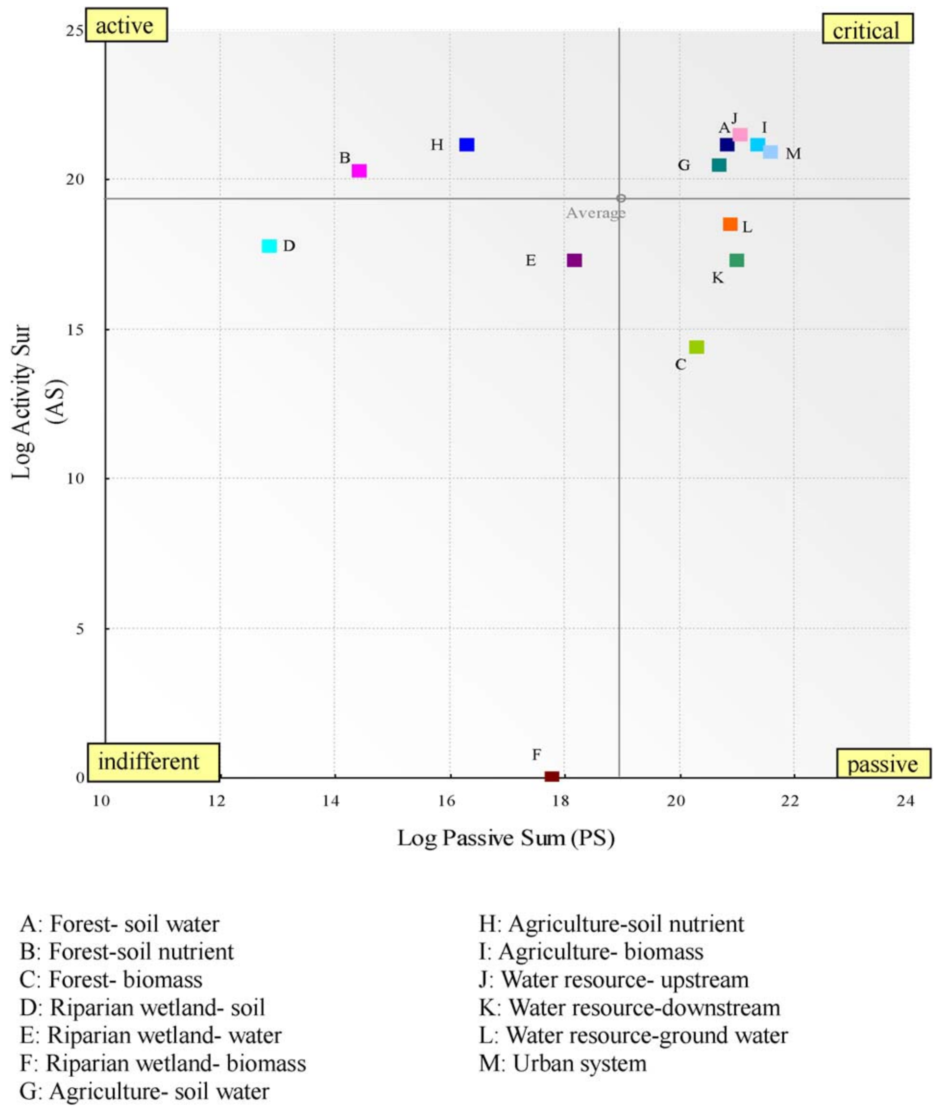

Fig. 9. System grids showing systemic role of ecosystem services in the Taipei area.

has consequences on the functions of ecosystem services in adjacent areas. Conversion of productive and valuable landscape usually benefits a few private interest groups while the costs are assumed by many stakeholders and future generations (de Groot, 2006). An important step for raising the awareness of peri-urban development issues and global environmental change is to analyze the effect of land use and land cover change on ecosystem change in peri-urban areas.

Table 6
Comparison of systemic roles of different system components between 1971 and 2006.

Solar emergy (sej/yr)	Active sum (AS)		Passive sum (PS)		Total sum (TS)		Quotient (AS/PS)	
	1971	2006	1971	2006	1971	2006	1971	2006
Forest ecosystem								
Soil water	1.104E+21	1.496E+21	4.07E+20	6.36E+20	1.51E+21	2.13E+21	2.714	2.353
Soil nutrient	2.365E+20	1.993E+20	2.55E+14	2.55E+14	2.37E+20	1.99E+20	9.28E+05	7.82E+05
Biomass	7.961E+18	2.549E+14	2.31E+20	1.94E+20	2.39E+20	1.94E+20	0.034	0.000
Riparian wetland								
Soil	2.125E+17	5.991E+17	1.23E+12	6.99E+12	2.12E+17	5.99E+17	1.73E+05	8.57E+04
Water	6.582E+16	1.975E+17	3.06E+17	1.41E+18	3.72E+17	1.61E+18	0.215	0.140
Biomass	–	–	2.12E+17	5.99E+17	2.12E+17	5.99E+17	–	–
Agricultural production system								
Soil water	3.419E+20	3.143E+20	6.26E+20	4.65E+20	9.68E+20	7.80E+20	0.546	0.676
Soil nutrient	4.511E+21	1.572E+21	7.45E+16	1.89E+16	4.51E+21	1.57E+21	6.06E+04	8.33E+04
Biomass	4.499E+21	1.564E+21	9.93E+21	2.16E+21	1.44E+22	3.72E+21	0.453	0.725
Water resource								
Upstream	1.109E+21	3.204E+21	6.73E+20	1.10E+21	1.78E+21	4.30E+21	1.647	2.925
Down stream	6.582E+16	1.975E+17	7.61E+20	9.64E+20	7.61E+20	9.64E+20	0.000	0.000
Ground water	8.764E+18	3.385E+18	6.59E+20	7.62E+20	6.67E+20	7.65E+20	0.013	0.004
Urban Area	5.505E+21	8.327E+20	4.64E+21	3.76E+21	1.01E+22	4.59E+21	1.187	0.222

Table 7
Aggregate emergy flows of 1971 and 2006.

Solar emergy (sej/yr)	Renewable emergy (*R*)		Emergy flows from economic system (*F*)		Emergy yield (*Y*)		Emergy yield ratio (*Y*/*F*)	
	1971	2006	1971	2006	1971	2006	1971	2006
Forest ecosystem	4.07E+20	6.36E+20	–	–	4.07E+20	6.36E+20	–	–
Riparian wetland	3.16E+17	1.44E+18	9.51E+18	1.11E+19	9.83E+18	1.25E+19	1.033	1.130
Agricultural production system	2.00E+20	2.12E+20	5.44E+21	5.94E+20	5.64E+21	8.06E+20	1.037	1.357
Surface water	7.87E+20	1.05E+21	1.34E+19	1.82E+20	8.00E+20	1.23E+21	12.293	5.158

Table 6 summarizes the active sum (AS), passive sum (PS), total sum (TS) and quotient (AS/PS) of each ecosystem component during the period of 1971–2006. The forest area decreased 7% from 2290 km^2 in 1971 to 2125 km^2 in 2006. Both the AS (emergy flows to other components) and PS (emergy received from other components) of the soil nutrients and biomass of the forest ecosystem decreased, which slightly decreased their TS (critical role). However, due to the lower precipitation in 1971, the AS of the soil water component in the forest areas, which can discharge ground water to surface water, was higher in 2006. The accumulated sediment deposition in downstream riparian areas doubled the size of wetlands areas in 2006. This increased the critical role (TS) of riparian wetlands in the study region. The agricultural area in the study region decreased more than 400 km^2 from 1100 km^2 in 1971 to 680 km^2 in 2006. The AS, PS and TS of all components of the agricultural production areas all decreased considerably. As ecosystem services in the agricultural production areas decreased, their critical role in the study region was reduced. Due to the increasing demand for water supply and hydroelectricity, the emergy flows from upstream rivers (AS) increased. The increases that emergy flows imported from economic systems for resource exploitation also caused increase in PS, so the systemic role of upstream rivers has become more critical then ever. The increased quotient (AS/PS) of upstream rivers is indicative of their more active role in providing ecosystem services. As for the changing role of urban areas in the overall system, the ecosystem service received by the urban area from other system (PS) was decreased due to peri-urbanization. The provision of goods and services from urban areas to agricultural production areas is decreased due to the loss of agricultural land, which resulted in decreased AS. The quotient (AS/PS) of urban area changed from >1 to <1; thus its role has changed from active to reactive.

Table 7 summarizes the aggregate emergy flows of forest ecosystems, riparian wetlands, agricultural production areas, and water resources. Owing to the higher precipitation in 2006, all four ecosystems had higher renewable emergy inflows (*R*) than in 1971. The feedback of emergy flows from economic systems (*F*) tends to increase for riparian wetlands and water resources due to the investment of goods and services into these components. The emergy yields (*Y*) of these components also increased from 1971 to 2006. Conversely, the loss of agricultural production areas in the study region resulted in decreased emergy flows from economic systems (*F*) and the consequent emergy yield (*Y*). The emergy yield ratio (*Y*/*F*) can be seen as an index of the ability of economic investment to generate ecosystem services to the economy; the higher the value, the greater is its ability. The increasing size of wetland areas increased its emergy yield ratio and increased the provision of ecosystem services to human society. Although the role of agricultural production areas diminished (see Table 6), the decrease in emergy inflows from the economic sector (*F*) improved the emergy yield ratio of agricultural production areas. The contribution of ecosystem services of agricultural production areas from inflows of renewable emergy increased. The emergy yield ratio of water resources decreased from 49.85 in 1971 to 5.99 in 2006, which indicates that more emergy flows from the economic system are needed to provide sufficient ecosystem services for society.

Land use and land cover changes in peri-urban areas are often neglected by both rural and urban administrations. As in most western societies, Taiwan has a land use control system intended to regulate the location and intensity of local development. It is worth mentioning that the local land use control in Taiwan is divided into two systems: one to regulate growth in urban districts and another to regulate growth in rural areas. Within urban planned districts, municipal governments exercise land use controls through strict and inflexible zoning ordinances. In rural areas, all land use density is designated as lower than in urban planned districts. However, land owners can choose from a list of permitted uses should they wish to convert their land to another uses. Spatial planning policies in Taiwan have targeted agricultural and hill slope areas outside designated urban planning boundaries for low density development. This has been done ostensibly to maintain the rural character and to protect the natural environment of these areas while still allowing some low density development to occur. However, designating rural areas for non-urban land use may be ineffective for preserving rural character or for protecting the environment. Agricultural lands converted to built-land and remnant agricultural lands are often fragmented into collections of small parcels, which can have adverse impacts the environment through increased traffic congestion and increased infrastructure costs. In rapidly transforming landscapes such as the greater Taipei area, planning for a more environmentally efficient urban agglomeration is an important challenge for urban planning professionals attempting to create a sustainable future. An adequate spatial plan should visualize future landscape changes and model ecosystem responses. The designation of long-term natural and agricultural production areas, combined with policies to encourage increased urban density and limit growth in more rural areas, is urgently needed. Without these long-term and strict enforcements, sprawl is likely to become more wide-spread throughout the country, which would decrease the rural characteristics of peri-urban areas with a resulting loss of ecosystem services.

6. Conclusion

Understanding the dynamics of land cover change in peri-urban areas is critical given that urbanization will continue to be one of the major factors impacting these landscapes in the foreseeable future. The main environmental consequences associated with peri-urban land cover change in the greater Taipei area include the conversion of natural ecosystems, loss of prime agricultural lands and changes in hydrological cycle. The problem of valuing ecosystem services in monetary terms is beyond the scope of this study, but the linkages between biophysical aspects of ecosystem services and the monetary value of benefits derived from ecosystem services are essential for safeguarding these valuable landscapes. This study presents an approach for evaluating ecosystem services that fulfills the systemic and biophysical requirements of an appropriate assessment.

The results of our emergy synthesis and impact matrix analyses indicate that water resources in upstream watersheds, ground water discharge from forest ecosystems, and soil fertility in agricultural areas play the most critical roles in providing ecosystem services in the study region. The major consequence of land cover change during 1971–2006 was the decreased provision of ecosystem services from agricultural production areas. The systemic role of agricultural production areas in providing ecosystem services is becoming less critical.

In addition to providing biophysical evaluation of ecosystem services in Taipei peri-urban areas, this study also reinforces the need for effective spatial plans for controlling urban growth while protecting ecosystem function. In rapidly transforming landscapes such as the greater Taipei area, the spatial plan should envision future landscape change and model ecosystem responses. Otherwise, poor planning and control could cause further urban sprawl and loss of ecosystem services. The current non-urban land use control system for rural areas should have a guiding plan or should be integrated with urban planned district into a single planning system to ensure consistent standards for regulating sprawl, fragmentation, loss of rural character, and environmental degradation.

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