Mapping the Spatial Structure of Urban Ecosystems and Calculating the Value of Trees in Yokohama City

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Abstract

This study attempts to map the spatial structure of urban ecosystems and to value the ecosystem services with GIS. We have practiced a multi-scale approach to map a wide urban area with satellite images for city ecomap, geographic datasets for district ecomap and field survey for block ecomap. These three ecomaps have different ecotope categories and can be used for urban planning, environmental design and community-based environmental conservation activities respectively. Regardless of the scales, the ecomaps provides three functions: inventorying elements of ecosystems, analyzing the spatial structures of ecosystems and valuing ecosystem services such as the fixation and sequestration of carbon dioxide and filtration of atmospheric pollutants etc. Yokohama City, Tsuzuki Ward, the Yokohama Campus of Musashi Institute of Technology and its neighbor residential quarter have been selected as study areas for the three scales respectively. The experimental ecomaps show that this is an effective method to grasp the complex of urban ecosystems spatially and the concept is applicable to other Asian megacities.

Keywords: ecosystems, ecostructure, ecomap, ecosystem services, GIS

1. Introduction

The natural environment surrounding us consists of factors including atmosphere, soil, vegetation and water, etc. These factors construct the complex of urban and regional ecosystems with a variety of environmental elements in different unit sizes and shapes. In Landscape Ecology, the agglomeration of similar environmental elements is called ecotope or patch. The mosaic of ecotopes in a city or a region forms the spatial context of ecosystems, that is, the urban or regional ecostructure, where the prefix “eco-“ indicates the natural environment (Smith, 1992).

Any ecostructure, even a small ecotope, could be understood as an ecosystem if it holds the basic functions of production, consumption, and decomposition. For achieving ecological planning and environmental conservation, it is essential to know what kinds of ecotopes exist, and how the ecostructure is formed, and, as a result, how they affect each other in the urban and regional ecosystems.
Maps are the most suitable for describing such spatial structure of ecosystem. We call a map that visually
describes the ecostructure. For convenience, the conducts of producing the ecomaps is called ecomapping. The concept of ecomap is common with the regional environmental characteristic maps produced with the method of Ecological Planning since 1970s (e.g. Yokohama City, 2001). However, those maps have difficulties to be widely applied because of the paper-based edition in small scale and static representation. With the advance of satellite remote sensing technology, we are able to collect geographical information on ecosystems at higher accuracy and higher frequency than ever. Meanwhile, the wide use of Geographic Information Systems makes analyzing and processing spatial information easier. As a result, ecomaps would be produced more efficiently and would be utilized more effectively compared with the traditional hand-made regional environmental characteristic maps.

This paper aims to map the spatial structure of urban ecosystems with the integration of satellite images and GIS data, and to calculate the environmental value of ecosystems like vegetation and trees in Yokohama City.

2. Method

2.1 The Concept of Ecomap

In Landscape Ecology, ecological landscape of a city or a region is caught by elements, structures, and functions. We are going to apply this concept for ecomapping, too. The problem is to what the spatial detail the complicated ecostructure can be described, or to what extent we have to? Considering the limitation of budget and manpower in any municipality or organization, we propose an idea to map the ecostructure of a large city in three scales, that is, city ecomap, district ecomaps and block ecomap, roughly corresponding to 1:100,000, 1:10,000 and 1:1000 respectively.

A city ecomap shows the ecostructure of the entire city and play a role in supporting urban environmental master plan. The users of the map would be urban planners or urban policy makers of the municipality. The city ecomap is not required to cover the wide municipal area with very detailed field information.

A district ecomap describes the ecostructure of a limited region in a city in detail. It shows the possibility and constraints in developing the natural resources of district and gives the guidelines to urban planners and landscape designers. A district ecomap contains natural, social and environmental conditions of the district in detail.

The block ecomap displays the ecostructure around houses or within the daily life sphere. The elements in block ecomaps concern the factors of living environment in detail. The block ecomap plays a role in promoting community-based environmental planning and conservation activities.

2.2 The Method of Ecomapping

Three functions have be combined into the ecomaps regardless of their scales: 1) inventorying the elements of ecosystems, 2) analyzing spatial structure of ecosystems and 3) valuing environmental services of ecosystems. None of them could be achieved without the support of Geographic Information Systems. In fact, using GIS makes our ecomaps distinguished with the traditional regional environmental characteristic maps.
Ecological and geographic data of regional ecosystems is classified and stored in the geographic database, and the information on ecotopes of ecostructures can be retrieved easily and displayed flexibly. This geographic database is constructed with accuracy correspondent to the specification of ecomaps at city level, district level, and block level respectively. The city ecomap requests high speed and low cost; the district ecomap requests details; and the block ecomap requests simplicity. Mapping the spatial structure of a city or a region is the special advantages of GIS. It is easy to overlay the thematic maps related to various environmental factors in GIS. For ecomapping, however, it is more important to define and to understand the meanings of ecotopes than any overlay operation. The calculation of ecosystem services is advanced applications of geographic databases and ecomaps. The ecosystems including soil, water, and green, etc., for instance, play important roles in the formation of urban and regional climate. It is certain that these ecosystems provide valuable services to our society though their value are not easy to be quantified. Some of the services such as air filtration and carbon dioxide storage have been accounted from the global to the city level (Costanza et al, Bolund et al, 1999, McPerson, Nowak et al, 1997. Costanza et al (1997) categorized 17 groups of such ecosystem services in global. Bolund et al (1999) accounted the ecosystem services of vegetation, soil and water in Stockholm City. American Forest, the oldest non-profit organization for forest conservation in the world, developed a GIS tools called CITYgreen to calculate the value of ecosystem services of trees over the cities in the United States. We are going to apply this tool to Japanese cities in this study.

2.3 The Study Area

2.3.1 Selection of the Study Areas

(1) City level: Yokohama City

Yokohama City is the largest megacity following Tokyo in Japan with 3 millions in population and area 300km$^2$. The coastal region in the eastern part, opened promptly in the modernization of Japan, has developed as a prosperous port in the world. The Tama Hill crosses the western part from north to south, and abundant greens remains here and there, though mostly fragmented by built-up lands. The high economic growth, started in 1950’s, had rapidly increased the population of Tokyo, and had also surged to Yokohama in south outskirts of Tokyo. For a certain period of time, people moved the suburbs of Yokohama City exceeded 100,000 a year. Then, for breaking the sprawl, the municipality has decided one fourth of the city as urbanization restrict zone. Meanwhile, the construction of Kouhoku New Town in the northwestern part with area up to 20km$^2$ was started for absorbing the population in a planned way. Today, Yokohama City is hoisting 7 green nodes and 3 green axes alone the costal line and the Tama Hill on an ecological city plan called "the Green Master Plan", as shown in Fig.1. Our ecomap at the city level could verify the situation of the nature preservation and the maintenance of the green space.
(2) District level: Tsuzuki Ward
We choose Tsuzuki Ward as a sample for making the district ecomap. Tsuzuki Ward was born in 1994 as a new administrative ward in the northwest of Yokohama City, as shown in Fig.1, where, the above-mentioned Kouhoku New Town occupies the most land. By using the abundant geomorphology, vegetation, and water systems of Tama Hill, the Kouhoku New Town practiced ecological city planning in advance of Japanese cities and has created a green network called Green Matrix within the new town area. On the other hand, farmland, forest, and industrial factories coexist in the southern part. Natural land is still decreasing today with the construction of housing and transport infrastructure. The ecomap of Tsuzuki Ward will confirm not only the developed ecosystems in the north, also the remnants of natural land in developing area in the south for the conservation and the expansion of the Green Matrix.

(3) Block Level: the university campus and neighbor residential quarter
We have selected the Yokohama Campus of Musashi Institute of Technology and the nearby low story residential quarter for mapping the ecostructure and evaluate the ecosystem services in block level. The Yokohama Campus owns a large forest on slope, which was a registrated natural forest in Yokohama City. The nearby residential quarter is a typical low story dwelling area in Japan. Mapping the ecostructure and quantifying the ecosystem services in such an organization or a residential quarter would give people who living or working in the site a direct impression on ecosystem services and activate their incentive to local environmental conservation activities.
2.3.2 Flow of Data processing

Fig.2 illustrates the procedures of the operations of ecomapping in this study. Here we briefly introduce steps while leaving the detailed explanation to next sections. We use satellite images for making the city ecomap. Moderate or high-resolution satellite images give a crisp description of the biomass storage over a city with low cost. Satellite images also capture the distributions of water, impervious land surfaces, and radiance in thermal infrared wavelength, which are valuable information for calculating energy balance near the earth surface.

The district ecomap shows the possibility and constraints to implement the "Green Master Plan" of the city in local scale. Ecological and geographic information such as geomorphology, geology, vegetation and land use is the fundamental data at this scale.

The block ecomap describes the texture of land use, the arrangement of buildings, the composition of plants etc within ecotopes classified in the district level. The amount of the carbon sequestration and other ecosystem services such as the removal of atmospheric pollutants is accounted with additional field investigation. As shown in the right of Fig.2, the ecosystem services valuated at the block level will be expanded to the district level and the city level. Therefore, the block ecomap is a sample of the valuation for the district and the city scale.
3. Data Preparation

3.1 ASTER Images for City Ecomap

The images of satellite ASTER were used for capturing the amount of biomass and the spatial distribution of vegetation over Yokohama City. ASTER sensors cover a wide wavelength from the visible to thermal infrared and provide multi-spectral image with the resolution 15m in VNIR, 30m in SWIR and 90m in TIR. We have only used a VNIR images for land cover classification in this study. The granule numbers of images we have used are ASTL1B 0208100134490209145813 and ASTL1B 0208100134580209145964. Both of them were observed on Aug 10, 2000. Fig.3 shows the mosaic of the geo-registered images.

Fig.3 ASTER/VNIR false color image (Red: B3, Green: B2, Blue: B1, 2002/08/10).
3.2 GIS data for District Ecomap

In Landscape Ecology, environmental factors such as geology, geomorphology, soil, climate and water are usually used for making ecological maps. We thought that the influences of factors such as asphalt pavement, shadow of buildings, and human activities of energy consumption are also important in urban area. Therefore, we have chosen geomorphology, geology, vegetation, land use, and land use zoning for ecomapping at this district. We have collected maps or digital datasets from the Urban Planning Bureau of Yokohama City, including Geology and Geomorphology Map (1986, 1:30000, paper map), Preent Vegetation Map (2001, 1:2500, digital), Land Use Zoning (2001, 1:2500, digital) and Land Use Map (1997, 1:2500, digital).

3.3 Block Level

For the sample sites at the block level, the 1:5000 aero photograph taken by Geography Survey Institute on Sep 2, 2000 was purchased and scanned with 600 dpi into digital files. We digitized the canopies of each tree and the boundaries of vegetation colonies into a canopy layer, and boundaries of buildings, roads and tennis courts, etc into an impervious layer using the geo-registrated digital aero photograph. The attributes of the extracted trees, buildings and roads were surveyed in field. As for the attribute items of trees, they are species, height, diameter, health condition and growth condition. For buildings, they are stories and materials.

4. Data Analysis

4.1 The City Ecomap

We conducted supervised classification to the ASTER/VNIR image with maximum likelihood method. The defined categories includes: forest/street trees, grassland, farmland or bare soil, built-up, new built-up, paddy field and riparian as well as water. 17 spots were randomly selected for verifying the classification. As a result, 14 spots were correct and 3 spots were misclassified because of the similarity of spectral reflectance between brick pavement and bare soil or the mixture of small patches. This misclassification at this extent will not affect the application at city scale. For our purpose, the classified categories was then integrated into the following 5 groups as the ecotope categories at city level: forest/street trees-> urban forest, grass->open space, paddy field and riparian->water, farmland and soil-> cropland, built-up->impervious area, new build-up -> impervious area. The last ecomap of Yokohama City derived by remote sensing images is shown in Fig.4.
4.2 The District Ecomap

We defined 20 ecotopes for the ecomap at district level as shown in Table 1. Ecotope 1: river, for example, is considered as such a landscape where streams flow through the riverbed and vegetation grows in riparian on the sediment soil. Then polygons with attributes of "river" in land use map, "riparian vegetation" in the vegetation map and "sediment soil" in the geology map are grouped into this ecotope.

For Ecotope 2: low story buildings, it is considered that the height of buildings in urban area, which affect the flow of wind and the shadow of buildings, is an important factor to the growth of plants. So the low story residential area in land use map and the exclusive residential area I and II in land use zoning map share the same environmental condition. Houses in this ecotope are lower than three stories with plenty of sunlight and garden vegetation.
Table 1 The definition of ecotopes in district level.

<table>
<thead>
<tr>
<th>Ecotope#</th>
<th>Ecotope Name</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rivers</td>
<td>Area of riverbed and riparian covered with vegetation in the sediment soil</td>
</tr>
<tr>
<td>2</td>
<td>Low story buildings</td>
<td>Residential buildings lower than 3 stories with good sunshine</td>
</tr>
<tr>
<td>3</td>
<td>High story buildings</td>
<td>Buildings higher than three stories</td>
</tr>
<tr>
<td>4</td>
<td>Roads</td>
<td>Paved surface with asphalts and concrete</td>
</tr>
<tr>
<td>5</td>
<td>Street trees</td>
<td>Trees that stand along roads</td>
</tr>
<tr>
<td>6</td>
<td>Industrial areas</td>
<td>Industrial land use area</td>
</tr>
<tr>
<td>7</td>
<td>Open space 1</td>
<td>Open spaces paved with asphalts or tiles</td>
</tr>
<tr>
<td>8</td>
<td>Open space 2</td>
<td>Open spaces covered with bare soils</td>
</tr>
<tr>
<td>9</td>
<td>Open space 3</td>
<td>Open spaces covered with muddy soils</td>
</tr>
<tr>
<td>10</td>
<td>Open space 4</td>
<td>Open spaces covered with volcanic ashes</td>
</tr>
<tr>
<td>11</td>
<td>Grasslands</td>
<td>Area that covered with grass or shrub</td>
</tr>
<tr>
<td>12</td>
<td>Forests</td>
<td>Forests composed of deciduous, evergreen trees and bamboos</td>
</tr>
<tr>
<td>13</td>
<td>Trees on slopes</td>
<td>Trees that live on slopes of hills</td>
</tr>
<tr>
<td>14</td>
<td>Trees in residential</td>
<td>Trees that live in residential areas</td>
</tr>
<tr>
<td>15</td>
<td>Croplands</td>
<td>Area composed of fields and orchards</td>
</tr>
<tr>
<td>16</td>
<td>Rice fields</td>
<td>Area composed of paddy fields that filled with water during spring to summer</td>
</tr>
<tr>
<td>17</td>
<td>Developing area 1</td>
<td>Developing area with vegetation</td>
</tr>
<tr>
<td>18</td>
<td>Developing area 2</td>
<td>Developing area with no vegetation</td>
</tr>
<tr>
<td>19</td>
<td>Parks 1</td>
<td>Public spaces with vegetation</td>
</tr>
<tr>
<td>20</td>
<td>Parks 2</td>
<td>Public spaces with no vegetation</td>
</tr>
</tbody>
</table>

Four thematic maps were overlaid and the polygons were integrated into 20 ecotopes as defined in Table 1. To eliminate sliver polygons, we converted the overlaid polygon map into 10m by 10m grid. The last ecomap of Tsuzuki Ward is shown in Fig.5.
4.3 Valuation of the Ecosystem Services

As we have mentioned in section 3.3, the canopies of trees, the land use categories and impervious surfaces were traced on a large-scale aero photograph at block level. The attributes of trees and buildings surveyed in field were attached to the traced geographic features. Fig.6 shows the obtained ecomap at block level with such detailed ecological and geographical information.
Then we run the ArcView extension CITYgreen developed by American Forest to valuing the services of trees and green spaces (American Forest, 2002). We only applied the functions of the fixation of carbon, the sequestration of carbon per year and the filtration of atmospheric pollutants though the software can calculate the services of trees on runoff and energy conservation. The parameters such as average concentration of atmospheric pollutants and some species of trees need to be localized to match the Japanese case. The last two columns in Table 2 show the calculated services at the two sample sites. Table 2 also illustrates the application of CITYgreen to Yokohama City and Tsuzuki Ward, where the attribute of trees in valuation were given with the average at the sample sites.

<table>
<thead>
<tr>
<th>Table 2 The estimated ecosystem services in Yokohama City.</th>
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<tbody>
<tr>
<td>Area (ha)</td>
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<td>------------------</td>
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<tr>
<td></td>
</tr>
<tr>
<td>Trees (%)</td>
</tr>
<tr>
<td>Impervious (%)</td>
</tr>
<tr>
<td>Open Space (%)</td>
</tr>
<tr>
<td>Water (%)</td>
</tr>
<tr>
<td>Carbon Storage (t)</td>
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<tr>
<td>Carbon Sequestration (t/yr)</td>
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<tr>
<td>Air Pollution Removal Annually (t/yr)</td>
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<tr>
<td>Air Quality Value Annually ($)</td>
</tr>
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</table>
5. Discussions

5.1 Ecostructure in Yokohama City

Green ecotopes (forest, open space, paddy field, and farmland) occupies about one third of Yokohama City. As the city ecomap of Fig.4 shown, impervious land cover extends in the eastern coast area, and the green spaces mostly appear in inland. Green spaces in the eastern area scatter within impervious lands. Remember that the "Green Master Plan" in Fig.1 illustrated the vision of 3 green axes along coastal line and Tama Hills, a considerable greening and planting would be required to develop the costal green belt. As for the 7 green nodes, its realization would not be easy, too because the remnants of natural land are largely surrounded by a mass of impervious land covers. On the other hand, the green ecotopes in the northern part look like continuing from the west to east along Tsurumi River, though there isn't any visions appeared in the Green Master Plan. As our opinion, this could be a potential green axis that improves the green network of the city better.

5.2 Ecomap in Tsuzuki Ward

Land use conditions in Tsuzuki Ward are characterized with three zones: New Town Zone in northern area, agriculture zone in middle area and southern industrial zone along Tsurumi River bank. The mixed land use in the ward exists comparatively few. The green space is abundant about 35.9%, lightly exceeding the average of 31.1% of the entire Yokohama City. With the ecomap in Fig.5, however, we find that the natural remnants and the designed open spaces are isolated each other. Linking the natural land with the present green matrix would be an issue for the ongoing development in south.

5.3 Ecosystem Services in Yokohama City

At the block level, Yokohama Campus has area 29.4ha with 30% or more coverage of trees. The carbon storage by trees in this site is about 799 tons and the sequestration is about 18 tons per year. Moreover, the removal of atmospheric pollutants including Ozone, NO$_2$, SO$_2$, CO and suspend particular matters is about 1 tons. The ecosystem services account up to $5,454 per year totally. Obviously, the forest on the southern slope has achieved most of this ecosystem services.

On the other hand, only 6% tree canopies cover the 9ha residential quarter, and most of the land is paved with concrete and asphalt for parking lots. It is hard to find large trees along the street, though there are more than 30 species living within private gardens. Trees standing in the residential quarter are too young to provide ecosystem services. The ecosystem services in the residential quarter account only $428 per year.

Nevertheless, the total area of ecotope as low story residential quarter exceeds up to 1220ha in Tsuzuki Ward. Then the total ecosystems services within the ward by trees in low story residential quarters will be $58,000 per year. Moreover, as shown in Table.2, green spaces and pervious area accounts up to 45% in
Tsuzuki Ward. It services 32,700 tons of carbon storage and 254 tons carbon sequestration per year. The removal of air pollutants is about 32 tons. The total ecosystem services of trees in Tsuzuki Ward account to about $167,000, one third of which is contributed by low story residential quarters.

As for the entire city of Yokohama City, pervious area raises up to 31% in which public parks only share 9%. The amount of the carbon storage is about 910,000 tons, and the sequestration per year is about 7,100 tons. The removal of air pollution is up to 894 tons, corresponding to $4,670,000. The low story residential area in Yokohama City is 13,685ha, and then the ecosystem services of trees in this type of ecotopes becomes about $651,000 per year.

6. Conclusions

This study attempted to map the ecostructure and to value the ecosystem services with the concept of ecomap and the support of GIS. We divided a wide city area into the city level, the district level and the block level and practiced ecomaps in this multi-scale approach. The experiment we have done shows that three ecomaps corresponding to three scales have different contents in detail and can serve for different users and purposes. The city ecomap produced by satellite images provides the ecostructure of the whole city with 5 ecotope categories. The district ecomap overlaid five basic ecosystem factors provides detailed ecostructure with 20 ecotope categories. The block ecomap, outlined the landscape elements in the most of detail with a large scale aero photograph, gives the ecological information for trees and their environmental services such as the storage and the sequestration of carbon and the removal of atmospheric pollutants. The calculations of the ecosystem services can be extend to the district level and the city level. It shows that CITYgreen developed in the United States is applicable to Japanese cities. And the practice of mapping the ecostructure and calculating the ecosystem services quantitatively could be a good approach to promoting the public consciousness on environmental conservation and the community-based amenity making activities.

For the spread of this approach in urban renewal and environmental conservation practice, the following issues need to be explored furthermore.

The first is to verify the integrity of ecotope categories among three ecomaps. We defined 5 ecotopes at city ecomap, 20 ecotopes at district ecomap and the detailed canopy at block ecomap respectively. The larger the map scale, the homogeneity decreases and the heterogeneity increases. There must be some physical relationships in the composition of ecotopes among the three scales. These relationships are important for the theoretic integrity and the convenience of practice. For example, the relationship of the amount of vegetations measured by satellite images at city level should be comparable with the district level and the block.

The second is the localization of CITYgreen. We have only applied the CITYgreen tool with the default parameter settings of the software, which have been originally designed to match with the American situations. For example, to use the growth simulation model of trees for the prediction of carbon storage, parameters such as the composition, the growth rate and morality of trees must be surveyed at local. Meanwhile, the ecosystem services on the removal of atmospheric pollutants must consider the local climate and concentration, too.
The third is the extension of ecosystem services to be valued. We have only valued services on storage and sequestration of carbon dioxide and the air filtration by trees and open space. There have more ecosystem services by trees and more services by other ecosystems like water. Even the energy conservation functions of trees, which have been installed in CITYgreen, haven’t been practiced yet. Our research for mapping the ecostructure and valuing the ecosystem services is just in its entrance, we are sure that the concept and the method are applicable to all the megacities in Asia as well as the world.

 Acknowledge

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Reference