An analysis on urban expansion using remote sensing data – case of Harbin, China–

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Spatial expansion of a city is one of critical clues to comprehend urban activities for planning social infrastructures. The temporal evolution of urban area and population density is the two most direct characterizations to demonstrate the expansion of the city. In this study, taking the case of Harbin, we intend to understand how a city has been developed and expanded in past decades by examining spatiotemporal trends of population in a city using remote sensing data. In detail, remote sensing data archives of Landsat data from 1984 to 2014 with intervals of five years are analyzed to capture the spatial characteristic evolution of Harbin in connection with demographic dynamics. For the comprehension of the urban expansion, we attempt to develop a primitive urban model for future estimate of urban expansion under data limitation that will be applied to the case of Harbin, China.

Key Words : *urban expansion, population distribution, spatiotemporal trend, primitive urban model*

1. INTRODUCTION

In a rapidly unbanizing world, urbanization in China is accerlated on an unprecedented scale; cities change day by day. Spatial extent and density of urban activites are key factors affecting environmental load, energy consumption, as well as quality of life of urban residents. Currently about half of population in the world reside in urban areas, and this number is projected to be almost 70% by 2030[1)]. This increase is expected to be concentrated in developing countries mainly where urban infrastructure is likely to be not sufficient, which causes bottle-necks in urban activities and make them more vulnerable against natural dissasters as well.

For urban planning and policy formation for developing cities to be harmonized with the global environment, future perspectives on urban expansion is essential information. In developed countires, some socio-economic models have been applied to estimate the impact of population change and infrastructure construction on urban expansion and its consequences. In developing countries, however, some detailed statistical data which is required for the application of the models does not always exist. Meanwhile, recent remote sensing data archives make it possible to capture the past trend of urban land-use changes, which could be a useful information for the projection of future urban expansion.

Various studies have estimated the long-term spatial distribution of population over the globe[2-5)]. These estimations have been based on a grid system in which the global land area is divided into a mesh, and the population distribution is estimated by downscaling the given regional` or national urban populations. However, there are no established methods for this downscaling, and each study assumed an ad-hoc allocation function for the population. For instance, Grübler et al. tried to downscale the future regional population consistent with the SRES scenario (Special Report on Emissions Scenarios from the IPCC) using a 0.5° × 0.5° global land grid system. In this study, the increasing rate of grid population rises as the population of the previous period increases. It reflects the population concentration in large cities, but these projections do not necessarily reproduce the experimentally well-known city-size distribution, the rank-size rule or Zipf's law.

Kii and Doi[6] estimated long term urban population for about 50,000 cities by 2100 under SRES scenarios using a random growth network model, but their spatial extent were not considered.

In this study, we attempt to develop a primitive urban model to estimate future urban expansion under data limitation and apply it to the case of Harbin, China, where rapid population growth has been observed in past decades.

2. URBAN MODEL

The traditional urban economic model successed in explaining the urban extent based on its population and transport condition[7]. Recent urban models[8-12] take various and more detail conditions into account, therefore they require huge input data for analysis of a city. However many developing countries do not survey or publish enough statistics required for the models. For the analysis of urban space in developing countries where the explosion of urban population is expected, a more primitive model which requires less data may be needed.

In this study, we develop a model based on Alonzo adding the component of building developer to consider the floor space, because the spatial density of urban activitiy is one of the most prominent factors affecting the urban efficiency.

(1) Assumptions

A urban system exists in continuous space with one central business district, i.e. we assume monocentric city. Its economy consists of a fix number of households, residence developer, and absentee landowner who maximize their utility or profit. The behaviors of these agents are formulated as follows.

(2) Household

Household maximize their utility under budget and time constraints. Assuming the utility function as Cobb-Douglas, this behavior is expressed as follows.

$$(\max) \qquad u = z^{\alpha z} l^{\alpha l} s^{\alpha s} \tag{1}$$

$$s.t. \quad I = w \cdot T_W = p \cdot z + r_H(x) \cdot l + c \cdot x \tag{2}$$

$$T_A = T_W + s + \tau \cdot x \tag{3}$$

Where, z, l, s are consumption of composit goods, floor consumption for residence, and disposable time respectively. αz, αl, αs are paremters ($\alpha z+\alpha l+\alpha s=1$), w is wage rate, T_w is hours spend for work, T_A is total hours available to work, travel and dispose. p, $r_H(x)$, c, τ are price of composit goods, floor rent at location x, travel cost per unit distance, and travel time per unit distance. Solving this problem, the Marshallian consumder demands take the following form.

$$z = \alpha_z \frac{I_x}{p} \tag{4}$$

$$l = \alpha_l \frac{I_x}{r_H} \tag{5}$$

$$s = \alpha_s \frac{I_x}{w} \tag{6}$$

where,

$$I_x = w \cdot T_A - (w\tau + c) \cdot x \tag{7}$$

substituting the demands in equation (1) by equations (4)-(6), the indirect utility function is obtained as follows.

$$\mathrm{V} = \alpha_0 \frac{I_x}{p^{\alpha z} r_H{}^{\alpha l} w^{\alpha s}} \tag{8}$$

where

$$\alpha_0 = \alpha_z{}^{\alpha z} \alpha_l{}^{\alpha l} \alpha_s{}^{\alpha s} \tag{9}$$

soloving equation (8) by r_H, the household's bid rent at location x is given as follows.

$$r_H = \left(\frac{\alpha_0}{p^{\alpha z} w^{\alpha s}} \frac{I_x}{V} \right)^{\frac{1}{\alpha l}} \tag{10}$$

substituting r_H in equation (5) by equation (10), the consumption level of floor area is expressed as follows.

$$l = \frac{\alpha_A}{\alpha_0{}^{1/\alpha l}} \left(p^{\alpha z} w^{\alpha s} V \right)^{\frac{1}{\alpha l}} \cdot I_x{}^{\frac{l-1}{\alpha l}} \tag{11}$$

(3) Developer

Using a given unit land, developer produces residential floor A_f by using capital K.

$$A_f = \gamma_0 K^{\gamma} \tag{12}$$

γ_0 and γ are paremters where $0 < \gamma < 1$. Under the condition of floor rent is r_H, the profit of developer is given as follows.

$$\prod = r_H \cdot A_f + \kappa \cdot K - r_G \cdot 1 \tag{13}$$

where, κ is capital price and r_G is land rent. Capital input which maximize profit is given as follows.

$$K=\left(\frac{r_H\cdot\gamma_0\cdot\gamma}{\kappa}\right)^{\frac{1}{1-\gamma}} \tag{14}$$

substitute equation (14) into equation (12), supply is given as follows.

$$A_f=\gamma_1\cdot r_H{}^{\frac{\gamma}{1-\gamma}} \tag{15}$$

where,

$$\gamma_1=\gamma_0{}^{\frac{1}{1-\gamma}}\cdot(\gamma/\kappa)^{\frac{\gamma}{1-\gamma}} \tag{16}$$

substituting equations (14) and (15) into equation (13),

$$\Pi=\frac{1-\gamma}{\gamma}\cdot\left(\frac{\gamma_0}{\kappa^{\gamma}}\cdot\gamma\cdot r_H\right)^{\frac{1}{1-\gamma}}-r_G \tag{17}$$

Zero profit condition derives bid land rent of developer as follows.

$$r_G=\frac{1-\gamma}{\gamma}\cdot\left(\frac{\gamma_0}{\kappa^{\gamma}}\cdot\gamma\cdot r_H\right)^{\frac{1}{1-\gamma}} \tag{18}$$

(4) Equilibrium

The absentee landowners provide their land developers if the land rent exceeds fixed rent r_A for agricultural land use, i.e. $r_G>r_A$. To satisfy this condition, floor lent has to meet following inequality.

$$r_H>\frac{\kappa^{\gamma}}{\gamma_0\cdot\gamma}\cdot\left(\frac{\gamma}{1-\gamma}\cdot r_A\right)^{1-\gamma} \tag{19}$$

Using equations (7), (10) and (19), the radius of urban area x_A is given as follows.

$$x=\frac{1}{c_t}\left[w\cdot T_A-\frac{p^{\alpha z}\cdot w^{\alpha s}\cdot V}{\alpha_0}\left\{\frac{\kappa^{\gamma}}{\gamma_0\cdot\gamma}\cdot\left(\frac{\gamma}{1-\gamma}\cdot r_A\right)^{1-\gamma}\right\}^{\alpha l}\right] \tag{20}$$

where,

$$c_t=(w\tau+c) \tag{21}$$

This means higher transport cost or higher agro land rent derives small spatial extent of the city.

Using equations (5) and (15), household density is derived as follows.

$$n=\frac{A_f}{l}=\frac{\gamma_1}{\alpha_l I_x}\cdot r_H{}^{\frac{\gamma}{1-\gamma}} \tag{22}$$

$$=\frac{\gamma_1}{\alpha_l}\left(\frac{\alpha_0}{p^{\alpha z}\cdot w^{\alpha s}\cdot V}\right)^{\frac{1}{\alpha_A(1-\gamma)}} I_x{}^{\frac{1}{\alpha_A(1-\gamma)}-1}$$

$$=\beta_0\frac{I_x{}^{\beta_1-1}}{V^{\beta_1}}$$

where,

$$\beta_0=\frac{\gamma_1}{\alpha_l}\left(\frac{\alpha_0}{p^{\alpha z}\cdot w^{\alpha s}}\right)^{\frac{1}{\alpha_A(1-\gamma)}} \tag{23}$$

$$\beta_1=\frac{1}{\alpha_A(1-\gamma)} \tag{24}$$

Here, the city is assumed to have one central business district (CBD) and have circular shape. A area locates at x distant from CBD with central angle $d\theta$ is given as follows.

$$dA=xdxd\theta \tag{25}$$

The total number of households is given as follows.

$$N=\int_0^{x_A}\int_0^{2\pi}\beta_0\frac{I_x{}^{\beta_1-1}}{V^{\beta_1}}xdxd\theta \tag{26}$$

$$=\frac{2\pi\beta_0}{V^{\beta_1}}\int_0^{x_A}I_x{}^{\beta_1-1}xdx$$

$$=\frac{2\pi\beta_0}{V^{\beta_1}}\cdot\frac{I_A{}^{\beta_1+1}-\{I_A-c_t\cdot x_A\}^{\beta_1}(I_A+c_t\cdot\beta_1\cdot x_A)}{c_t{}^2\cdot\beta_1\cdot(\beta_1+1)}$$

The derivation of N over V is given as follows.

$$\frac{\partial N}{\partial V}=-\frac{\beta_1 N}{V}+\frac{2\pi\beta_0}{V^{\beta_1}}\cdot\frac{\beta_1\cdot c_t{}^2\cdot\{I_A-c_t\cdot x_A\}^{\beta_1-1}\cdot x_A\cdot(\beta_1-1)}{c_t{}^2\cdot\beta_1\cdot(\beta_1+1)}\cdot\frac{\partial x_A}{\partial V}$$

Here, $0<\alpha_A<1$ and $0<\gamma<1$, therefore, $\beta_1>1$. In addition, equation (20) indicates $\partial x_A/\partial V<0$, therefore $\partial N/\partial V<0$. If V=0 then N=∞. Solving $x_A=0$ using equation (20), following utility level V_0 is obtained.

$$V_0=\frac{\alpha_0\cdot w\cdot T_A}{p^{\alpha z}\cdot w^{\alpha s}}\left[\frac{\gamma_0\cdot\gamma}{\kappa_{\gamma}}\left(\frac{1-\gamma}{\gamma}\cdot\frac{1}{r_A}\right)^{1-\gamma}\right]^{\alpha l} \tag{27}$$

This means the utility level which satisfies given total urban household is unique. Once utility level is determined, urban extent can be calculated using equation (20).

3. DATA

(1) Population data

To know China's urban population, it is necessary to clarify the composition of China's urban system and the spatial boundaries of urban areas. China's urban system is composed of four levels: cities at municipality level, cities at prefecture level, cities at county level, and towns[13)]. However as the Chinese government had modified the designation of cities and towns and the standards for rural-urban classification many times, we can not evaluate the index of population data under different caliber under the background of differed time periods .

Furthermore the information openness of Chinese cities is relatively low, and we could not precisely grasp the exact definition of the population and the area of cities that are defined by the Chinese government.

We take the population data of Harbin from the United Nations, Department of Economic and Social Affairs where the proportion of urban (and rural) population from the most recently available census or official population estimate, even though it inherits the change of city definition in the Chinese official statistics[15].

(2) Land cover data

The land cover maps of Harbin used in this paper were derived from remote sensing (i.e.,landsat TM images) data archives with a spatial resolution of 30m × 30m. The selection criteria of the seven datasets from 1984 to 2014 in intervals of five years were the same areas region with less than 20% cloud cover[14].

4. ANALYSIS

The Landsat images were pro-processed using the Win32 version of MultiSpec[16].

We classified the land use based on the maximum likelihood method under supervised learning using all of the spectral bands. Selection of the training sample is based on visual observation of natural color composit bands (Fig.1 left). Here, we assume that the land use is classified into 'Urban', 'Water', and 'Cropland and others', the result for 2014 land use is shown in the Fig.1 right.

Table.1 Accuracy of each projec

	Reference Accuracy (%)			Reliability Accuracy (%)		
year	urban	water	cropland and others	urban	water	cropland and others
1984	95.0	99.5	96.4	91.5	78.3	98.7
1989	94.4	99.8	95.4	79.2	94.0	99.0
1994	96.0	98.2	95.9	79.2	80.3	99.5
1999	96.4	98.7	98.7	97.5	77.3	99.1
2004	96.1	98.9	96.8	95.4	99.6	97.3
2009	93.1	99.0	96.8	94.6	98.3	96.1
2014	93.2	99.2	98.4	96.9	99.2	96.1

The accuracy of each project also can be checked after finishing classifying the training samples, the result chart is shown in Table.1. This result indicates that the reliability for urban land use classification is relatively low in 1989 and 1994 compare to the other period.

The Urban Development Intensity (UDI), was defined as the proportion of built-up areas in each 1 km × 1 km grid based on the 30 m × 30 m urban land covermaps[17]. We classified the UDI of urban land covermaps into five zones based on Zhou's definition. The zones are rural [UDI $\leq$ 0.05], exurban [0.05 < UDI$\leq$ 0.25], suburban [0.25 < UDI $\leq$ 0.5], urban [0.5 < UDI $\leq$ 0.75], and urban core [0.75 < UDI $\leq$ 1]. The classification results of each year are shown in Fig.2.

Based on the result, we extract the Halbin metropolitan region as a maximum agglomeration of continuous build up area. Here, we assume "urban core", "urban", and "suburban" are the class of build up land use (Fig.3).

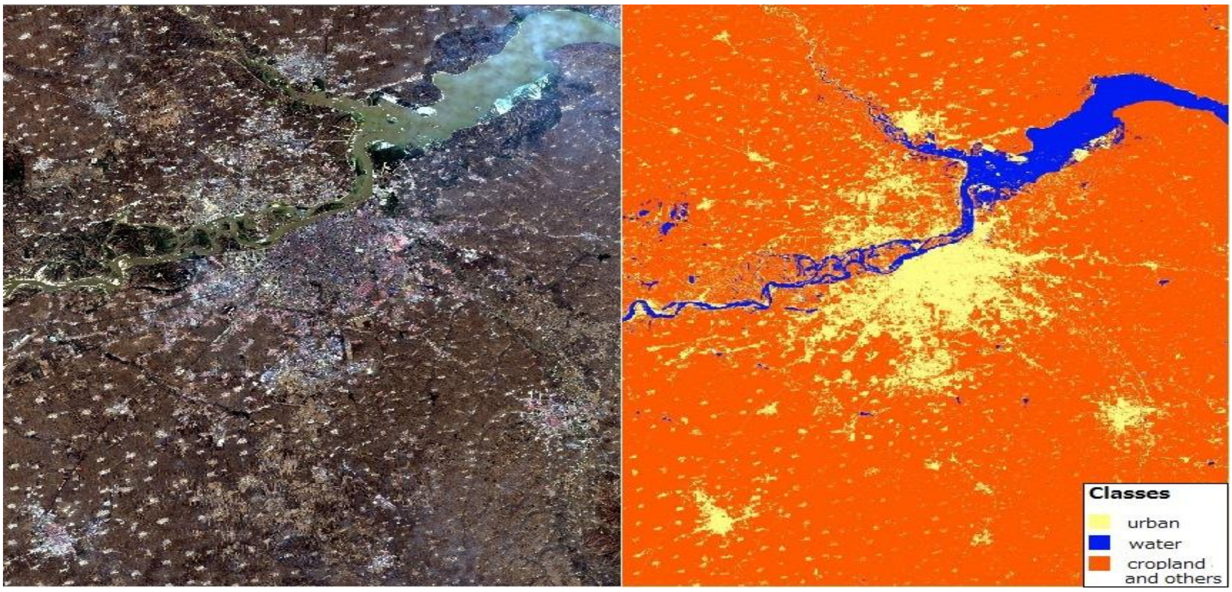

Fig.1 Natural color composit of landsat data (left) and estimated land use classification (right) in 2014.

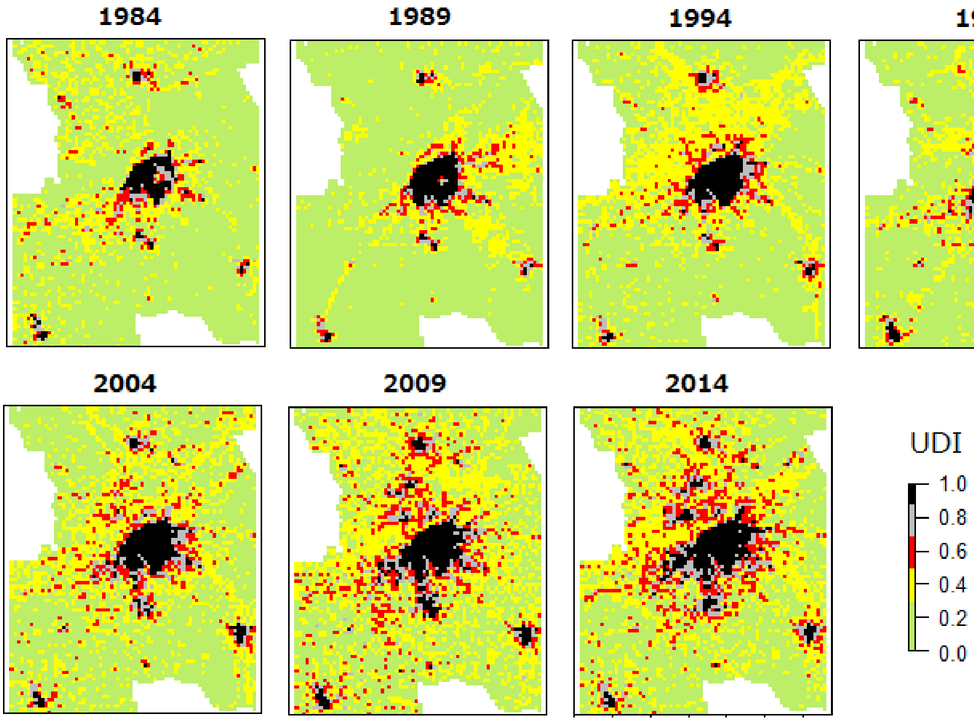

Fig.2 the landcover images of Harbin with different urban development intensity (UDI) obtained by the means of Language R ([UDI ≤ 0.05], exurban [0.05 < UDI≤ 0.25], suburban [0.25 < UDI ≤ 0.5], urban [0.5 < UDI ≤ 0.75], urban core [0.75 < UDI ≤ 1])

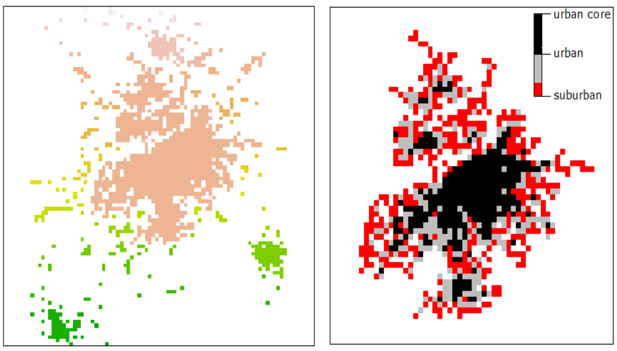

Fig.3 Extract of urban agglomeration (left) and UDI class of Halbin metropolitan region in 2014

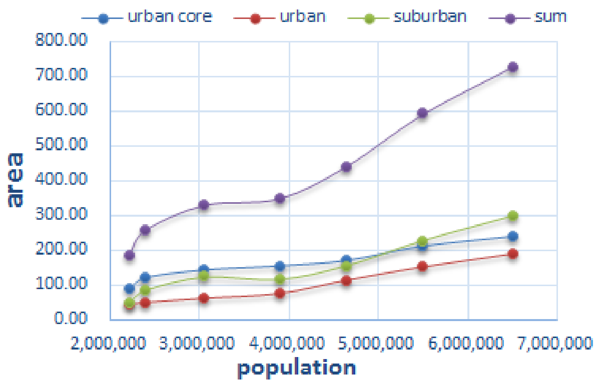

Fig.4 Population and urban area of Harbin from 1984 to 2014

Fig.4 shows the urban evolution of Harbin in terms of its population and urban land use. Both of the population and the total urban area in 2014 are more than three times of those in 1984.

The increase of urban area over the population increase seems to change its mode after 2004, especially expansion of suburban area looks speed up during past decade. It seems due to both of the expansion of build up area and merging surrounding towns into the metropol-itan area.

5. DISCUSSION

Some studies indicate that the urban area varying sublinearly with its population based on cross section analysis[18,19]. However, the urban evolution of Harbin analyzed above indicates superlinearity of builtup area with population. This might be caused due to the change of conditions of urban activities during this period.

Fig.2 indicates that the Halbin metropolitan region had expand its build up area by changing land use before 2004, while it seems to have grown by merging adjacent towns into the metropolitan area. This might be caused due to the improvement of transport conditions; development of transport infrastrucutes, enhancement of public transport services, and increase of car ownership. As shown in equation (20) in chapter 2, the urban area increases as time and cost for travel decrease even though the population does not change.

Notably, via the landuse-transportation model taken account in the UDI, the investigation on urban expansion can be futher analyzed. Linkage between the model in chapter 2 and observation in chapter 4 will be reported at the conference.

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