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Analysis on global urban expansion and its sensitivity to the transportation cost variation

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Abstract:

Urban expansion is considered to bring a substantial impact on the environment including biodiversity and climate change. In this study, we develop an urban spatial model incorporating the housing sector, and apply it to about 3,600 cities all over the world. This model is based on the monocentric-city model by Alonso, but it separates the land market and the floor market. Using the global data of urbanized area, we start with inversely estimating transportation costs for each city. Then, setting a socio-economic scenario over a long-term period, we forecast urban expansion in conjunction with utility of local residents by 2050. We particularly examine the sensitivity of urban expansion to housing productivity improvement and transportation cost reduction. As a result, we found that population growth has a substantial impact on urban expansion, in which, while housing productivity improvement would restrain urban expansion, transportation cost reduction would overwhelmingly accelerate the expansion.

Keywords: Global urban land use; Urban economic model; Urban planning; Climate change; Transportation; Housing;

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1. Introduction

Global-scale projections of urban land-use changes and their impacts on GHG emissions are required by climate policy arena. The IPCC fifth assessment report indicated the relationship between urban forms and GHG emissions as; urban forms significantly affect GHG emissions; key urban-form-related drivers of energy and GHG emission growth are density, land use mix, connectivity, and accessibility; existing climate action plans in cities bring uncertain impacts on urban forms (Seto et al., 2014). Currently, 54% of global population lives in urban areas (UN DESA, 2014) and more than 70% of global CO2 emissions are attributed to urban areas (Marcotullio et al, 2013; Grubler et al, 2012). The share of urban population is expected to be around 70% in 2050, and mitigation actions are therefore inevitable in urban areas. Various studies indicated that vehicle travel distance and its energy use are elastic to urban forms that consist of density and land use (Ewing and Cervero, 2010; Salon et al., 2012).

There are several studies attempting to estimate the spatial distribution of urban population and land use globally (Grübler et al., 2007; Gaffin et al., 2004; Asadoorian, 2008; Seto et al., 2012) which includes distribution not only of intra-urban population but also of inter-urban population. However they employ ad-hoc rule-based simulators or Monte Carlo simulation techniques, and these approaches do not incorporate transportation factors which are considered the essential drivers of urban formation in locally developed urban models represented by Land-Use Transport Integrated (LUTI) models.

Recent development of various global datasets including population (Balk and Yetman, 2004; Balk et al., 2004), land use (Bartholome and Belward, 2005; Elvidge et al., 2007; Schneider et al., 2009), nighttime lights (Elvidge, 2001), and transport networks (Danko, 1992; OpenStreetMap, 2015) can be cue for the development of a LUTI model applicable to global estimation of urban form changes. Angel et al. (2011a, 2011b) developed a global-city database, which contains population and urbanized area of 3646 cities with populations of more than 100,000 in 2000. Using this dataset, they made regression analysis to estimate areas of urban land cover at a national level, using independent variables of population, income, agricultural land, gasoline price, and share of informal settlements. They successfully found the macro-scale relationship between those indicators and urbanized areas.

Using their global-city database, the relationship between population and urbanized area and the relationship between GDP per capita and population density are derived as shown in Figure 1. It is expectably that, the larger population, the larger urbanized area, but the variation of the relationship becomes larger among larger cities. Moreover, higher per capita GDP brings lower population density, although the variation of the relationship is also quite large. These may suggest the importance of local factors of land-use transport development to be considered in estimating urban forms in addition to these simple global indicators.

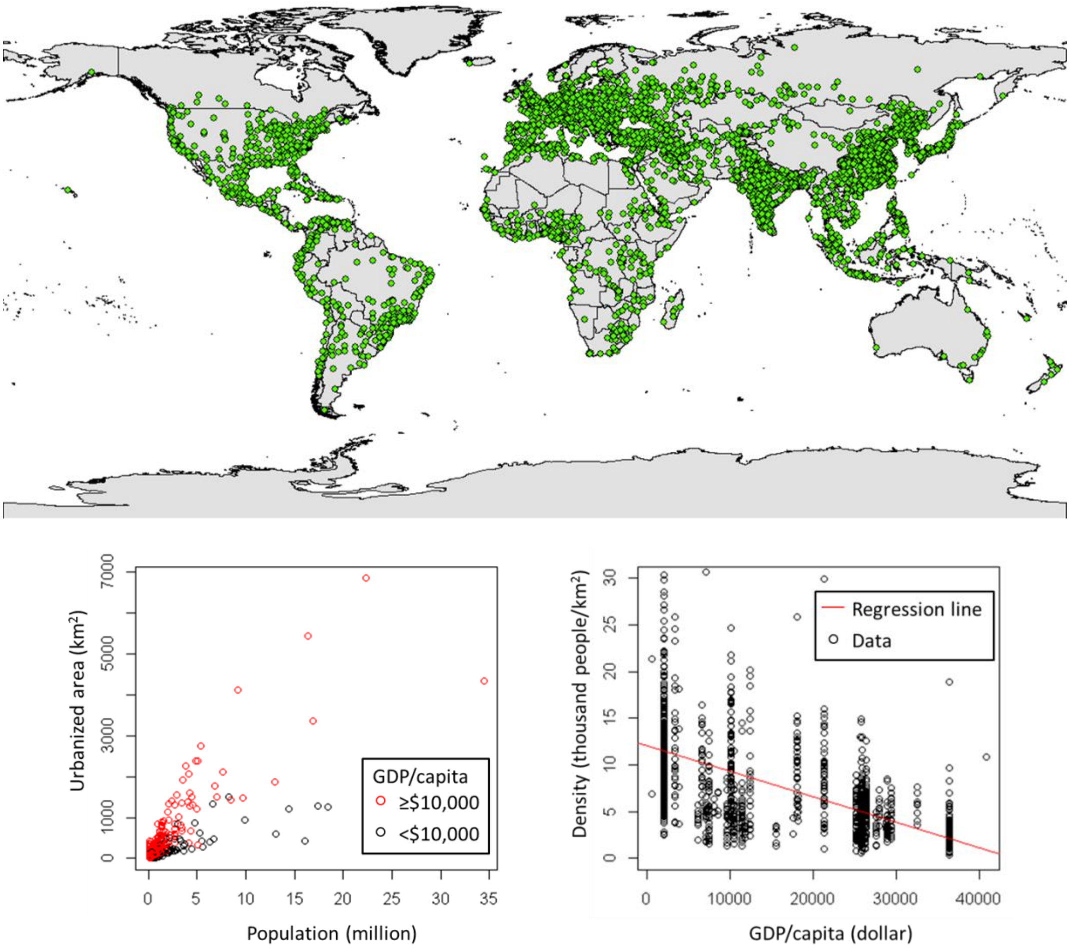

Fig. 1 Location of cities (Top), population vs city area (bottom left), and GDP/capita vs population density (bottom right)

This study aims to globally estimate long-term changes in urbanized area by 2050 and analyze the sensitivity to local cost of transport and housing productivity. We utilize the classic urban economic model to analyze the global impact of the local factors on urban forms by estimating the utility of local residents which is an important index for policy evaluation. The urban model and data used for it are explained in Chapter 2 and the Chapter 3 respectively. Chapter 4 and Chapter 5 respectively show analytical results of the impacts of global and local factors on urbanized areas and projections of changes in urbanized areas and its sensitivity to transport and housing cost.

2. Urban Economic Model

The classic monocentric-city model by Alonso (1964) is expanded to separate the land market and the floor market by introducing developer as an economic entity in addition to household and land owner. This separation allows the impact analysis of productivity of housing construction on urbanized area. Households are assumed to be homogeneous; they work at a single Central Business District (CBD) and earn same income. The city is developed on uniform space where travel cost per distance is indifferent. The symmetric property of assumed space leads a circular urban form which centers CBD. Hereafter, household and developer behaviors and market clearance conditions are formulated.

Household

All households work at CBD and earn income I. They decide consumption of composite goods z and floor for resident l to maximize their utility u. Travel cost per distance is denoted as c, then commuting cost of a household who resides at x distant from CBD is $c \cdot x$ which is spent from income. Assuming the Cobb-Douglas utility function, the utility maximization problem is formulated as follows.

$$\max\left(u = z^{\alpha_z} \cdot l^{\alpha_l}\right) \tag{1}$$

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

α_z and α_l are preference parameters for composite goods and residential floor respectively, where $\alpha_z + \alpha_l = 1$. p is price of composite goods, and r_H is floor rent. Solving this problem, demand for composite goods and floor is derived as follows.

$$z = \alpha_z \frac{I - c \cdot x}{p} \tag{3}$$

$$l = \alpha_l \frac{I - c \cdot x}{r_H} \tag{4}$$

Substituting Eqs.3 - 4 into Eq.1 and denoting the indirect utility as V, bid rent of floor is expressed as follows.

$$r_H = \alpha_0 \left(\frac{I - c \cdot x}{p^{\alpha z} \cdot V} \right)^{\frac{1}{\alpha l}} \tag{5}$$

$$\alpha_0 = \alpha_z{}^{\frac{\alpha_z}{\alpha_l}} \cdot \alpha_l \tag{6}$$

Substituting Eq.5 into Eq.4, floor demand of a household is given as follows.

$$l = \frac{\alpha_l}{\alpha_0} \left(p^{\alpha z} \cdot V \right)^{\frac{1}{\alpha l}} \cdot \left(\frac{1}{I - c \cdot x} \right)^{\frac{1-\alpha_l}{\alpha_l}} \tag{7}$$

Developer

Developers supply residential floor A_f, using land G and capital K. The production function of floor is given as follows.

$$A_f = \gamma_0 \left(\frac{K}{G} \right)^{\gamma_1} G \tag{8}$$

γ_0 and γ_1 are parameters of housing productivity, and $0< \gamma_1 <1$ is assumed. Using floor rent r_H, the profit of developers is given as follows.

$$\Pi = r_H \cdot A_f - \kappa \cdot K - r_G \cdot G \tag{9}$$

κ is capital price and r_G is land rent. The input of capital which maximizes the profit is given as follows.

$$K = \left(\frac{r_H \cdot \gamma_0 \cdot \gamma_1}{\kappa} \right)^{\frac{1}{1-\gamma_1}} G \tag{10}$$

Substituting Eq.10 into Eq.8, floor supply is expressed as follows.

$$A_f = \gamma_0 \left(\frac{r_H \cdot \gamma_0 \cdot \gamma_1}{\kappa} \right)^{\frac{\gamma_1}{1-\gamma_1}} G \tag{11}$$

Substituting Eqs.10-11 into Eq.9, the indirect profit is obtained as follows.

$$\Pi = G \left\{ (1 - \gamma_1)(r_H \cdot \gamma_0)^{\frac{1}{1-\gamma_1}} \left(\frac{\gamma_1}{\kappa} \right)^{\frac{\gamma_1}{1-\gamma_1}} - r_G \right\} \tag{12}$$

Assuming developers are perfectly competitive and the profit thus equals zero, bid rent of land is given as follows.

$$r_G = (1 - \gamma_1)(r_H \cdot \gamma_0)^{\frac{1}{1-\gamma_1}} \left(\frac{\gamma_1}{\kappa} \right)^{\frac{\gamma_1}{1-\gamma_1}} \tag{13}$$

Market clearance

Land owners are assumed to provide their land to developers when their bid rent r_G exceeds agricultural land rent r_{GA}. Floor rent r_H have to meet a following condition to satisfy $r_G>r_{GA}$.

$$r_H \geq \frac{1}{\gamma_0}\left(\frac{r_{GA}}{1-\gamma_1}\right)^{1-\gamma_1}\left(\frac{\kappa}{\gamma_1}\right)^{\gamma_1} \tag{14}$$

Using Eq.5 and Eq.14, distance between CBD and urban boundary x_A is given as follows.

$$x_A = \frac{1}{c}\left[I - \left\{\left(\frac{\kappa}{\gamma_1}\right)^{\gamma_1}\left(\frac{r_{GA}}{1-\gamma_1}\right)^{1-\gamma_1}\right\}^{\alpha l}\frac{p^{\alpha z}\cdot V}{(\alpha_0\cdot\gamma_0)^{\alpha_l}}\right] \tag{15}$$

The household density n_x can be defined as total floor supply A_f divided by floor consumption per household l. Using Eq.7 and Eq.11, the household density can be expressed as follows.

$$n_x = \frac{A_f}{l} = \beta_0 V^{-\beta_1}(I-cx)^{\beta_1-1}G \tag{16}$$

$$\beta_0 = \frac{(\gamma_0\alpha_0)^{\frac{1}{1-\gamma_1}}}{\alpha_l}\left(\frac{\gamma_1}{\kappa}\right)^{\frac{\gamma_1}{1-\gamma_1}} p^{-\frac{\alpha_z}{\alpha l}\frac{1}{(1-\gamma)}} \tag{17}$$

$$\beta_1 = \frac{1}{\alpha_l(1-\gamma)} \tag{18}$$

As the city is assumed to have a circular form centering CBD, developed land area framed by (x, x+dx) with center angle $d\theta$ is expressed as follows.

$$dG = R_b x dx d\theta \tag{19}$$

R_b is the share of developed land area to the total land area. Using this notation, the number of households N is given as follows.

$$N = \int_0^{x_A}\int_0^{2\pi}\beta_0 V^{-\beta_1}(I-cx)^{\beta_1-1}R_b x dx d\theta \tag{20}$$

$$= \frac{2\pi\beta_0 R_b}{V^{\beta_1}}\cdot\frac{I^{\beta_1+1}-\{I-c\cdot x_A\}^{\beta_1}(I+c\cdot\beta_1\cdot x_A)}{c^2\cdot\beta_1\cdot(\beta_1+1)}$$

Based on Eq.15 and Eq.20, urbanized radius x_A and utility level V can be calculated when the number of household N, income I, transport cost per distance c, capital price κ, agricultural land rent r_{GA}, price of composite goods p, preference for residential floor α_l, and housing productivity parameters γ_0 and γ_1 are given. This means that, when urban radius x_A is observed, transport cost c can be estimated in an abductive approach. Given population and income scenarios, the future impacts of transport cost and housing productivity on urbanized area and utility can be estimated.

3. Data

Angel et al. (2011a) provides a dataset of population and area in 3646 urban agglomerations of 161 countries in 2000. These cities in the dataset cover 33% of global population, 70% of global urban population, and 52% of global urbanized area. Assuming a circular urban form, urban radius x_A can be derived from urbanized area. There is no global dataset of the other variables at an urban level. Here their national averages are given for each city as explained below.

Income I is assumed to be represented by GDP per capita, which is given by GDP in PPP (purchasing power parity) in the World Development Indicators (WDI) by World Bank (WB). Capital price κ is given interest rates in WDI as well. Preference for residential floor α_l is given by United Nations National Accounts Official Country Data, and imputed rent is estimated based on development cost. Agricultural land rent r_{GA} is given by GTAP database (Lee et al., 2008), but we added capital price to cost of building-lot development. The development cost is estimated as ground-level cost which is \$4/m^2 in Japan, and it is adjusted by the ratio of per capita GDP for each country. Housing productivity parameters are estimated using building construction statistics in Japan, 2007. The price of composite goods is assumed to be unity as numéraire. All of these data are provided for 1455 cities in 42 countries.

Lack of data for floor preference, capital price, and agricultural land rent are supplemented by following models. First, regarding floor preference, the expenditure ratio of housing to income is low when income is low because lower income usually requires the higher expenditure of food. Income growth is expected to increase the expenditure of housing, but it would be saturated at a certain level. We assume the floor preference can be estimated as follows.

$$\alpha_l = \theta_{p1} - \frac{\theta_{p2}}{\left(I + \theta_{p3}\right)^{\theta_{p4}}} \tag{21}$$

Second, higher capital needs and business risks may bring higher interest rates, and we thus assume that capital price is a function of per capita GDP as follows.

$$\kappa = \frac{\theta_{r1}}{\left(I + \theta_{r2}\right)^{\theta_{r3}}} \tag{22}$$

Agricultural land rent is affected by agricultural productivity and land scarcity. Here, we assume that the productivity is related with per capita GDP, and land scarcity can be represented by agricultural land per capita which is given by WDI database. The agricultural land rent can be estimated as follows.

$$r_{GA} = \theta_{a1} I^{\theta_{a2}} + \frac{\theta_{a3}}{\left(A_{GA} + \theta_{a4}\right)^{\theta_{a5}}} + \theta_{a6} \tag{23}$$

The parameters of these functions are estimated using datasets of 82 countries for floor preference, 147 countries for capital price, and 63 countries for agricultural land rent. The estimated parameters are shown in Table 1, and data and model estimation are plotted in Figure 2.

These results indicate that the models behave correctly, even though the accuracy of estimation and the significance of parameters are not high. Using these models, lack of data for floor preference, capital price, and agricultural land rent are complemented. Here, PPP and agricultural statistics are provided for 151 countries, and supplemented data are given for 2151 cities. In total, 3606 cities with the 1455 original full dataset cities are targeted for the future projection of urbanized area.

Table 1 Results of parameter estimation for floor preference, capital price, and agricultural land rent models

		Parameters	St.dev	t-value
Floor preference	θ_{p1}	0.361	0.254	1.422
	θ_{p2}	0.383	0.131	2.930
	θ_{p3}	2.526	3.742	0.675
	θ_{p4}	0.330	0.602	0.549
Capital price	θ_{r1}	335.5	293.1	1.145
	θ_{r2}	13.79	5.635	2.447
	θ_{r3}	0.951	0.223	4.267
Agricultural land rent	θ_{a1}	93.70	182.7	0.513
	θ_{a2}	0.200	0.280	0.711
	θ_{a3}	102.4	139.7	0.733
	θ_{a4}	0.741	0.299	2.478
	θ_{a5}	4.571	2.053	2.226
	θ_{a6}	-124.1	193.0	-0.643

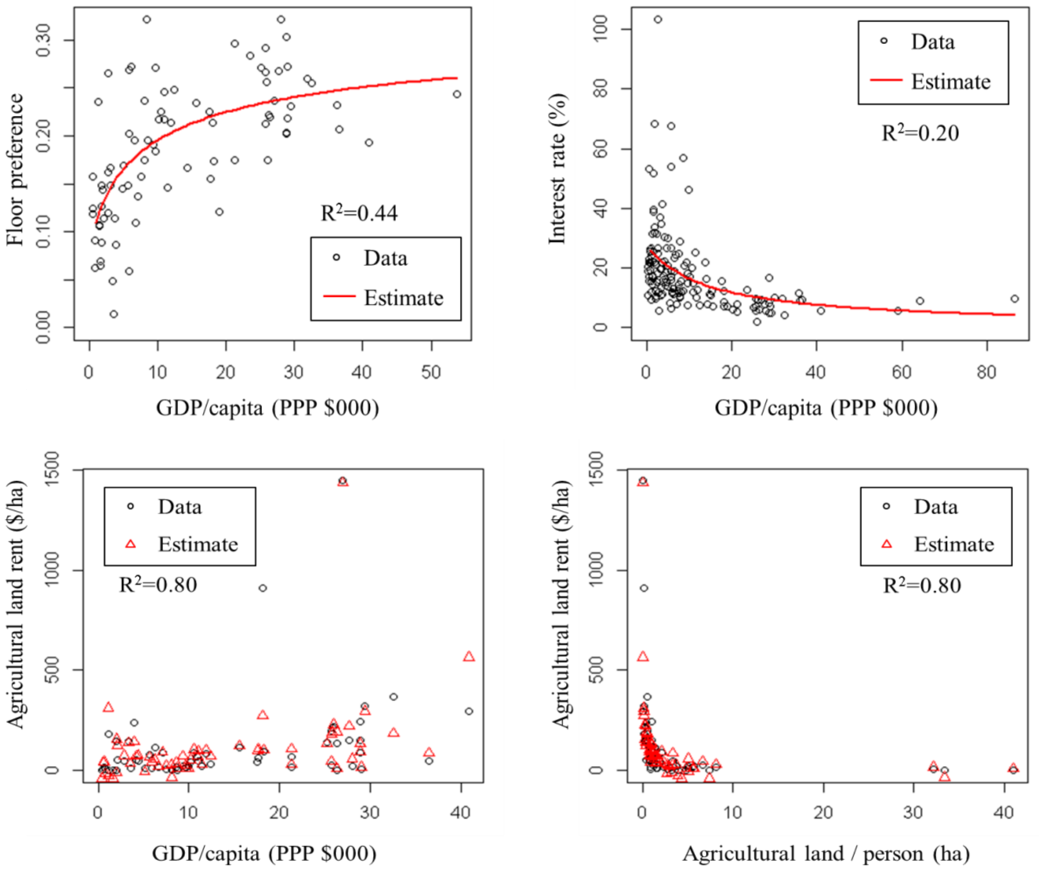

Fig. 2 Data and estimation of floor preference over GDP/capita (top left), capital rent over GDP/capita (top right), agricultural land rent over GDP/capita (bottom left), and agricultural land rent over per capita agricultural land (bottom right)

4. Estimation of Current Transport Cost and Utility

In this section we estimate transport cost and utility of 1455 cities in 42 countries where all of the required data are obtained. Solving V in Eq.15 and substitute it into Eq.20, the following equation is obtained.

$$N = \beta_4 \cdot \beta_3^{\beta_1} \frac{1}{c^2} \left(\left(\frac{I}{I - cx_A} \right)^{\beta_1} I - \left(I + c\beta_1 x_A \right) \right) \tag{24}$$

$$\beta_3 = \left(\left(\frac{\kappa}{\gamma_1} \right)^{\gamma_1} \left(\frac{r_{GA}}{1-\gamma_1} \right)^{1-\gamma_1} \right)^{\alpha_l} \frac{1}{(\alpha_0 \gamma_0)^{\alpha_l}}, \quad \beta_4 = \frac{2\pi\beta_0 R_b}{\beta_1(\beta_1 + 1)} \tag{25}$$

Here, we assume that a household consists of one person. All of the variables other than transport cost c are given in this equation. c can be solved to meet this equation if the other variables are consistent each other. Then V can be calculated by using obtained *c* in Eq.15. Here, in the real world, urbanized area is affected not only by population and transport cost but also by various factors including geographical/landscape constraints, travel time cost with traffic jam, and building regulations which are not considered in this model. The estimated transport cost *c* may reflect these various factors implicitly.

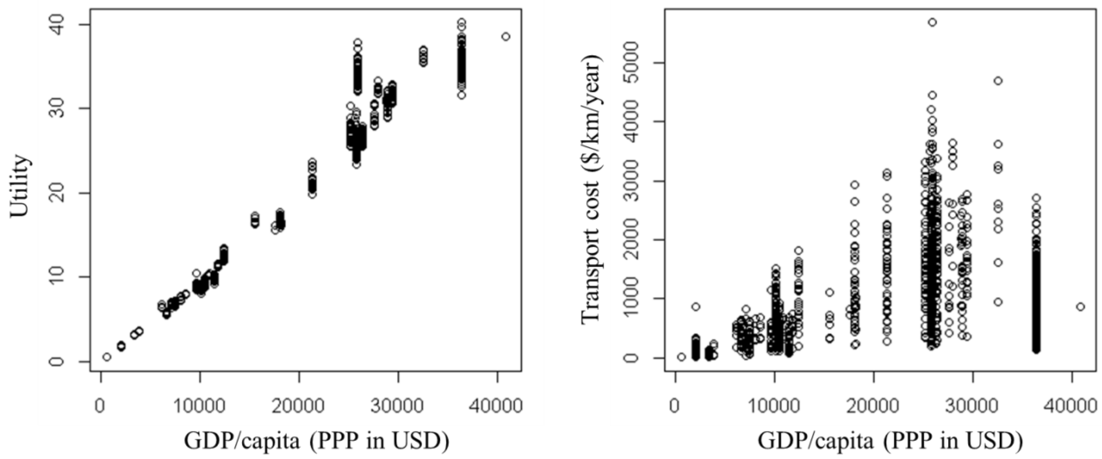

Fig. 3 GDP per capita, utility (left), and transport cost (right)

The estimated transport cost and utility over GDP per capita are shown in Figure 3. Utility is in the almost linear relationship with GDP per capita. Transport cost also has positive correlation with GDP per capita but it varies largely. Higher income may cause higher employment cost for the transport sector, higher travel time cost of users, and using more expensive travel modes, like private cars, which drastically increase mobility. In addition, as described above, this estimated transport cost reflects various factors of urban properties and constraints that may lead larger variation. For example, if geographical constraint limits urbanized area in reality, this model interprets this limit is caused by higher transport cost. Nevertheless, we set this estimated transport cost for 2000 in each city, and we assume that the transport cost would change proportionately with changes in GDP per capita in the scenario analysis below.

5. Projection of Urbanized Area and Population Density

Urbanized area and population density are estimated by 2050, using the model by applying future scenarios of population and economic growth. World Urbanization Prospects of the 2014 version (UN DESA, 2014) is used for the national population scenario. We employ the preferential attachment model (Kii et al., 2012; Kii and Doi,

2013) to downscale the national population into population by city. For the national-level GDP scenario, we referred to the database of Shared Socioeconomic Pathways (SSP) 1 –Sustainability-, version 0.93 (IIASA, 2015). We assume that per capita GDP is indifferent among cities within a country. Figure 4 shows the scenario of urban population and GDP/capita for aggregated 6 global regions which is defined by United Nations (UN DESA, 2014). In this scenario, Asia is significant for its growth in both of population and GDP/capita. On the other hand, Africa has higher growth in population but not in GDP/capita.

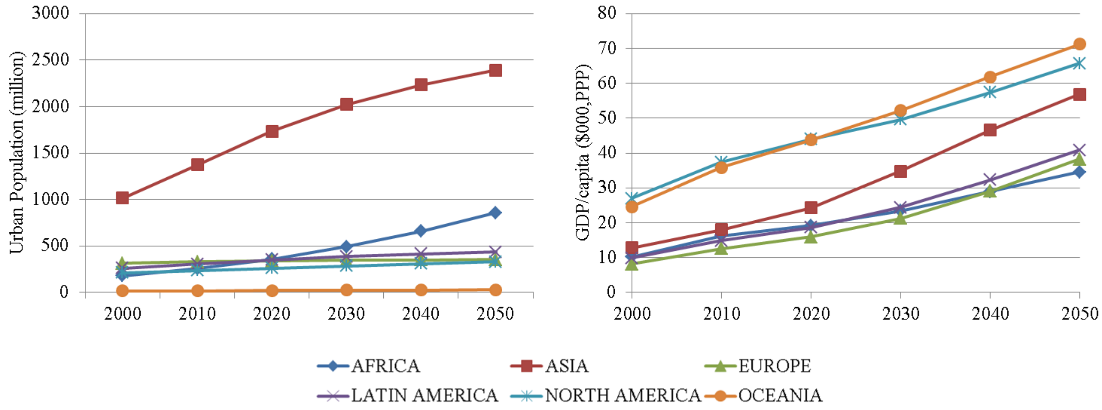

Fig. 4 Scenario of urban population (left) and GDP/capita (right)

5.1 Impact of Population Growth and Economic Development

Using Eq.15 and Eq.20, urban radius x_A and utility V can be estimated under the scenario above. Figure 5 shows trajectories of urbanized area, population density, and average utility. The urbanized area increases in all the regions, but their increase rates vary by region, reflecting transition of population and floor demand.

Population density has a significant variety of trajectories by region. That of Africa is estimated to increase monotonically in this period, but it seems to be almost saturated in 2050. Population growth tends to increase land rent and floor rent, which reduces floor demand per capita and increases population density. Income growth improves affordability of floor rent and transport cost, which leads lower population density. Therefore, the trajectory of population density is determined by the balance of population growth and economic growth. In Africa, population growth can be interpreted to exceed income growth in terms of their impacts on urban density.

In Asia, population density is estimated to peak out in 2010, and after that it decreases drastically. This implies that the pattern of urban expansion in Asia changes; urban expansion is mainly affected by population increase before 2010, but it is induced after that by economic growth and subsequent increase in floor demand of households. Population density in the other regions is estimated to decrease almost monotonically during the period.

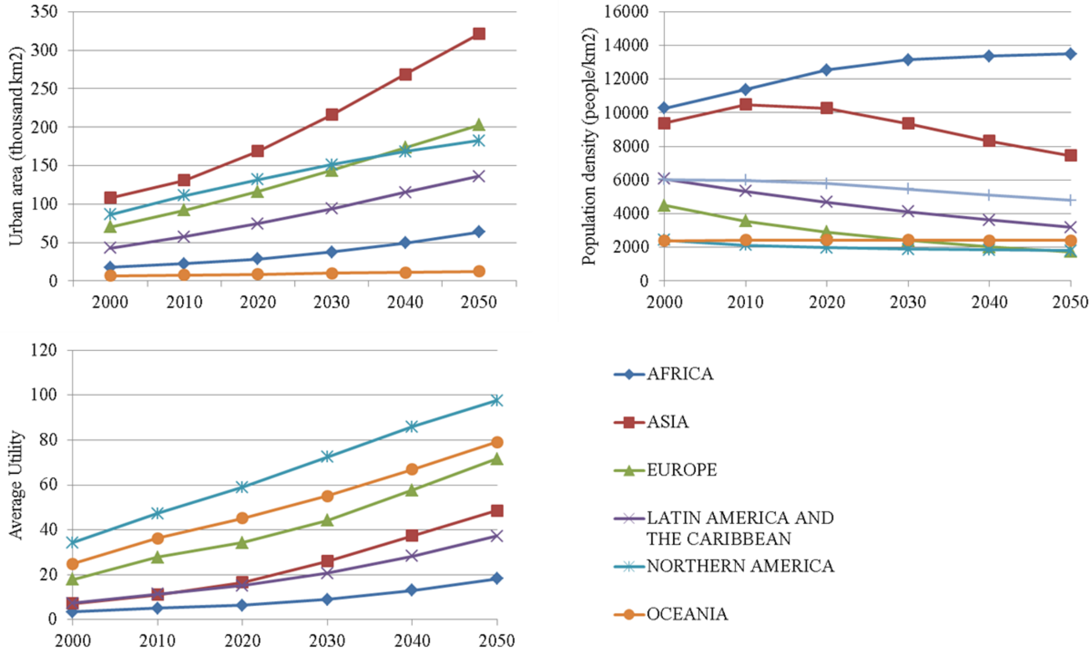

Fig. 5 Estimated urbanized area (top left), population density (top right), and average utility (bottom left)

5.2 Sensitivity to Transport Cost and Housing Productivity

Sensitivities of transport cost and housing productivity to population density, benefit, and travel distance are analyzed. Here, benefit can be formulated as $B=\Delta V/(\mathrm{d}V/\mathrm{d}I)$ approximately where ΔV is differentiated utility.

In the case of transport cost reduction, we assume that transport cost c decreases by 5% for every 10 years. In the case of housing productivity improvement, the productivity parameter γ_1 is assumed to increase by 1% for every 10 years. Annual travel distance per household for commuting can be calculated as follows.

$$L_T = \int_0^{2\pi}\int_0^{x_A} 2D\frac{n_x}{G}x^2 dx d\theta \Big/ N \tag{26}$$

Where, D denotes annual working days.

Figure 6 shows the trajectories of population density, benefit, and travel distance change from the baseline scenario in the cases of transport cost reduction and housing production improvement. In the case of transport cost reduction, population density goes down; that of Africa peaks out in 2020 and decreases after that. The global average of population density decreases by 27% in 2050, compared to the baseline scenario. On the other hand, housing productivity improvement increases population density in all the regions, and the global average of population density increases by 44% in 2050.

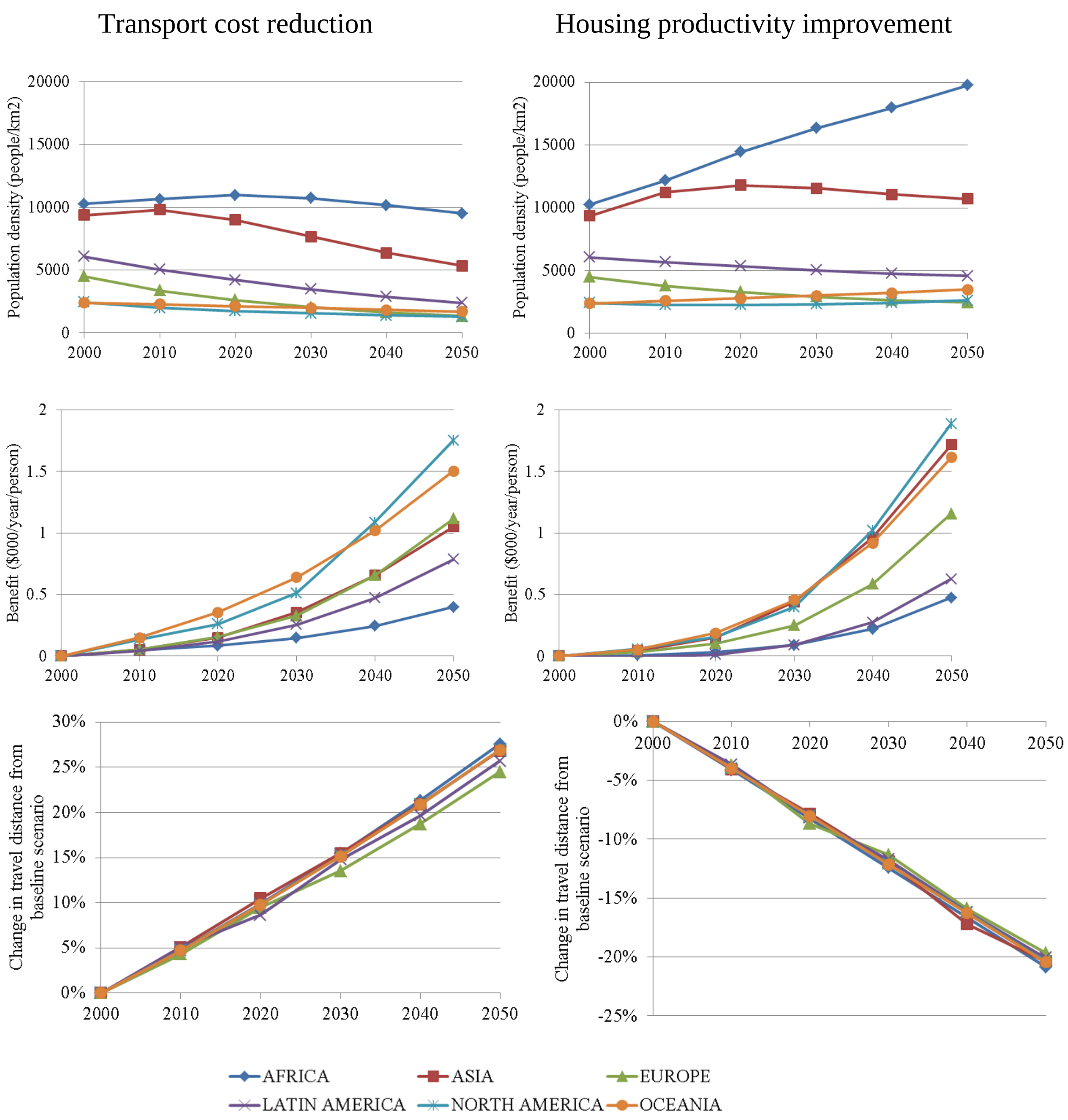

Fig. 6 Estimated population density, benefit, and travel distance change from the baseline scenario in case of transport cost reduction (left) and construction technology improvement (right)

Benefits in both of these cases take similar figures, despite the large difference in population density. Housing productivity improvement increases population density with more towering residential development, and the estimated trajectory of floor area per person is similar to that in the case of transport cost reduction.

Travel distance change from the baseline scenario has opposite patterns between these two cases. In the case of transport cost reduction, travel distance is further increased beyond the baseline case, reflecting the decline of population density. On the other hand, housing productivity improvement curbs the increase of travel distance. These results regarding population density and travel distance are consistent with the cross-sectional observation by Kenworthy and Laube (1999). Our result implies that the similar levels of utility can be achieved under these 2 cases, higher density and lower density, if the cost and productivity conditions in transport and housing are controlled appropriately.

6. Conclusion

In this study, we developed a global-scale urban spatial model incorporating the transport sector and the housing sector, applicable to estimate urban expansion in about 3,600 cities all over the world by 2050. By separating the land market and the floor market in a monocentric city model, we make it possible to analyze the impact of the housing productivity on urban forms as well as utility of local residents.

As a result, we found that population growth and economic growth have a substantial impact on urban expansion, but its magnitude is different by region depending on development stages; population density of Africa is estimated to increase till 2050; that of Asia peaks out in 2010; in the other regions, population density declines during the period.

Sensitivity analysis figures out that housing productivity improvement would restrain urban expansion. On the other hand, transportation cost reduction would overwhelmingly accelerate the expansion. These 2 cases bring the similar levels of benefit on households but different impacts on travel distance; transport cost reduction increases travel distance, but housing productivity improvement decrease it.

Our model is developed based on numerous strong assumptions which should be alleviated to improve its plausibility in some policy analyses. To do so, we first need city-level data for income, expenditure, and land/floor rent, which are given as the national averages in this study. Second, our model assumes a monocentric city, homogeneity in households, indifference in transport resistance, and uniformity of space. To include more detailed and realistic situations of each city, these assumptions have to be alleviated.

References:

Alonso, W. (1964). Location and land use. Harvard University Press. Cambridge, MA.

Angel, S., Parent, J., Civco, D. L., Blei, A. M. (2011a) The atlas of urban expansion. Cambridge, MA: Lincoln Institute of Land Policy. Online at http://www.lincolninst.edu/subcenters/atlasurban-expansion/.

Angel S., Parent, J., Civco, D. L., Blei, A, Potere, D. (2011b) The dimensions of global urban expansion: Estimates and projections for all countries, 2000 – 2050. Progress in Planning, 75, 53 – 107.

Asadoorian, M.O. (2008). Simulating the spatial distribution of population and emissions to 2100. Environmental and Resource Economics, 39, 199–221.

Balk, D., Yetman, G. (2004). The global distribution of population: evaluating the gains in resolution refinement. Documentation for GPW Version 3, available online at http://sedac.ciesin.columbia.edu/downloads/docs/gpw-v3/gpw3_documentation_final.pdf

Balk, D., Pozzi F., Yetman, G., Deichmann, U., Nelson, A (2004). The distribution of people and the dimension of place: Methodologies to improve the global estimation of urban extents. Working Paper, CIESIN, Columbia University. http://beta.sedac.ciesin.columbia.edu/gpw/docs/UR_paper_webdraft1.pdf. Accessed 1 Feb 2015

Bartholome, E., Belward, A.S. (2005). GLC2000: A new approach to global land cover mapping from earth observation data. International Journal of Remote Sensing, 26, 1959–1977.

Danko, D. M. (1992). The digital chart of the world project. Photogrammetric Engineering and Remote Sensing, 58, 1125–1128.

Elvidge, C.D., Imhoff, M.L., Baugh, K.E., Hobson, V.R., Nelson, I., Safran, J. (2001). Nighttime lights of the world: 1994–95. ISPRS Journal of Photogrammetry and Remote Sensing, 56, 81– 99.

Elvidge, C.D., Tuttle, B.T., Sutton, P.C., Baugh, K.E., Howard, A.T., Milesi, C. (2007). Global distribution and density of constructed impervious surfaces. Sensors, 7, 1962–1979.

Ewing R., Cervero, R. (2010). Travel and the built environment: A meta-analysis. Journal of the American Planning Association, 76, 265–294.

Gaffin, S.R., Rosenzweig, C., Xing, X., Yetman, G. (2004). Downscaling and geo-spatial gridding of socio-economic projections from the IPCC Special Report on Emissions Scenarios (SRES). Global Environmental Change, 14, 105–123.

Grubler A., Bai, X., Buettner, T., Dhakal, S., Fisk, D., Ichinose, T., Keirstead, J., Sammer, G., Satterthwaite, D., Schulz, N., Shah, N., Steinberger, J., Weisz, H. (2012). Urban energy systems. In: Global energy assessment: Toward a sustainable future. Cambridge University Press, Cambridge, UK.

Grübler, A., O'Neilla, B., Riahia, K., Chirkova, V., Goujona, A., Kolpa, P., Prommera, I., Scherbova, S., Slentoe, E. (2007). Regional, national, and spatially explicit scenarios of demographic and economic change based on SRES. Technological Forecasting and Social Change, 74, 980–1029.

IIASA (2015). SSP Database (version 0.93), https://secure.iiasa.ac.at/web-apps/ene/SspDb. Accessed 1 Feb 2015

Kenworthy J. R., Laube, F. B. (1999). Patterns of automobile dependence in cities: an international overview of key physical and economic dimensions with some implications for urban policy. Transportation Research Part A: Policy and Practice 33, 691 – 723.

Kii, M., Akimoto, K., Doi, K. (2012). Random-growth urban model with geographical fitness. Physica A, 391, 5960–5970.

Kii, M. and Doi, K. (2013). Projecting global urbanization and the growth of megacities. In Mackett, R., May, A.D., Kii, M., Haixiao, P. (Eds.), Sustainable transport for Chinese cities. Emerald Group Publishing, Bingley, WA.

Lee,H.L., Hertel,T.W., Rose,S., Avetisyan,M.(2008). An Integrated Global Land Use Data Base for CGE Analysis of Climate Policy Options, GTAP Working Paper No. 42.

Marcotullio P. J., Sarzynski, A, Albrecht, J., Schulz, N., Garcia, J. (2013). The geography of global urban greenhouse gas emissions: An exploratory analysis. Climatic Change, 121, 621 – 634.

OpenStreetMap (2015). OpenStreetMap. http://www.openstreetmap.org. Accessed 1 Feb 2015

Salon, D., Boarnet, M. G., Handy, S., Spears, S., Tal, G. (2012). How do local actions affect VMT? A critical review of the empirical evidence. Transportation Research Part D, 17, 495–508.

Seto, K.C., et al. (Eds.), Climate change (2014). Mitigation of climate change: Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Seto K. C., Fragkias, M., Güneralp, B., Reilly, M. K. (2011). A Meta-Analysis of Global Urban Land Expansion. PLOS ONE 6, e23777. doi: 10.1371 / journal. pone.0023777

Seto, K. C., Güneralp, B., Hutyra, L. R. (2012). Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proceedings of the

National Academy of Sciences 109, 16083–16088.
Schneider, A., Friedl, M.A., Potere, D. (2009). A new map of global urban extent from MODIS data. Environmental Research Letters, 4, 1–11.
IPCC (2000). Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press.
UN DESA (2014). World urbanization prospects: The 2014 revision. United Nations, Department of Economic and Social Affairs, Population Division, New York.