Urban Scaling and Economic Analysis of Materials Stocked in Japanese Cities

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ABSTRACT

This research aims to explore the complexity inherent in the physical mass of cities—specifically in the materials that are stored within buildings and infrastructure. There is an important link between stocked materials and urban sustainability, particularly related to better understanding the resource requirements for the maintenance and growth of cities. This research explores materials stocked in Japanese cities, using a database with detailed GIS data of materials stored in buildings and roads at a resolution of one square kilometer. The analysis focuses on a single year, 2009 for buildings and 2010 for roads, and it includes two primary investigations: 1) urban scaling analyses to explore relationships between mass stocked, urban population, and other variables; and 2) non-parametric kernel estimations to better understand influential factors contributing to per-capita mass values. Results show a linear scaling relationship between mass stocked in buildings and urban area population, as well as a sublinear scaling relationships between mass stocked in roads, urban area population, and land area. The non-parametric kernel estimations revealed population density as a potentially influential factor.

Introduction

Cities are complex systems with a variety of interacting agents, resource inputs, and internal processes, all of which combine to create complex economies, cultures, and built environments. The overall objective of the research is to explore the complexity inherent in materials stocked in Japanese cities; that is, the mass of materials stored in all the buildings and infrastructure that make up the built environment. This could allow researchers to make further links to physical infrastructure growth and the mass of cities, which has implications for urban resources requirements and sustainability.

One way to explore the complexity in cities is through urban scaling analysis. Urban scaling relationships are observed as the slope of a log-log plot between city size (i.e., population) and other indicators, such as crime rates, GDP, length of infrastructure, and household electricity consumption, for all cities in a given country or region. This determines the scaling exponent, b, for a given indicator, Y, determined for cities with populations N (Equation 1). While urban scaling is empirically observed in countries around the world, there is also a theoretical foundation for the phenomenon rooted in the understanding that cities are networks of social interactions (see Bettencourt[1]).

$$Y = N^b \tag{1}$$

In their work on urban scaling, Bettencourt et al.[1,2] observe three consistent scaling relationships. First, there is a superlinear scaling of social quantities (b is greater than 1), including both desirable social quantities (e.g., wages, GDP, new inventions) and undesirable social quantities (e.g., crime, disease transmission). This indicates that social effects in cities exhibit agglomeration economies; that is, larger cities show social phenomena that are orders of magnitude greater than their smaller-city counterparts. Second, physical quantities display sublinear scaling (b is less than 1), including per-capita urban infrastructure, such as electricity network length and length of road surface. Cities achieve economies of scale with respect to urban infrastructure: larger cities use infrastructure more efficiently than smaller ones. Finally, quantities required for individual maintenance show linear scaling (b is equal to 1), such as total housing, total employment, and household electricity consumption. In each system of cities, certain individual needs remain consistent.

This research addresses a gap in the existing urban scaling literature by focusing on the mass of cities; that is, the weight of concrete, wood, asphalt, and other materials that make up the physical form of the city. In the language of material flow analysis (MFA), these are called *stocked materials*. The analysis uses a database developed by Fishman et al.[3,4] with the mass of materials stocked in buildings and infrastructure for all of Japan (see Figures 1 and 2).

In addition to an urban scaling analysis, the research includes an economic analysis of the underlying mechanisms influencing the generation of stocked materials. Fishman et al.[5] conducted panel regression and decomposition analyses of the socio-economic drivers influencing material stock accumulation at the prefecture level. The analysis herein is conducted at the city-level and uses non-parametric kernel estimation.

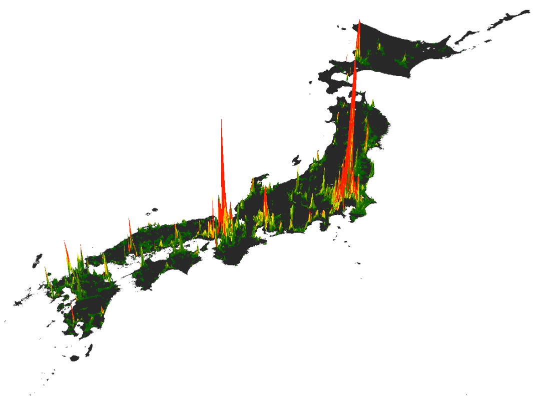

Figure 1. Spatial distribution of material stocked in buildings for 2009. Generated from data from Fishman et al.[3,4]

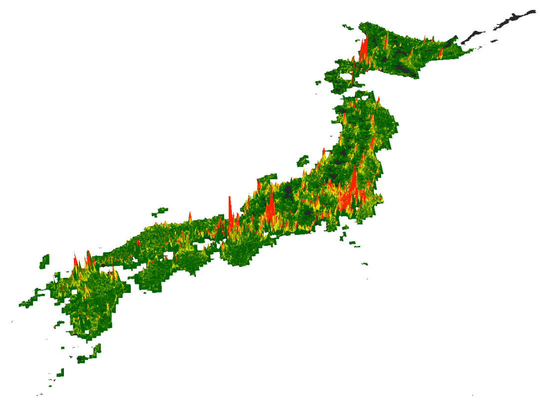

Figure 2. Spatial distribution of material stocked in infrastructure (roads) for 2010. Generated from data from Fishman et al.[3,4]

Results

Scaling Analysis

Scaling analysis was conducted for three city definitions:

- *Metropolitan Employment Area (MEA)*: a central city and its surrounding municipalities that make up the commuter shed, with populations greater than 50,000 people. The analysis used data from 108 MEAs in Japan.
- *MEAs and Micropolitan Employment Areas (McEA)*: all employment areas with populations over 10,000 people. The analysis used data from the 108 MEAs as well as 121 McEAs (populations greater than 10,000 but less than 50,000).
- *Municipality*: the basic administrative unit of Japan on a national level. The analysis used data from 1799 municipalities in Japan.

For each city definition, scaling analysis was conducted on building mass and road infrastructure mass. Results shown below include the scaling relationships and a comparison of the residuals to a normal distribution. The closer the residuals are to a normal distribution, the more reliable the scaling relationship. In addition, the MEAs were checked to see if they followed Zipf's Law[6] with respect to population rank.

Metropolitan Employment Areas (MEAs)

There were 108 MEAs tested in the analysis. Population rank scaling looked Zipfian (Figure 3), but there were significant deviations from normal distribution of residuals (Figure 4). Scaling of building mass was found to be stronger linear, with residuals indicating a power law (Figures 5 and 4 respectively). Figure 7 shows a comparison of the actual and predicted values for linear scaling of building mass. For mass of road infrastructure, there was a weak sublinear scaling relationship (Figures 8 and 9). However, when inhabitable land area was introduced as a third variable, the scaling relationship was strongly (Figures 10 and 11, also see Table 1), which is confirmed by a plot of the actual versus scaling predicted values (Figure 12).

Metropolitan and Micropolitan Employment Areas (MEAs, McEAs)

The scaling relationships were much weaker when McEAs were included in the analysis. Buildings showed a linear scaling relationship (Figure 13) and roads showed a sublinear relationship (Figure 15). However, it appears as if expectations of homoskedasticity are violated (see Figures 14 and 16 for buildings and roads respectively).

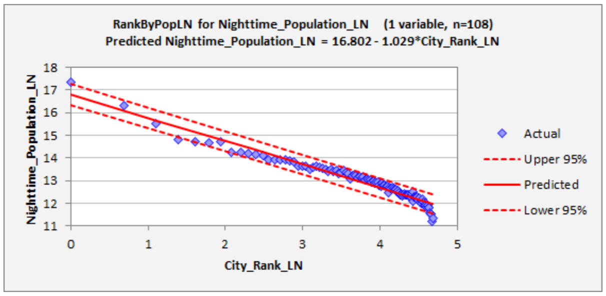

Figure 3. Ln-ln plot of MEA population by rank.

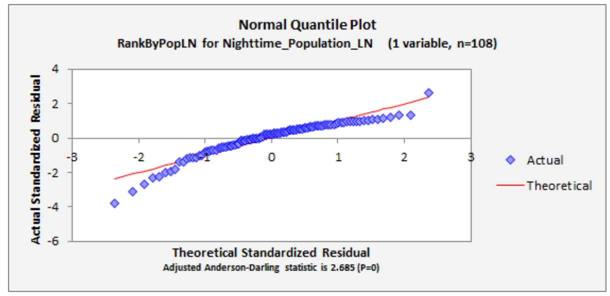

Figure 4. QQ plot of MEA population by rank regression - note that A-D statistic indicates heteroskedasticity.

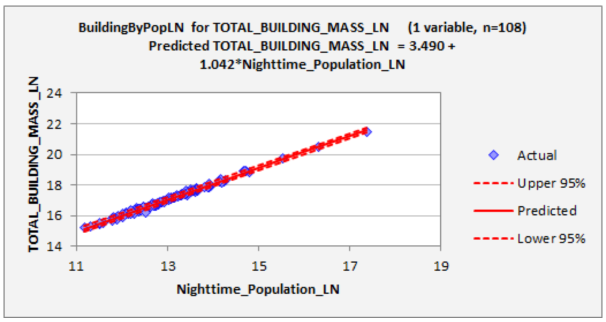

Figure 5. Ln-ln plot of MEA building mass by population.

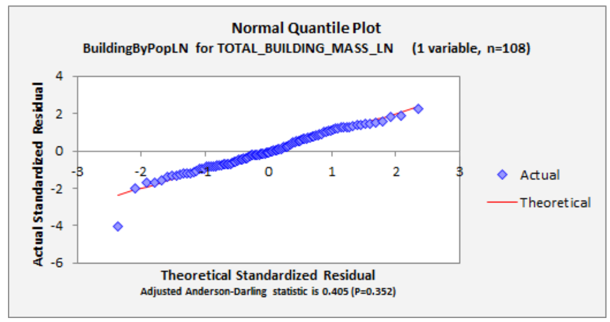

Figure 6. QQ plot of MEA building mass by population regression.

All Municipalities

When considering municipalities, the scaling results followed similar general trends: buildings were linear (Figure 17) and roads were sublinear (Figure 17). However, the linear regression models were weak (see Figures 18 and 20).

Economic Analysis

The economic analysis focused on city by city variations in per-capita building mass. By looking at the micro-scale characteristics of the cities, the analysis aimed to give a better understanding of the mechanisms driving the material stock generation. As shown in Figure 21, there are variations at the per-capita level that are not captured in the urban scaling analysis. The analysis looked at the relationship between per-capita building mass and various socioeconomic variables using a non-parametric kernel regression estimation.

Four variables tested displayed interesting behavior: inhabitable density (Figure 22), total per-capita production (Figure 23), size of the real estate industry, per capita (Figure 24), and share of agriculture, forestry, and fisheries in production (Figure 25).

Discussion

The strongest scaling relationships were shown by MEAs alone. Both the combination of MEAs and McEAs and municipalities showed similar scaling trends, but their linear regressions were not as strong. The strength of MEA scaling relationships over the other two delineations concurs with results in the existing literature[1,2]. MEAs, which are akin to Metropolitan Statistical Areas in the United States, are the best representation of the economic and social systems in a city because they have the most mixing among people. The definition of MEA as a commuter shed indicates that people are moving within the MEA having social and economic interactions: they are not bound by the administrative boundaries that define municipalities. In this sense, the MEA is the physical extent of the city network, and as described by Bettencourt[1], the network of social interactions in cities underlies scaling observations. Furthermore, it has also been observed that scaling relationships are more prominent in populations over 50,000 people[1,2], which may represent a minimum threshold for optimal city mixing.

The sublinear scaling of road mass was expected, as this aligns with previous observations of the sublinear scaling of road length and other physical infrastructure quantities[2]. However, the observed linear scaling relationship of building mass was a surprise. Previous work on urban scaling[2] has shown that housing has a linear scaling relationships, while infrastructure is sublinear and socioeconomic characteristics are superlinear. Presumably, building mass would include housing (linear), as

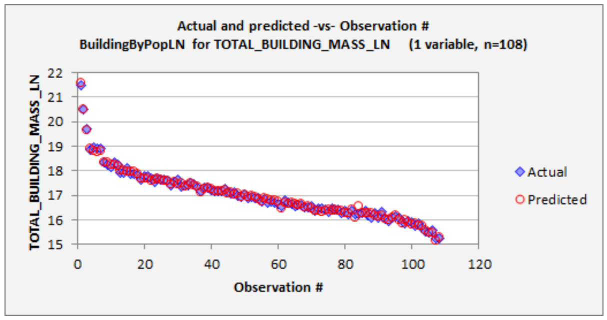

Figure 7. Actual vs predicted values of MEA building mass by population.

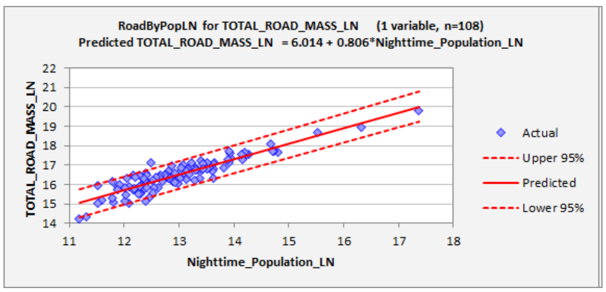

Figure 8. Ln-ln regression of road mass by population.

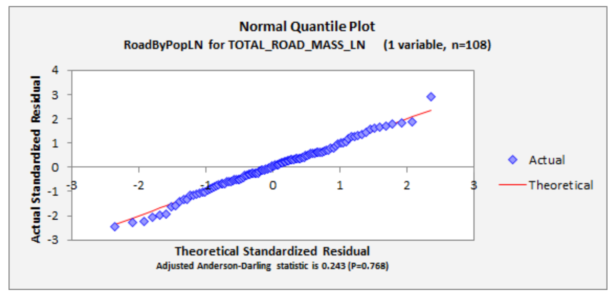

Figure 9. QQ plot for road mass by population regression.

well as commercial and industrial properties (superlinear). To look into this result further, the researchers tested the scaling relationship between population and total production (as a proxy for GDP). This socioeconomic variable was found to be linear–not superlinear as predicted by theory! This indicates that there may be forces at work in the Japanese city system that result in scaling relationships that diverge from the American and European city systems. In the case of buildings, one such force may be the Japanese tradition to demolish and construct new buildings upon ownership change[7].

The four kernel regressions in the economic analysis–inhabitable density, total per-capita production, size of the real estate industry, and share of agriculture, forestry, and fisheries in production–were particularly interesting because they give some indication to the amount of construction and level of urbanization the city. It is important to note that none of these variables can alone explain the variations in per-capita mass across Japanese cities, yet they can be useful to further research in understanding what factors to include when modeling transition dynamics.

The results indicate that there is still more to learn about material stocks, urban scaling, and economic drivers, particularly in the Japanese context. Further research opportunities include investigating scaling of material stocks in different countries, a time-series analysis of stocked materials in Japan, and non-linear econometric analyses.

Methods

Data

Four datasets were used in the analysis, with the primary being material stocks in Japan developed by Fishman et al.[3,4]. Additional datasets were obtained for population and other indicators for different city definitions. The four datasets are described in turn below.

Material Stock Data

The material stock datasets (Fishman et al.[3,4]) consisted of vector shapefiles containing grid features at 1km x 1km resolution. Each feature identified the urban area, prefecture, and the total mass in tonnes of the relevant indicator (buildings for 2009, or roads for 2010). See Tanikawa et al.[4] for more details on the data.

Since the data covered all of Japan, the data was processed to obtain values for cities. Both the Buildings2009 and RoadInfra2010 layers were transformed into rasters using ArcGIS and FME, with a cell size and alignment calibrated to the GPWv4 population raster (Figure 26). Two versions of each raster were produced: one in which all NoData/NA values were preserved, and another in which all NoData/NA values were replaced with 0.

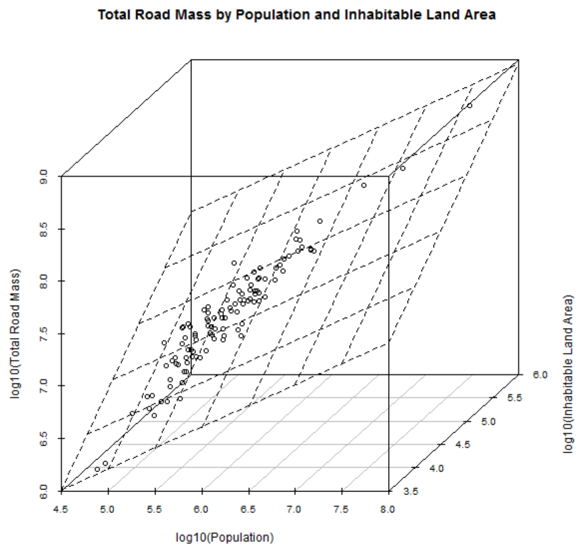

Figure 10. log-log regression of road mass by population and inhabitable land area.

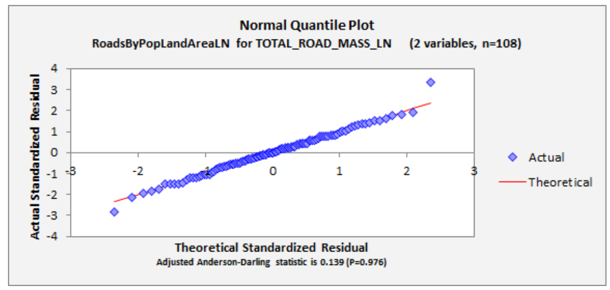

Figure 11. QQ plot for road mass by population and inhabitable land area regression.

Variable	Coefficient	Std Err	P-value	Lower95	Upper95	Std Dev
Constant	4.671	0.238	0.000	4.200	5.142	
Inhabitable_Land_Area_LN	0.617	0.034	0.000	0.550	0.685	0.814
Nighttime_Population_LN	0.403	0.028	0.000	0.347	0.459	0.982

Table 1. Coefficient Estimates: RoadsByPopLandAreaLN for TOTAL_ROAD_MASS_LN (2 variables, n=108).

Population Data
Population data was obtained from the Gridded Population of the World (GPW) dataset, Version 4[8]. This dataset is a raster at 1 km spatial resolution to provide population estimates for the entire world surface. The GPWv4 data for Japan was derived from 2010 Japan census data, therefore of the same currency as the material stock data. A major caveat in the use of the GPWv4 data is that for Japan, population is recorded at the municipality level, so the raster normalizes this population across all cells of the municipality and there is no meaningful difference from cell to cell within a given municipality.

Municipality Data
Data on municipalities for the date 2009-10-01 (n=1799) was obtained from Kirimura[9]. Municipality polygons were overlaid on the GPW and material stock data (using FME) to obtain TOTAL_POPULATION, TOTAL_ROAD_MASS, and TOTAL_BUILDING_MASS measures for each municipality.

UEA (Urban Employment Area) data
Data on Urban Employment Areas (UEAs) was obtained from Kanemoto[10] in tabular form. This was spatially joined with the municipality data to aggregate municipalities into UEAs, including both MEAs and McEAs with appropriate statistical information added. The resulting polygons were overlaid on the material stock data (using FME) to obtain TOTAL_ROAD_MASS and TOTAL_BUILDING_MASS measures.

Scaling Analysis
Scaling analysis was performed in Excel (including the RegressIt plugin) and R as appropriate. A linear regression was performed on log-log transformed variables and the resulting fit was calculated using both the Anderson-Darling test (Excel/RegressIt) and the Breusch-Pagan test (R).

Economic Analysis
The analysis looked at the relationship between per-capita building mass and various socioeconomic variables using a non-parametric kernel regression estimation in Python.

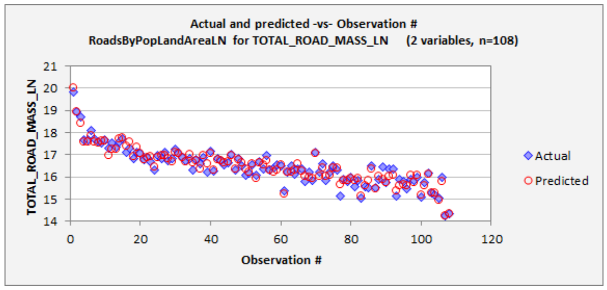

Figure 12. Actuals and predicted values for road mass by population and inhabitable land area regression.

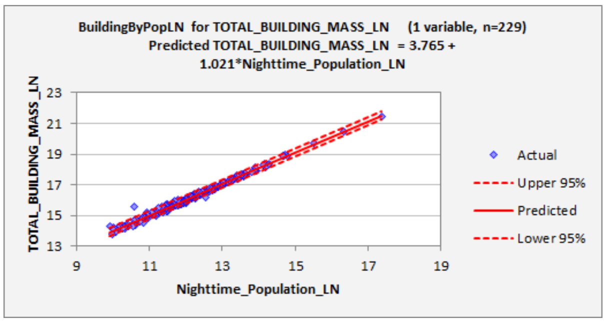

Figure 13. Ln-ln regression of MEA and McEA building mass by population.

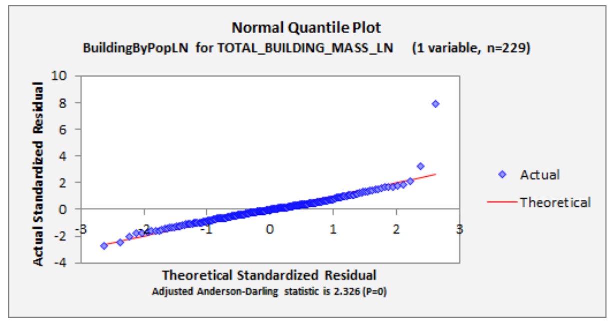

Figure 14. QQ plot for MEA and McEA building mass by population regression.

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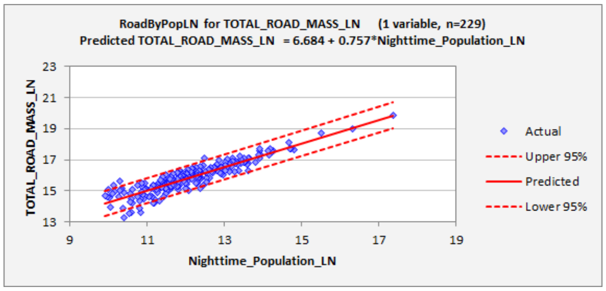

Figure 15. Ln-ln regression of MEA and McEA road mass by population.

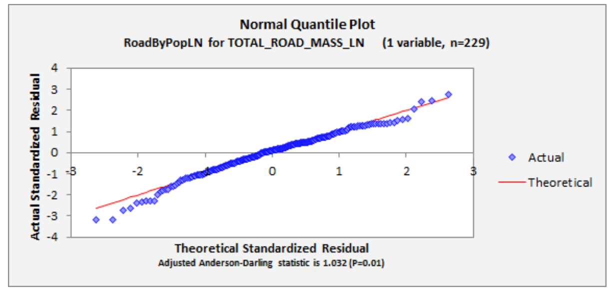

Figure 16. QQ plot for MEA and McEA road mass by population regression.

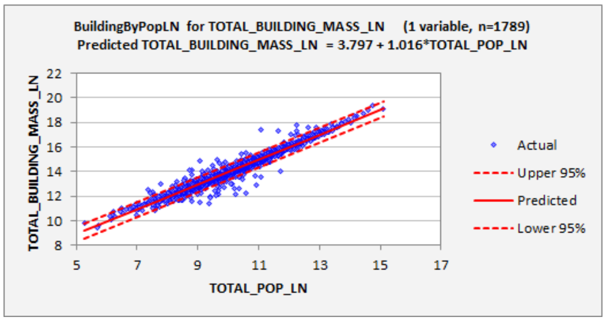

Figure 17. Ln-ln regression of municipality building mass by population.

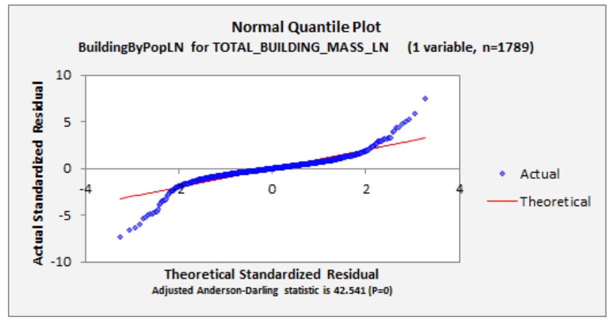

Figure 18. QQ plot for municipality building mass by population regression.

Author contributions statement

L.S. conceived the project and conducted literature reviews, E.B. conducted the GIS data processing and the scaling analysis, L.S. and E.B. analyzed the scaling results, D.I. and L.L. conducted the economic analysis and analyzed its results.

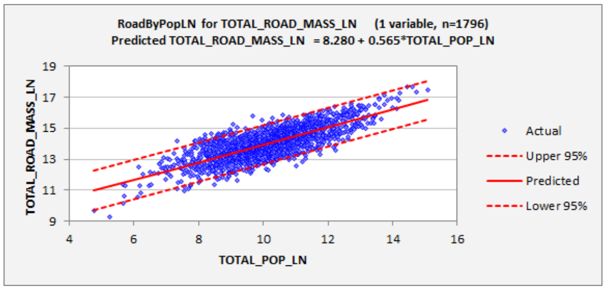

Figure 19. Ln-ln regression of municipality road mass by population.

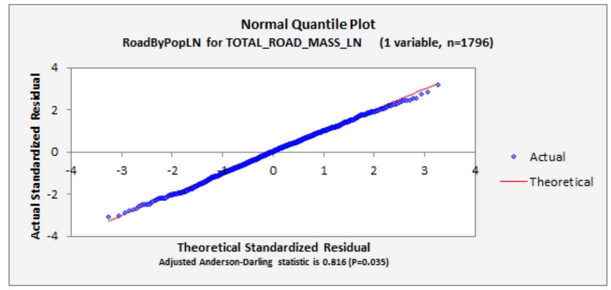

Figure 20. QQ plot for municipality road mass by population regression.

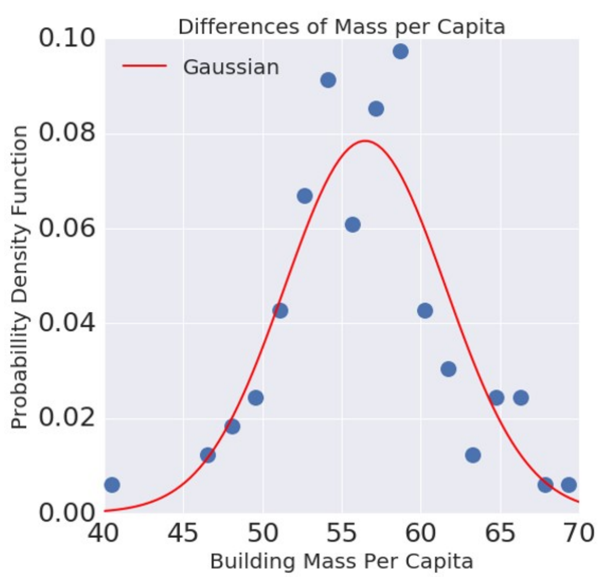

Figure 21. Per-capita building mass distribution

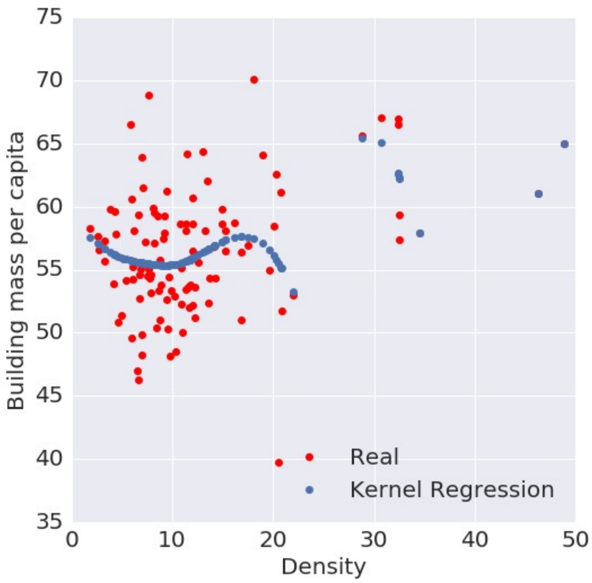

Figure 22. Kernel regression: Per-capita mass v. Inhabitable Density

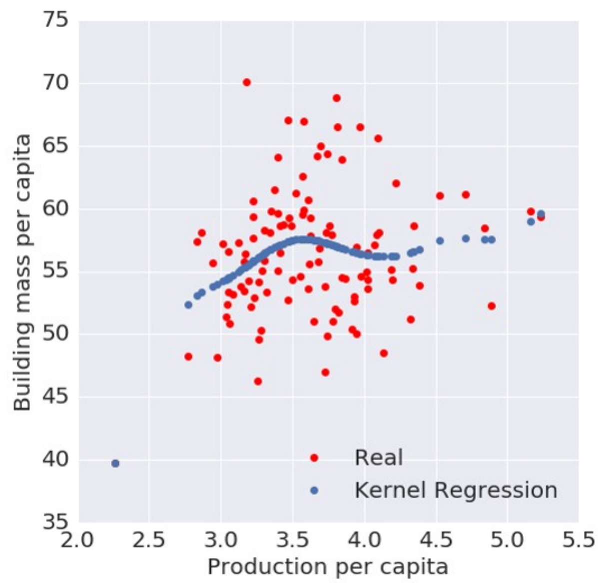

Figure 23. Kernel regression: Per-capita mass v. Total Production per-capita

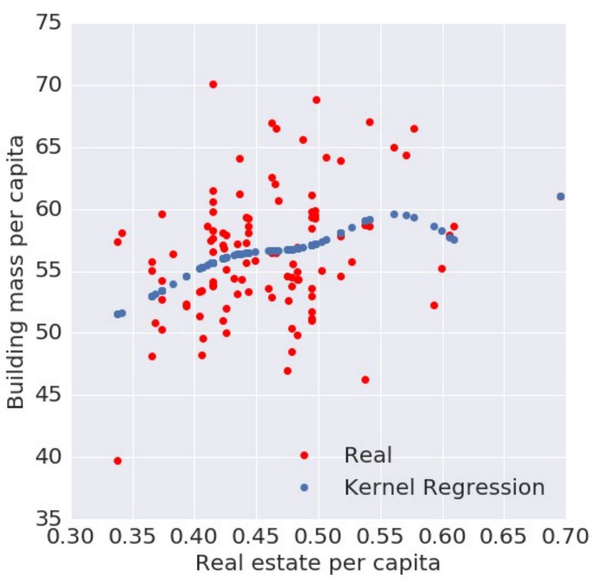

Figure 24. Kernel regression: Per-capita mass v. Size of the Real Estate Industry per-capita

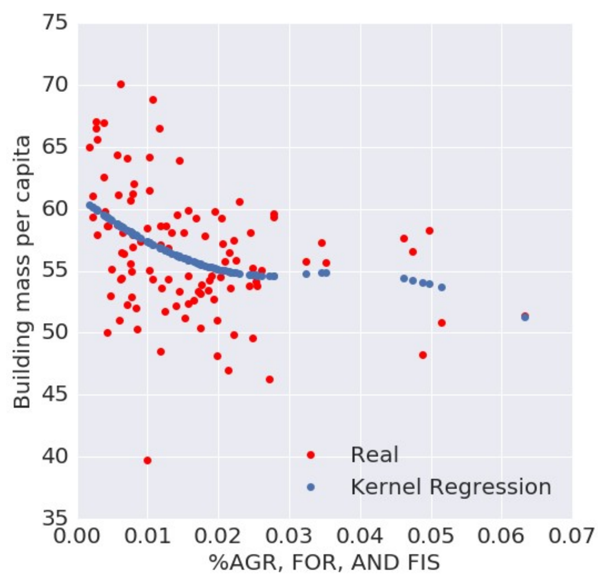

Figure 25. Kernel regression: Per-capita mass v. Share of Agricultural, Forestry and Fishery in Production

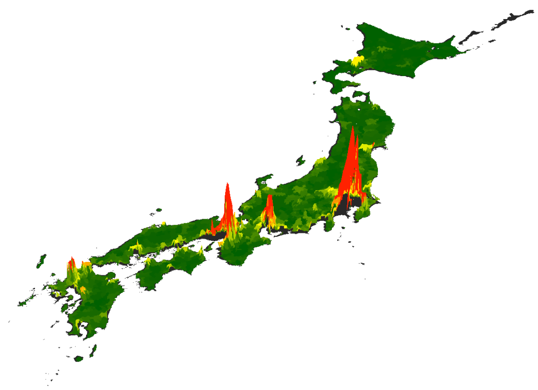

Figure 26. Spatial distribution of population in Japan, 2010. Source: Tanikawa et al.[4]