Correlation Analysis Between Land Use and Urban Street Patterns

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Abstract

Urban morphology, the study of urban forms that were formed by roads represents the result of dynamic interactions between multiple factors, such as transportation efficiency, population size, and local land use. Thus, investigating the geometry of street patterns has the potential to reveal information on the main factors in street pattern systems that drive the formation of street structures. In this study, we speculated and validated our hypothesis that among multiple factors, land use in each region contributed significantly to determining the area of the urban blocks bounded by roads; we found that the areas of urban blocks and land use were closely connected. The results showed that the block area tended to be larger in regions where land use was predominantly meant for companies and schools, while it tended to be smaller in regions where land use was predominantly for residential purposes. This trend in land use, which has been difficult to evaluate quantitatively, was defined clearly for the first time when the concept of land use was examined from the perspective of the ratio of daytime to nighttime population (RDN), which represents the amount of human movement in an urban area.

Introduction

Street patterns developed in urban areas globally reflect the result of the interaction of various geographic, socioeconomic, and historical factors, such as the access and distribution efficiency, population size, and traffic volume of the target city [1–5]. The construction of a hierarchical road network form under such multiple constraints is similar to the formation of structures by self-organization [6–10]. Among other influential factors, land use [11, 12] in each region might be the main factor in determining urban morphology, especially the size of blocks — defined as cells formed by streets [13–15]. Here, the term “land use” refers to the purpose for which land is used most frequently. Ideally, when new facilities are planned, they should be determined by the needs of the people who will use the land [16]. Observing the street patterns on a map, it was expected that a certain block size would be needed for constructing parks, large buildings, and universities. On the other hand, old residential and shopping regions may require smaller block areas than these areas do. Therefore, it is reasonable to assume a significant correlation between land use and block size. Several similar studies have reported on the interpretation of block areas, such as the difference between urban and rural regions [17] and that between the building lots and natural regions in cities [14]. However, none of these studies has examined the relationship between land use and the area of urban blocks. Therefore, we conducted a correlation analysis to clarify this relationship.

The term “land use” refers to an abstract concept and trying to concretize it using quantitative indicators raises several problems. When quantifying land use, it is necessary to define categories according to the different purposes of land use. This categorization is difficult because actual land use is extremely variable. If the number of groups in a land-use category is too small, the evaluation of land use will be inaccurate. Conversely, if the number of groups is too large, it becomes difficult to detect the regional features of land use. In addition, it is not possible to define a single all-encompassing purpose for land use when several complex buildings with different functions, such as offices, stores, entertainment facilities, housing complexes, and medical care units, are built. Such problems make it unrealistic to define land use in a clear way as is and express it using quantitative indicators.

Under these circumstances, in this study, we introduced an indicator that could indirectly quantify land use i.e., the ratio of daytime to nighttime population (RDN). The RDN is an excellent and powerful indicator for indirectly evaluating land use in a target region. It can determine whether a region has had an influx of people from other regions during the day. Thus, a higher RDN indicates a business or downtown region, whereas a lower one indicates a residential region. The RDN works on the concept of "population per hour," but what it actually represents is "land use." By using the RDN, it is easy to evaluate land use simply by examining the amount of population movement, avoiding the multiple issues that usually arise in land use evaluation. A schematic diagram showing the relationship between the RDN and land use assumed in this study is shown in Fig. 1.

In this study, we examined the areas of urban blocks to determine their correlation with land use. Recent empirical studies have shown that there are similarities in block size despite the fact that the mechanisms of street pattern formation differ from city to city. For example, the distribution of urban blocks has been studied in urban areas in North America, South America, and Europe, and it has been reported to follow the power law $P(A) \propto A^{-\alpha}$[14, 18–21], where α is in the interval $1 \leq \alpha \leq 3$; this power law holds for a block area, regardless of the differences between cities. Similar results have been reported for desertified patch area, glass rods/plates, fragmented food [22–25], and even the Zip law [26]. Some studies have estimated the value of α theoretically by applying the local optimization principle [27] or percolation theory [28], revealing that the main factors in the system that drive the formation of street patterns can be inferred by examining the exponent of the block area distribution. Our study focuses on land use as the main factor in influencing street pattern systems.

We examined the correlation between land use and the area of urban blocks in Tokyo, the capital of Japan. Tokyo has been undergoing active development for approximately 400 years from the 1600s to the present, and it is one of the most densely populated cities in the world that has a well-developed street pattern. In developing cities, the street pattern is still in the process of reflecting the influence of various factors [18]; therefore, it is difficult to examine the correlation between these factors and the form of the street pattern. However, a street pattern that is close to the final form of urbanization, such as that of Tokyo, can be treated as one that reflects the influence of all these factors and is suitable for verifying this correlation.

In this study, we focused on Tokyo, one of the world's largest cities, especially on the 23 special wards that were overcrowded and functioned as the economic and cultural centers of the city. Figure 2 shows the general outline and location of these wards. In this study, we adopted RDN r as a quantitative indicator of land use in each ward (2015 Census Report by the Bureau of General Affairs [29]). In the census, the daytime population was calculated by counting the places where people commuted to work or school and the people who worked or went to school at night. The nighttime population refers to the population living in the ward, which is also known as the de jure population. The color of each ward in Fig. 2 indicates the difference in the RDN, which is higher in the central region and lower in the outer edges. The central region was considered as an economic and industrial center, whereas the outer edges were considered as residential regions. As land use was clearly different between the center and outer edges, we expected that there may have been differences in the distribution of the area of the urban blocks.

Results And Discussion

Area distribution of urban blocks in the 23 wards as a whole

Figure 3(a) shows the probability density distribution of the urban blocks in the 23 wards of Tokyo. In the preliminary stage of plotting Fig. 3(a), a histogram of the area of the blocks was constructed, and the bin width was fixed at 500 m^2. Hence, in both logarithmic plots in Fig. 3(a), the interval between the data points becomes narrower as the area increases. The data points are lined up horizontally around a large area of 10^5 m^2 because of the small number of large-area blocks; the block area did not become extremely small or large. Thus, as shown in the probability distribution in Fig. 3(a), the peak value was approximately 10^3 m^2, and the frequency of occurrence decreased as the area increased or decreased. The location of the peak appeared around 10^3 m^2, which agreed with the findings in New York, USA, and Vancouver, Canada [14]. We conducted a least-squares regression analysis for area $10^3 \leq A$, which had a large block area and found that it followed the power law like other urban areas did. The correlation coefficient was R^2 = 0.96, indicating a good fit. The power-law exponent was $\alpha \approx 2.56$, which was consistent with the results of surveys in Europe, North America, and South America [14], predictions based on percolation theory [28], and theoretical values obtained by solving local optimization problems [27]. According to Fialkowski et al., the more that urbanization progresses, the more the fragmentation process of urban blocks progresses, and the larger the value of the exponent [17]. Based on this view, the result $\alpha \approx 2.56$ indicated that Tokyo was a region with significant urbanization, even from a global perspective.

The result in Fig. 3(a) describes the 23 wards as a whole. Thus, when the block area distribution was examined separately for each ward, the exponent value was different for each ward. Figure 3(b) and 3(c) show the results of the area distribution in two wards: Chiyoda and Nerima. 10^3 m^2 was the most frequently observed area in both wards. The red and blue lines in the figure represent the results of fitting using the least-squares method in the range $10^3 \leq A \leq 10^5$. The exponent values were quite different between the Chiyoda and Nerima wards. This difference in slope was caused by the difference in the ratio of the number of relatively large blocks to the total number of blocks in the target ward. The slope was gentler in wards with larger blocks and steeper in ones with smaller blocks. Comparing Figs. 3(b) and 3(c), the probability density values of the data points lining up horizontally are different. This difference can be attributed to the fact that the total number of blocks n varied from ward to ward. As the total number of blocks in the Chiyoda ward was smaller than that in the Nerima ward, the minimum probability density of 10^{-6} in the former was larger than that of 10^{-7} in the latter. The results of fitting each of the 23 wards using the same method as that in Fig. 3(b) and 3(c) are summarized in Table 1. In the next section, we show the results obtained from examining the correlation between land use and urban block areas in the 23 wards, using the results from Table 1.

Table 1
Fitting results for the area of the urban blocks in each of the 23 wards.

Ward	α	R^2	RDN
Chiyoda	-1.12 ± 0.06	0.74	1461
Chuo	-1.60 ± 0.08	0.82	431
Minato	-1.40 ± 0.04	0.87	387
Shibuya	-1.70 ± 0.05	0.89	240
Shinjuku	-1.65 ± 0.04	0.89	233
Bunkyo	-1.55 ± 0.06	0.85	158
Taito	-1.93 ± 0.09	0.84	153
Toshima	-1.85 ± 0.06	0.88	143
Shinagawa	-1.83 ± 0.05	0.89	141
Koto	-1.52 ± 0.05	0.84	122
Sumida	-1.77 ± 0.08	0.8	109
Meguro	-1.97 ± 0.07	0.85	106
Ota	-2.13 ± 0.04	0.93	97
Kita	-1.86 ± 0.05	0.89	97
Nakano	-1.98 ± 0.05	0.9	95
Setagaya	-2.24 ± 0.04	0.93	95
Arakawa	-1.65 ± 0.07	0.81	91
Adachi	-2.22 ± 0.04	0.93	91
Itabashi	-2.01 ± 0.04	0.92	90
Suginami	-2.17 ± 0.05	0.92	85
Katsushika	-2.16 ± 0.05	0.92	84
Nerima	-2.11 ± 0.04	0.94	84
Edogawa	-2.20 ± 0.05	0.91	82

Relationship between the urban block and RDN

In this section, before discussing the correlation between the RDN and block area, we discuss the relationships between the daytime population and block area, and that between the nighttime population and block area. A separate analysis of the daytime and nighttime populations revealed different trends.

Figure 4(a) shows the results from comparing the daytime population density and exponent shown in Table 1. The daytime population density is the daytime population divided by the area of the ward. Usually, the larger the area of a ward, the larger the number of people who can use the land in the ward. The daytime population was divided by the area of the ward to eliminate the effect of differences in the area of each ward. The higher the daytime population density, the more land in that ward was used for companies and schools. The red line in the graph indicates the results of the regression analysis with a correlation coefficient of 0.65. From this graph, it is obvious that the value of the exponent is smaller for wards with a higher daytime population density. This indicated that wards with more land use like that of companies and schools had a larger percentage of blocks with larger areas. The interpretation of this result is discussed in section 3.3.

Figure 4(b) shows the results of comparing the nighttime population density with the exponent. Similar to the daytime population density, the nighttime population density is the nighttime population divided by the area of the ward. The higher the nighttime population density, the more land in that ward was used for residential purposes. The blue line in the graph indicates the results of the regression analysis with a correlation coefficient of 0.06. This result clearly shows that there is no correlation between the block area and the nighttime population. It is worth noting that the range of values for the nighttime population density was narrower than that for the daytime population density. We attributed this difference to the fact that the space required per person for offices, schools, and houses was different. In the case of a company or school, at least one desk space per person was sufficient for deskwork. However, more space was required for housing. Consequently, land used for a company or school can be available to many people even if the land is small, and the value of the daytime population density can be large. Meanwhile, in the case of housing, because there is a limit on the number of people who can use the land, the value of the nighttime population density is unlikely to be large.

The results in Fig. 4 revealed trends for the daytime and nighttime populations. However, the actual area of an urban block was expected to be determined by the balance of requirements for both daytime and nighttime land use. The RDN was used to determine what time there was more land use for a target ward. Therefore, we analyzed the correlation between the area of the urban blocks and RDN, an indicator of both daytime and nighttime balance.

Correlation analysis between RDN r and exponent α

In this study, we adopted RDN r as a quantitative indicator of land use and conducted a correlation analysis between RDN r and the block area for each ward. The results are shown in Fig. 5. The straight line in the figure shows the result of the fitting, and the correlation coefficient is $R^2 = 0.55$. The graph shows that r and α have a negative correlation. Thus, the higher the ratio r, the larger the blocks tend to be, whereas the lower the ratio r, the smaller the blocks tend to be. This trend can be understood more clearly by looking at the color map of the block shown in Fig. 5, which compares the two wards with different r-values. In Fig. 6(a), Chiyoda ward has the smallest α and the largest r among the 23 wards, corresponding to the blue triangle symbol in Fig. 5. We examined land use within a region of 10^4 or more; it was used for purposes that required a certain amount of block area, such as the Imperial Palace, government offices, parks, skyscrapers, and universities, as indicated by the asterisk symbol in the figure. In business and downtown regions where people gathered during the daytime, it was natural to understand that the stronger the trends in land use, the more the requirements for the installation of large facilities, and the more the block area tended to increase. In contrast, the Nerima ward in Fig. 6(b) has the largest exponent value among the 23 wards, and the ratio r is below 100, indicating that it is an area where the population flows out during the daytime. This corresponds to the red squares symbol in Fig. 5. As seen from the color map of the block, Nerima ward has a very large number of areas with a block area of 10^4 m^2 or less. In addition, these small blocks are often used as residential regions, other than those marked with asterisks in Fig. 6 (b). Therefore, the result in the upper left of the graph in Fig. 5 reflects the fact that regions with a ratio r less than 100 are in high demand as residential areas, and thus, do not require a large block area.

Previous studies with research objectives similar to those of this study interpreted the block size as follows. Riascos compared the distribution of block areas close to the city center and rural regions a few km away from the city center. The study reported that the area distribution of the urban and rural regions was $\alpha \approx 2$ and 1, respectively [14]. Fialkowski et al. demonstrated that the block area distribution in regions with dense buildings was $\alpha \approx 3$, whereas that in regions with a lot of nature was $\alpha \approx 1$[17]. Similarly, previous studies have shown that the value of the exponent increased in regions with more buildings near the center of the city and decreased in regions with more nature at the outer edges of the city.

According to the results of this previous study, we can infer the following regarding land use. The block areas in the regions used as business centers are located in the center of the city and might have more buildings. Therefore, the exponent value is likely to be large in these regions. On the other hand, regions that are mainly used for residential purposes can be assumed to be located on the outer edges, away from the city center, and often have more parks. Thus, the exponent value is likely to be small there. Surprisingly, the results obtained in this study contradicted this assumption. We were able to demonstrate the unexpected tendency of land use and street patterns by conducting this verification for the first time. Although our study focused only on Tokyo, we speculate that other cities that have experienced the doughnut effect — a development where the city center becomes more hollow or empty, as businesses and people move into the outskirt of the city — may also show similar trends in terms of RDN and urban blocks.

Conclusions

The significant finding of this study was the negative correlation between the area of blocks and land use in the 23 wards of Tokyo. The block area tended to be larger in business and downtown regions and smaller in residential regions. By conducting this correlation analysis, we were able to reveal unexpected tendencies in land use and street patterns. The analysis indicated that the block area was strongly influenced by the land use of each region and that the exponent α was useful as a characteristic quantity to represent the land use of a region. This also suggested that urban street patterns could not be analyzed solely by the fragmentation process of the block area.

A noticeable contribution in this study is the introduction of the RDN as an indicator of land use. By using the RDN, the land use of the target region can be easily expressed in an indirect way, without directly dealing with the issues that usually arise in evaluating land use. We believe that this evaluation indicator will support a new direction for research on urban morphology and planning.

Methods

The map data (Vector White Map [30]), published free of charge by the Geospatial Information Authority of Japan (GSI), were used to calculate the area of the urban blocks. The map data were imported into ArcGIS (Esri), a geographic information platform, and image analysis was performed using the procedure shown in Fig. 7 to calculate the area of the urban blocks. The analysis procedure was as follows:

i. The vector white map was imported using only the roads displayed in GIS. This image was assigned Cartesian coordinates to reflect the actual scale.
ii. Binarization was applied to the image. Binarization refers to the process of converting an image into two shades, black and white. In this case, we converted the road part of the image into black and the other part into white. This process made it easier to extract the road information.
iii. The GIS was set up to automatically recognize the road, which is the black part of the binarized image. For a polygon surrounded by roads, a file called a shapefile that integrated information about the position, shape, and attributes of the figure was created.
iv. Using the shapefile, the area of the polygon was calculated.

The above image analysis was done for all 23 wards.

Declarations

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Author contributions

Y. A and M. S conceived and designed the study, contributed to the method development, and interpretation of results. Both authors contributed to the writing of the manuscript. Y. A contributed to image analysis, literature collection and to the manuscript preparation. M. Y conducted the image analysis and contributed to the improvement of the analysis method. H. S contributed to the writing of the manuscript.

Data availability statement

The datasets used in this study will be stored on Figshare, and their copies are temporarily uploaded as supplementary Information for review purposes (Tokyo_area.csv).

Additional information

Competing interests

The authors declare no competing interests.

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Figures

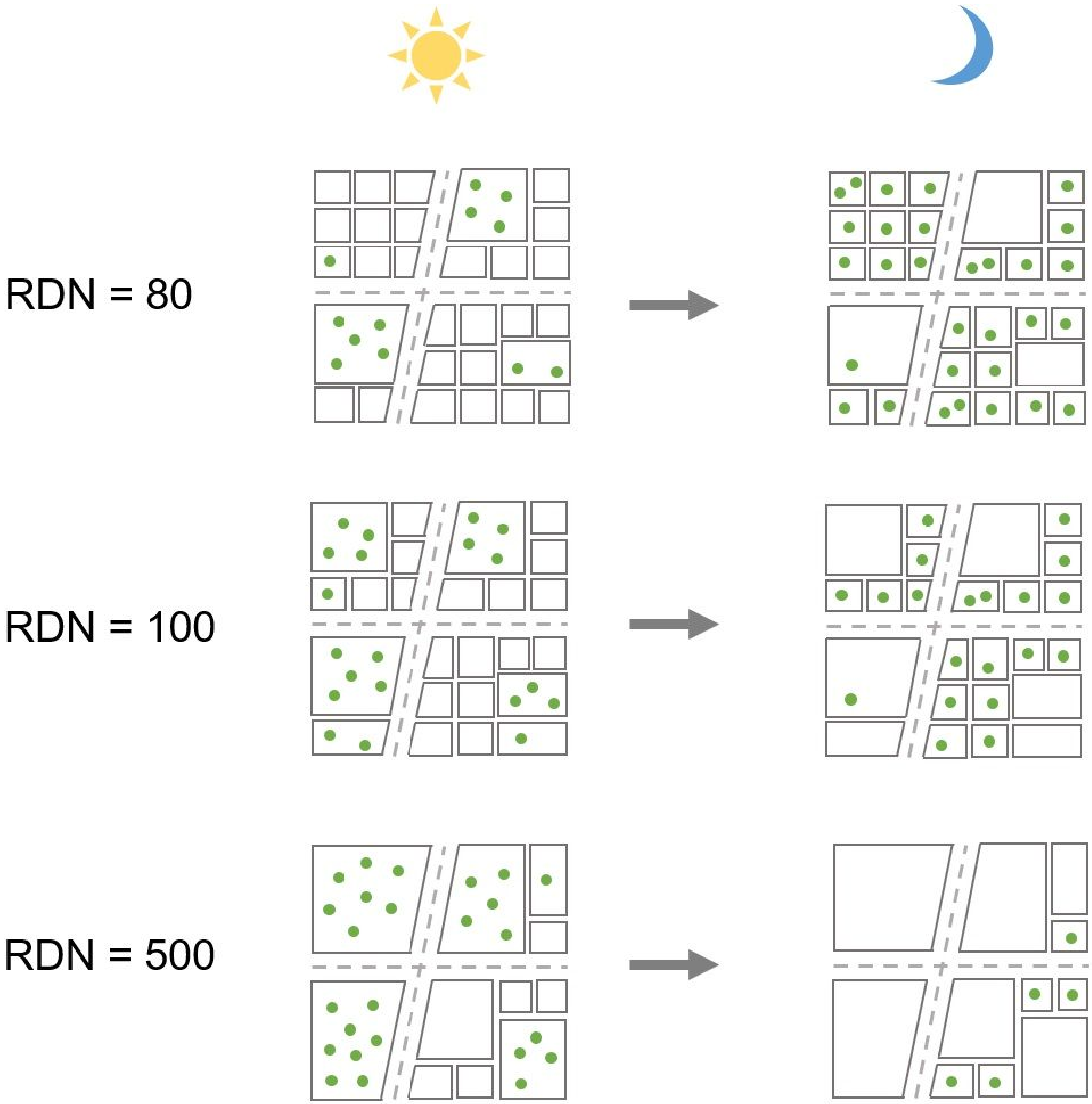

Figure 1

Schematic diagram showing the relationship between RDN and land use.

The left side shows the daytime, and the right side shows the nighttime. The green dots represent people and the number of dots corresponds to the value of the RDN. In this study, we expected that companies and schools, where many people gathered during the daytime, would have a large block area, whereas houses, where people mostly gathered at night, would have a small block area.

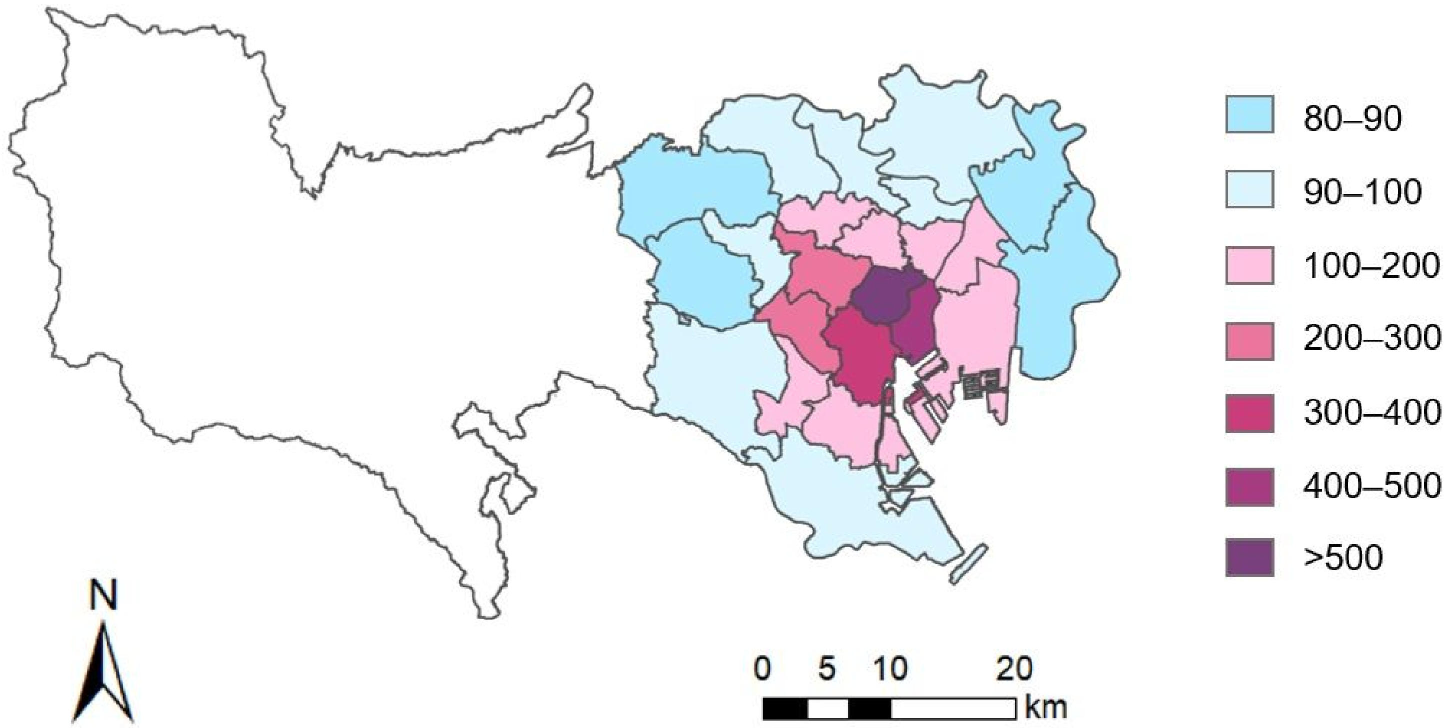

Figure 2

Outline and location of the 23 wards (special wards) and their RDNs.

The areas in color on the right half of Tokyo are the special wards that had central urban functions. The RDN was colored with 100 as the border, with red wards having a daytime population inflow and blue wards having a nighttime population inflow; the darker the color, the stronger the trend. As seen in this figure, the RDN is decreasing in concentric circles around the Chiyoda ward (r = 1461), which has the highest ratio.

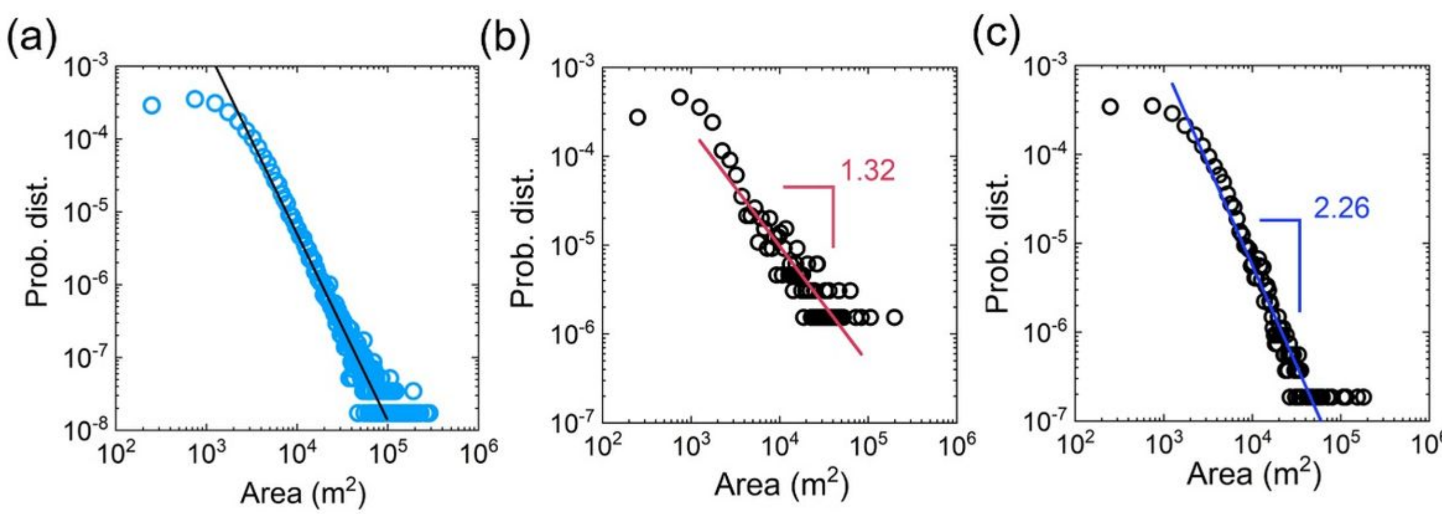

Figure 3

Probability distribution of the area of urban blocks.

a) The whole of Tokyo's 23 wards. The vertical and horizontal axes are both logarithmic, and the straight line in the graph shows the result of the regression analysis for $10^3 \leq A$. The correlation coefficient is R^2 = 0.96, which is a good fit, so it follows the power law. In addition, the power-law exponent is α ≈ 2.56 which is consistent with the results for the other urban cities. b) Chiyoda ward: *n* = 1306. c) Nerima ward: *n* = 10812. The straight line in the figure shows the result of fitting, and the exponent is α ≈ 1.32 in the Chiyoda ward and α ≈ 2.26 in the Nerima ward.

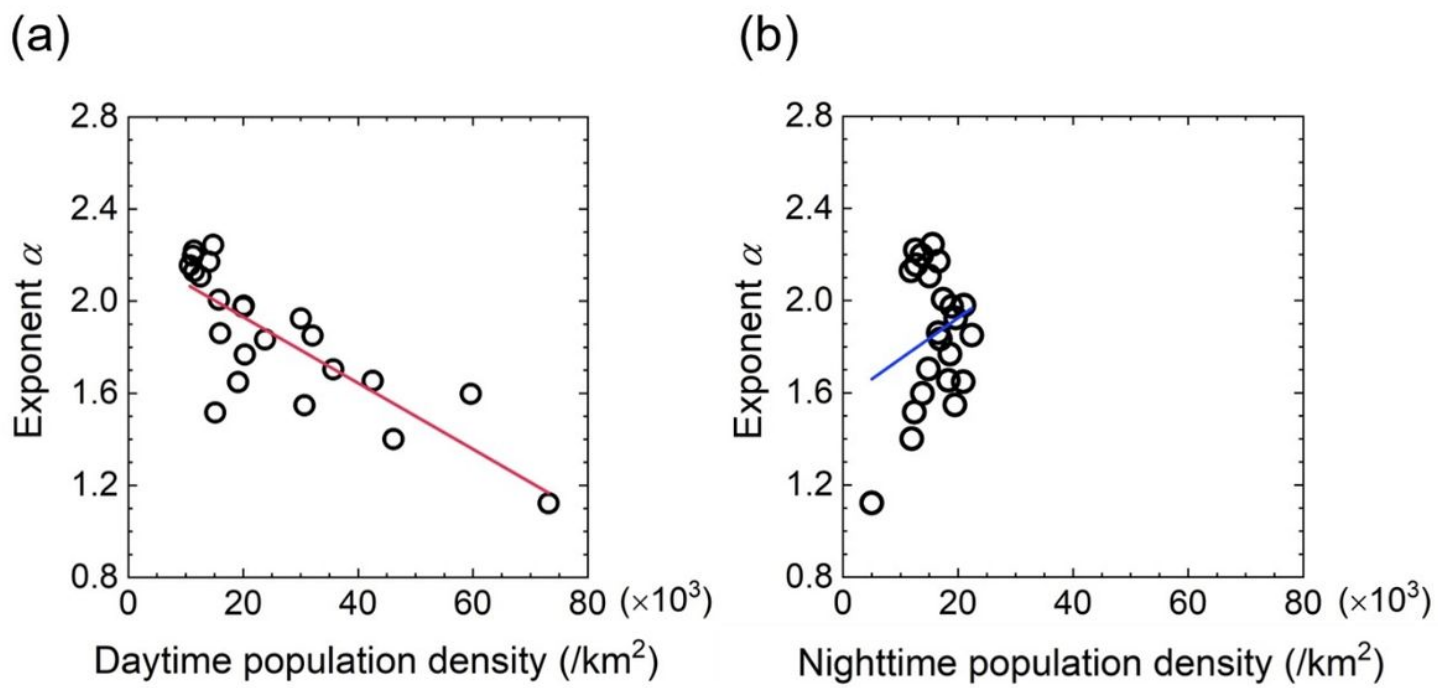

Figure 4

Relationship between the area of the urban block and the (a) daytime population and (b) nighttime population.

The straight line in the figure shows the result of fitting, and the correlation coefficient is R^2 = 0.65 in the daytime population and R^2 = 0.06 in the nighttime population.

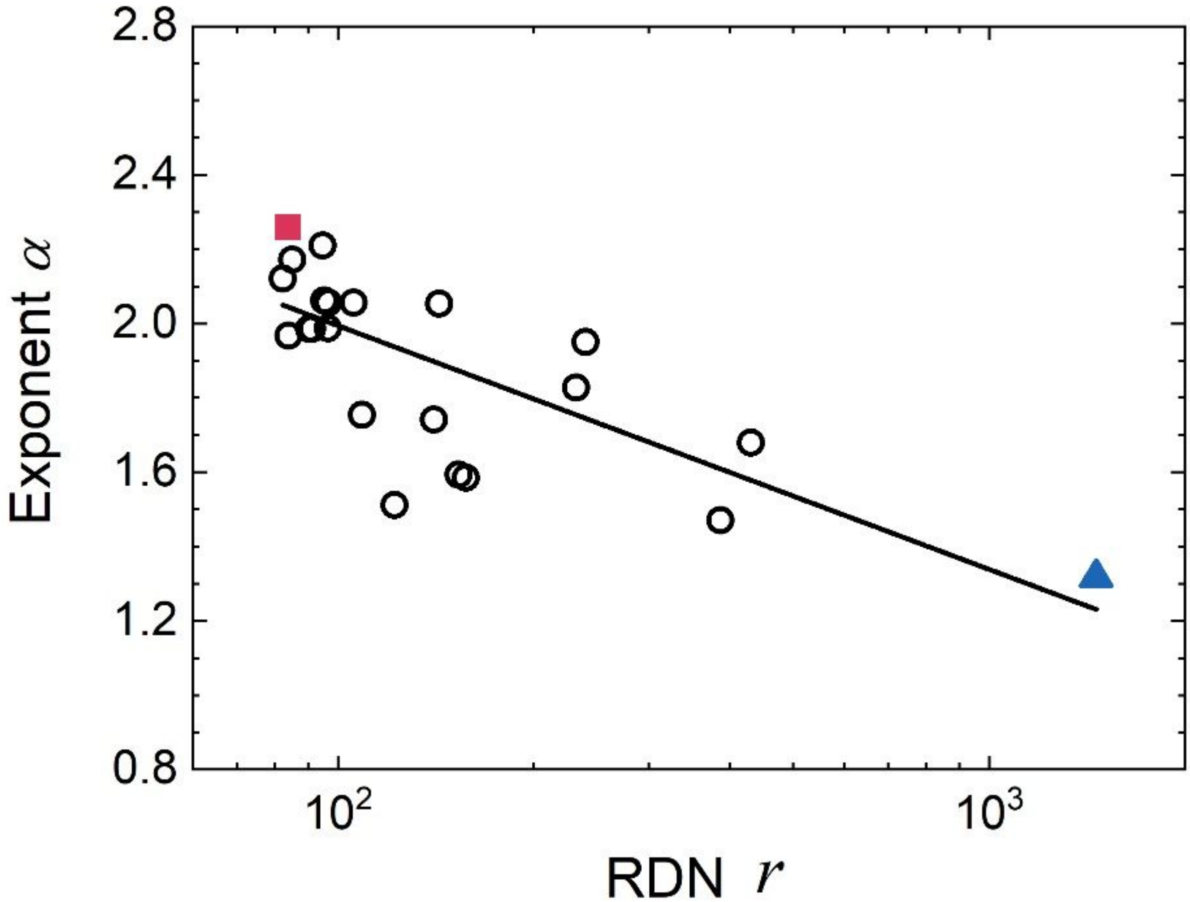

Figure 5

Comparison of RDN *r* and exponent *α*.

The RDN on the horizontal axis is logarithmic. The symbols in the blue triangle and the red square indicate the Chiyoda and Nerima wards, respectively. The straight line in the figure shows the result of the fitting, and the correlation coefficient is $R^2 = 0.55$.

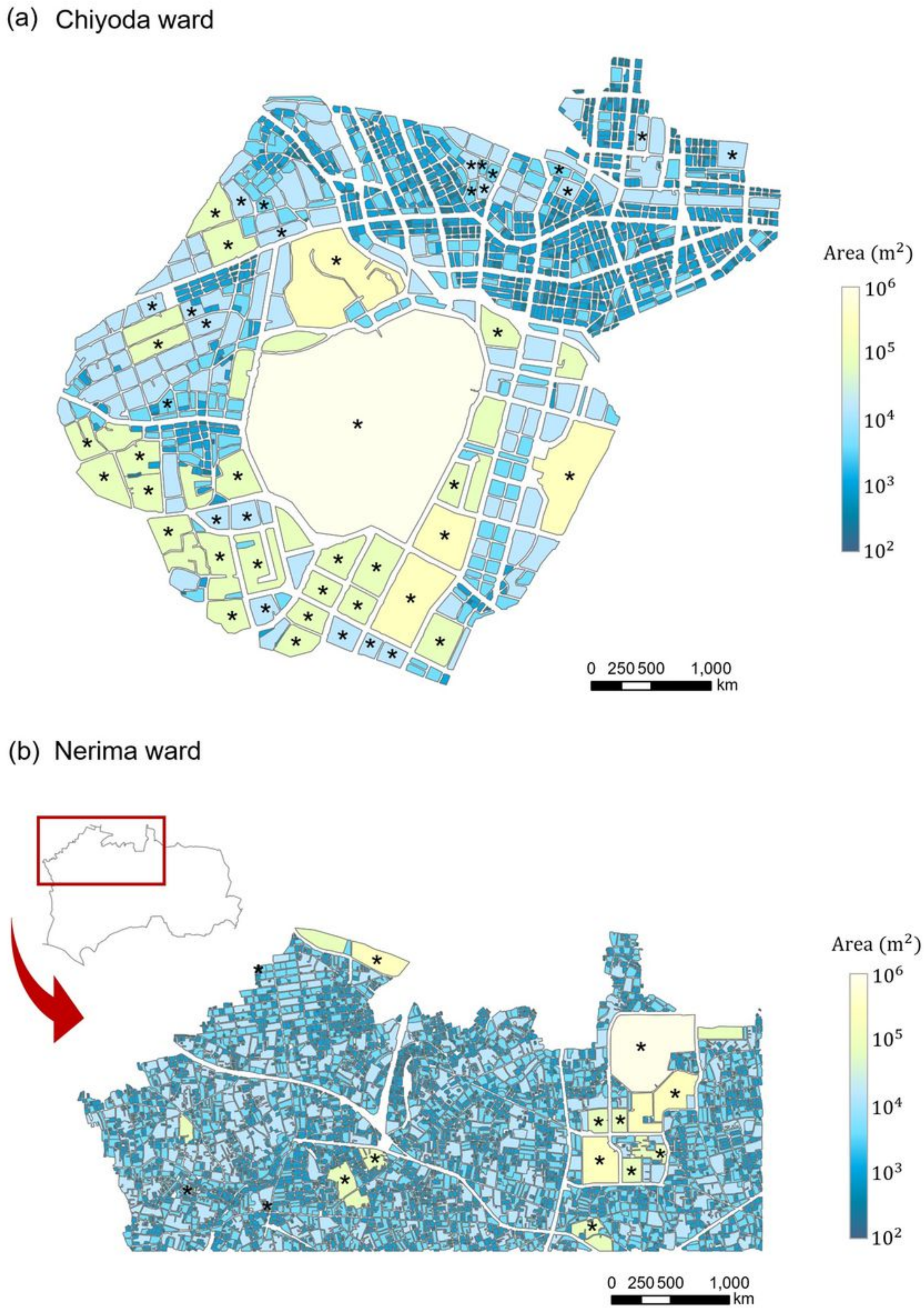

Figure 6

Color map of the area of urban blocks in the a) Chiyoda ward, where the exponent is the smallest among the 23 wards, and the b) Nerima ward, where it is the largest.

The logarithmic area indicates that the darker the shade of blue, the smaller the area. In the Chiyoda ward, regions with a large area of blocks are prominent. This is due to the construction of large facilities such as government offices, parks, large commercial facilities, and universities, indicated by the asterisk symbol. In Nerima ward, on the other hand, regions with a small area are prominent, indicating that such small blocks are mainly used for residential purposes.

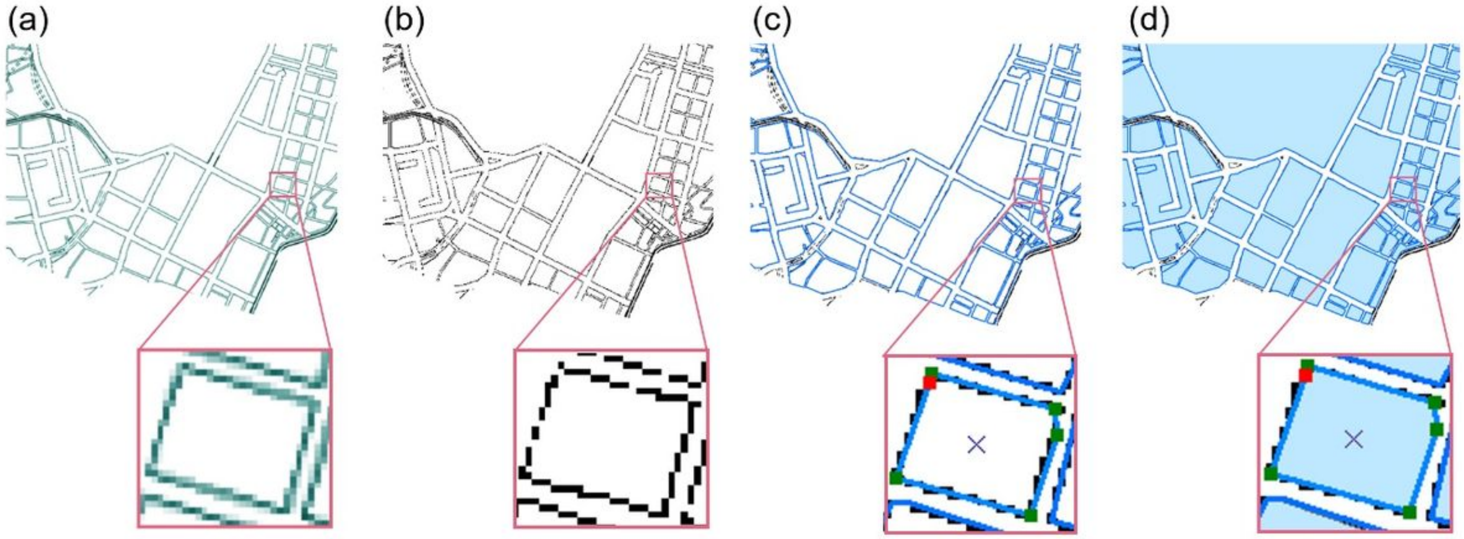

Figure 7

Image analysis procedure of a map in ArcGIS.

a) The map data are imported into ArcGIS. b) The image is binarized and converted into a raster image. The outer edge of the urban block is converted to black and the rest of the area to white. c) The raster image is converted to a vector image so that only the outer edges of the urban block will be automatically recognized and traced with lines. d) The area surrounded by lines is converted into polygon data and a shapefile is created with the number of vertices and position information of the polygon.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Tokyoarea.csv