Quantitative analysis of relationships among building density, height, land surface temperature, and population density in Tokyo

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ABSTRACT: With the accelerated development of urbanization and rapid population growth, the pattern of urban buildings is changing. As an important component of urban structure, buildings have complex relationships with the surface thermal environment and human habitation. In this study, we selected the area around Shinjuku, Tokyo as the study area. The datasets used in this study were airborne thermal infrared image, airborne LiDAR data, building footprint data, and population census data. The relationships among building density, the height of roughness elements (mean height), mean land surface temperature (LST), and population density were quantified at the grid scale using correlation analysis. The results showed that: (i) The correlation ($p < 0.001$) with mean LST was most strong for building density ($r = 0.6718$), followed by population density ($r = 0.6050$) and mean height ($r = –0.3814$). (ii) Building density was positively correlated with population density ($r = 0.4949$, $p < 0.001$). The research hopes to provide a reference for further seeking the coordinated and balanced development of environmentally sustainable and energy-efficient cities.

1. INTRODUCTION

In recent years, with the rapid advancement of urbanization and the continuous increase of population density, the boundaries of building development have continued to expand, and the construction intensity has remained high. After large-scale engineering construction, the natural conditions of the original underlying surface have changed, resulting in changes in the thermal environment around the buildings (Parsaee et al., 2019).

Tokyo has grown very rapidly in the past few decades and studies have shown the relationships between urban growth and population density (Bagan and Yamagata, 2012, 2015). Nowadays, Tokyo has formed a large number of high-density building clusters and has housed a large population. Environmental problems (e.g., the urban heat island effect) continue to intensify. The urban heat island effect will cause the deterioration of the air environment, the deterioration of water quality, and the destruction of the biological living environment, seriously threatening the health of urban residents and the ecological environment (Tan et al., 2010). The height of roughness elements (mean height) and building density in cities are the basic parameters of urban spatial morphology (Berger et al., 2017; Huang and Wang, 2019). Therefore, the main objective of this study was to investigate the relationships among building density, mean height, mean LST, and population density at the grid scale.

2. METHODOLOGY

2.1 Study area, data, and preprocessing

Our study area is located in the central part of Shinjuku, Tokyo (Fig. 1). The study area includes parts of Shinjuku-Ku, Shibuya-Ku, Nakano-Ku, Toshima-Ku, Chiyoda-Ku, and Minato-Ku. Shinjuku station is included in our study area. The study area covers approximately 22.25 km^2, with various buildings.

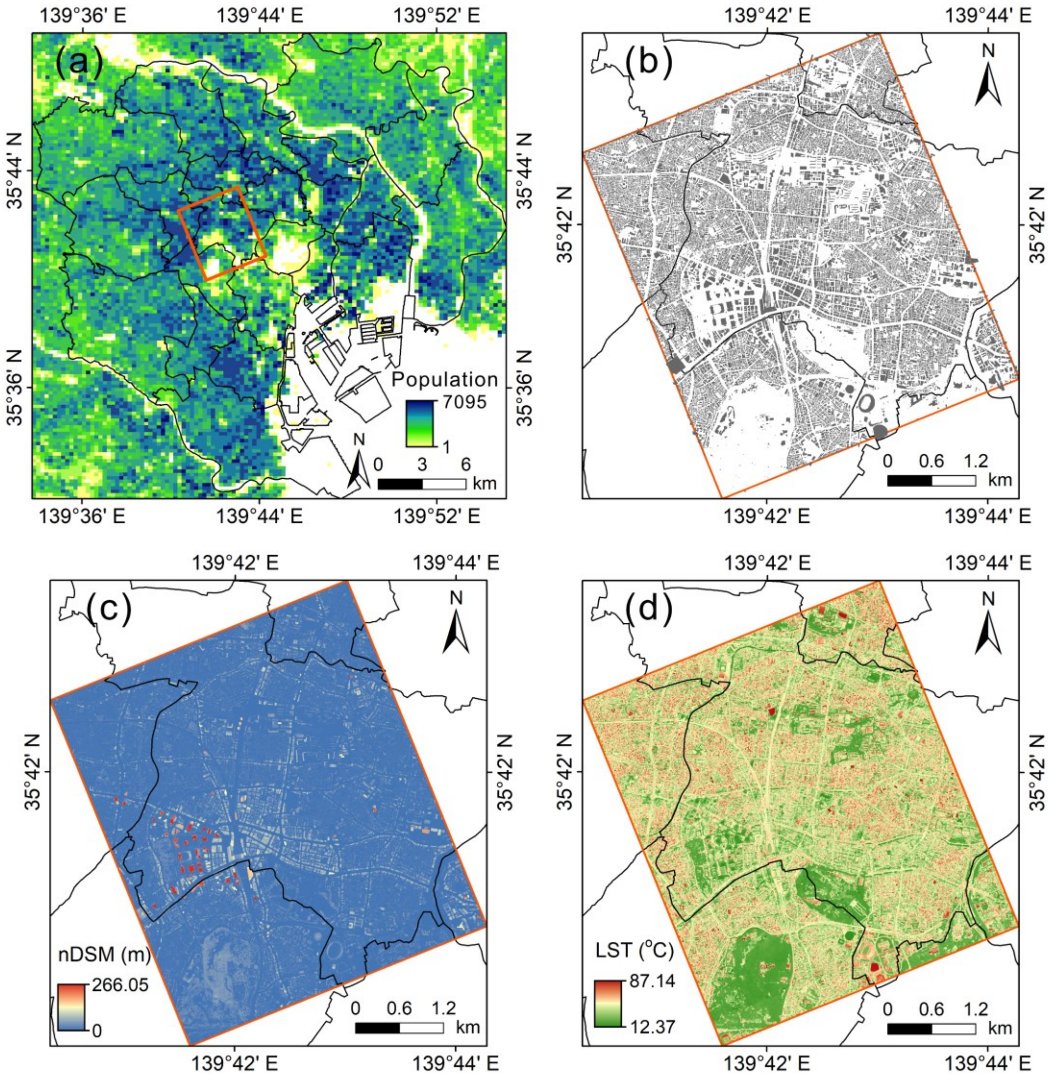

Fig. 1. (a) Location of the study area (red rectangle) and 2015 population density map for Tokyo; (b) building footprint (Zmap-TOWNII product); (c) nDSM (0.5-m spatial resolution); (d) summer daytime LST (2-m spatial resolution).

The datasets used in the study were airborne thermal infrared image, airborne LiDAR data, building footprint data, and population census data (Table 1).

The airborne thermal infrared image was obtained from the aerial flight that was conducted on 19 August 2014 (12:01–12:50 [local time]). The LST at a spatial resolution of 2 m was derived from this daytime thermal infrared image by orthorectification.

The LiDAR point cloud data were used to generate a digital surface model (DSM) and a digital terrain model (DTM) at a grid cell size of 0.5 m. A normalized digital surface model (nDSM) at a grid cell size of 0.5 m was then generated by the following equation:

$$nDSM = DSM - DTM \tag{1}$$

The building footprint data was obtained from the ZENRIN Company's residential map database (Zmap-TOWNII product).

The population census data, in the form of a grid coordinate system (mesh), were available from the Statistics Bureau of Japan. We chose the 2015 population census data consisting of small meshes of about 250 m based on a latitude interval of 7.5 seconds and a longitude interval of 11.25 seconds.

Table 1. Summary of data used in this study.

Data	Date	Spatial Resolution
Airborne thermal infrared image	19 August 2014, 12:01–12:50 (local time)	2 m
Airborne LiDAR data	2001–2002	4–5 points/m^2
Building footprint product (Zmap-TOWNII product)	2017	Polygon vector (irregular)
Population census data	2015	Polygon vector (mesh)

2.2 Correlation analysis at the grid scale

In this study, we used small meshes of about 250 m from the 2015 population census data as the unit of statistical analysis. To calculate the building density, the building footprint vector was intersected with the statistical meshes. The building density was then obtained by dividing the area of the building footprints within the statistical meshes by the area of the statistical meshes. The mean height was obtained by averaging the pixel values of the nDSM rasters (0.5-m pixel spacing) within the statistical meshes. The mean LST was obtained by averaging the pixel values of the LST rasters (2-m pixel spacing) within the statistical meshes. To examine the relationships among building density, height, land surface temperature, and population density, we used Pearson's correlation coefficient (Pearson's r).

3. RESULTS

It was found that building density, mean LST, and population density were significantly correlated positively ($p < 0.001$) (Fig. 2). The mean LST was strongly and positively correlated with building density ($r = 0.6718$, $p < 0.001$) and population density ($r = 0.6050$, $p < 0.001$). There was also a positive correlation between building density and population density ($r = 0.4949$, $p < 0.001$). The mean height was correlated negatively with the mean LST ($r = –0.3814$, $p < 0.001$). The study area was characterized mainly by low heights. The mean LST in the study area was mostly high (around 40°C).

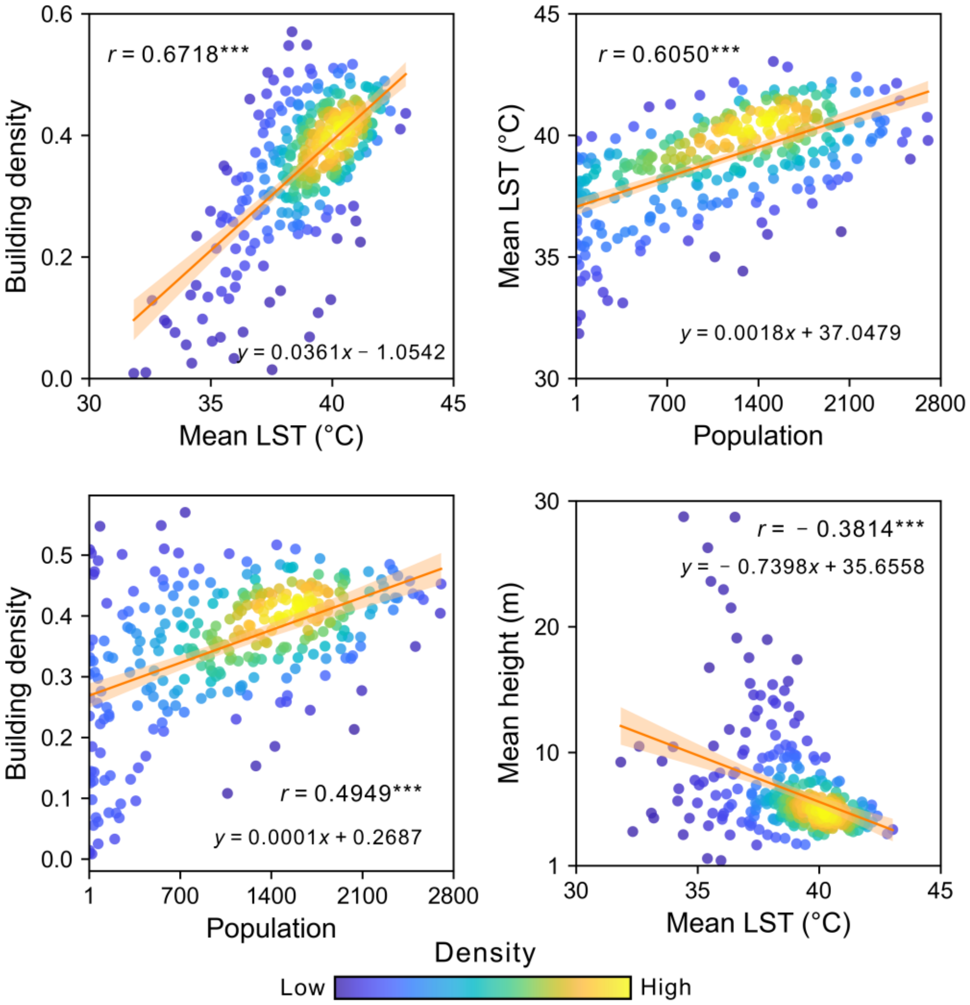

Fig. 2. 2D density scatter plots (using Gaussian kernel density estimates) of the relationships among building density, mean height, mean LST, and population density. The Pearson correlations were calculated using data for all 313 statistical meshes (about 250 m) (*p < 0.05, **p < 0.01, ***p < 0.001). Solid lines represent the results of linear regression analysis, and the area around the solid lines represents the 95% confidence interval of the regression line.

4. CONCLUSION AND DISCUSSION

As the building density increased, the mean LST during daytime in the summer and population density tended to increase. High building density may impede air circulation and trap heat. In addition, high building density may indicate more human habitation. Population density may have a negative effect on the thermal environment. The increase in population density may lead to an increase in anthropogenic heat discharges. The negative correlation between mean height and mean LST may be explained by shadows and aerodynamic differences.

Due to the many influencing factors of the urban thermal environment, the interactions between the artificial environment and natural conditions are complex. Various studies are affected by many factors (e.g., data used, analytical methods, variables included, short-term meteorological conditions, etc.), leading to current concerns about the impact of urban morphology on the thermal environment.

Based on the above conclusions, corresponding suggestions can be provided for improving the thermal environment of Tokyo's high-density urban areas. First of all, building density can be controlled appropriately, which can be implemented in conjunction with urban construction and renewal. In addition, the coverage of green spaces or water bodies can be increased to reduce building density in order to improve the urban thermal environment. Secondly, anthropogenic heat discharges can be reduced through better control of population distribution.

5. ACKNOWLEDGMENTS

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