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Measurement of urban built-up volume using remote sensing data and geospatial techniques

Manjula RANAGALAGE [a] and Yuji MURAYAMA [b]

Abstract

The vertical analysis is becoming more important to capture rapid changes in urban growth. It helps to measure the urban intensity of complex urban land use pattern. The development of geospatial technology provides a sophisticated methodology to examine the changing urban environment. At present, the satellite images of medium resolution including ALOS PRISM DSM have become more popular due to the availability and vast range of coverage. The grid-based method has been used to obtain the urban volume (UV) with the surface feature height (SFH) which was extracted from the difference between digital terrain model (DTM) and digital surface model (DSM). In this study, an attempt was made to develop a new method to generate DTM based on ALOS PRISM DSM by using buffer distance from building footprint data. The buffer distances of 5 m, 10 m, and 15 m were used to select minimum DSM points generated by the grid-based method. The selected points were used to produce DTM by employing empirical Bayesian Kriging surface interpolation method. The SFH derived from the 10 m buffer zone of each building showed the lowest root-mean-square error (RMSE). This modified approach is valuable to grasp changing urban dynamics.

Key words: ALOS PRISM, DSM, DTM, SFH, Tsukuba, building footprint, urban volume

1. Introduction

Knowledge on urban diversity such as the intensity and distribution of urban land use is getting more attention in academic disciplines including urban morphology, urban geography, urban ecology, urban sustainability and so on (Koomen *et al*., 2009; Estoque *et al*., 2015; Ranagalage *et al*., 2018). The changes in urban environment lead to transformations in urban intensity. In this connection, urban growth approach focusing on the horizontal two-dimensional is not always sufficient to trace the urbanization process (Koomen *et al*., 2009). Hence, a three-dimensional (3D) approach different from the traditional method is required to fully grasp the mechanism of the complex urban diversity (Koomen *et al*., 2009). The estimation of urban volume (UV) becomes more important to capture the accelerating urban growth (Ranagalage *et al*., 2018).

The increasing access to satellite image data and the development of geographic information systems (GIS) and remote sensing technologies have encouraged the UV estimation analysis in highly urbanized areas (Estoque *et al*., 2017). The UV can be classified into two categories: urban built-up volume (UBV) and urban green volume (UGV). In this study, we focus on UBV to discuss the urban morphological dynamics. The spatial information with 3D is crucial in the urbanized areas due to the vertical changes in complex land use pattern (Batty *et al*., 2003). The use of airborne Light Detection and Ranging (LiDAR) is popular in volumetric studies. However, the availability of the LiDAR is very limited because of high operating cost (Estoque *et al*., 2015; Estoque *et al*., 2017; Handayani *et al*., 2018a). The remote sensing data is useful to overcome this limitation. Advanced Land Observing Satellite panchromatic remote-sensing instrument for the stereo mapping digital surface model (ALOS PRISM DSM) is one of the candidates for this purpose (Estoque *et al*., 2017).

Today, the use of ALOS PRISM DSM to generate DTM from DSM is becoming popular. The grid-based method proposed by Estoque *et al*. (2015) has been widely employed in many studies. Estoque *et al*. (2017) discussed the accuracy of the method in the six cities of Tokyo, Beijing, Shanghai, Tsukuba, Lusaka, and Surabaya (Estoque *et al*., 2017). Handayani *et al*. (2018a) employed the grid-based method to calculate UBV and UGV in Surabaya, Indonesia. Ranagalage *et al*. (2018) used ALOS PRISM DSM and grid-based method to calculate the UBV and UGV in Tsukuba and Tsuchiura, Japan. These studies have achieved the root-mean-square error (RMSE) between 6-7 m. In reference to these outcomes, this study attempted to develop a new method for generating DTM from ALOS PRISM DSM by using buffer distance from building footprint.

[a] Graduate School of Life and Environmental Sciences, University of Tsukuba, Japan
[b] Faculty of Life and Environmental Sciences, University of Tsukuba, Japan

2. Materials and Methods

2.1. Study areas

The study area consists of the 2.5 km landscape from the center of Tsukuba City (between 35°59′42″ and 36°14′2″ N latitude and 140°0′2″ and 140°10′39″ E longitude). Tsukuba has developed rapidly after the construction by a modern city concept in 1960 (Thapa and Murayama, 2009). The city has grown under the proper planning with the population of 234,000 in 2018 (Fig. 1).

2.2. Data and preprocessing

We used the data of ALOS PRISM DSM with a spatial resolution of 5 m from the Japan Aerospace Exploration Agency (JAXA) which was obtained on 23 February 2011. The selected DSM was geometrically corrected using the WGS84/UTM 54 N projection system. The DSM value ranged from 7.31 to 73.03 m. The building footprint data in 2012 was obtained from Geospatial Authority of Japan.

2.3. Deriving DTM from DSM: The modified grid-based method

The grid-based method was employed: (1) sample point generation, and (2) spatial interpolation (Estoque *et al*., 2015; Estoque *et al*., 2017; Handayani *et al*., 2018a). We allocated points with the lowest DSM value in grid sizes including 100, 200, 300 and 400 m (Estoque *et al*., 2017). Then spatial interpolation was conducted to generate DTM in each grid size.

Estoque *et al*. (2017) revealed that SFH data was much more accurate in the smaller or less densely built-up area rather than the highly and densely built-up area (Estoque *et al*., 2017). In this study, we applied the “modified grid-based method” which is shown in Fig. 2.

1. (Part a): The grid-based method by Estoque *et al*. (2015) was employed here to extract the points recording the minimum DSM value. We used the grid sizes of 100 m and 200 m. Estoque *et al*. (2015) revealed that the use of a 200 m grid size had the lowest RMSE in the less

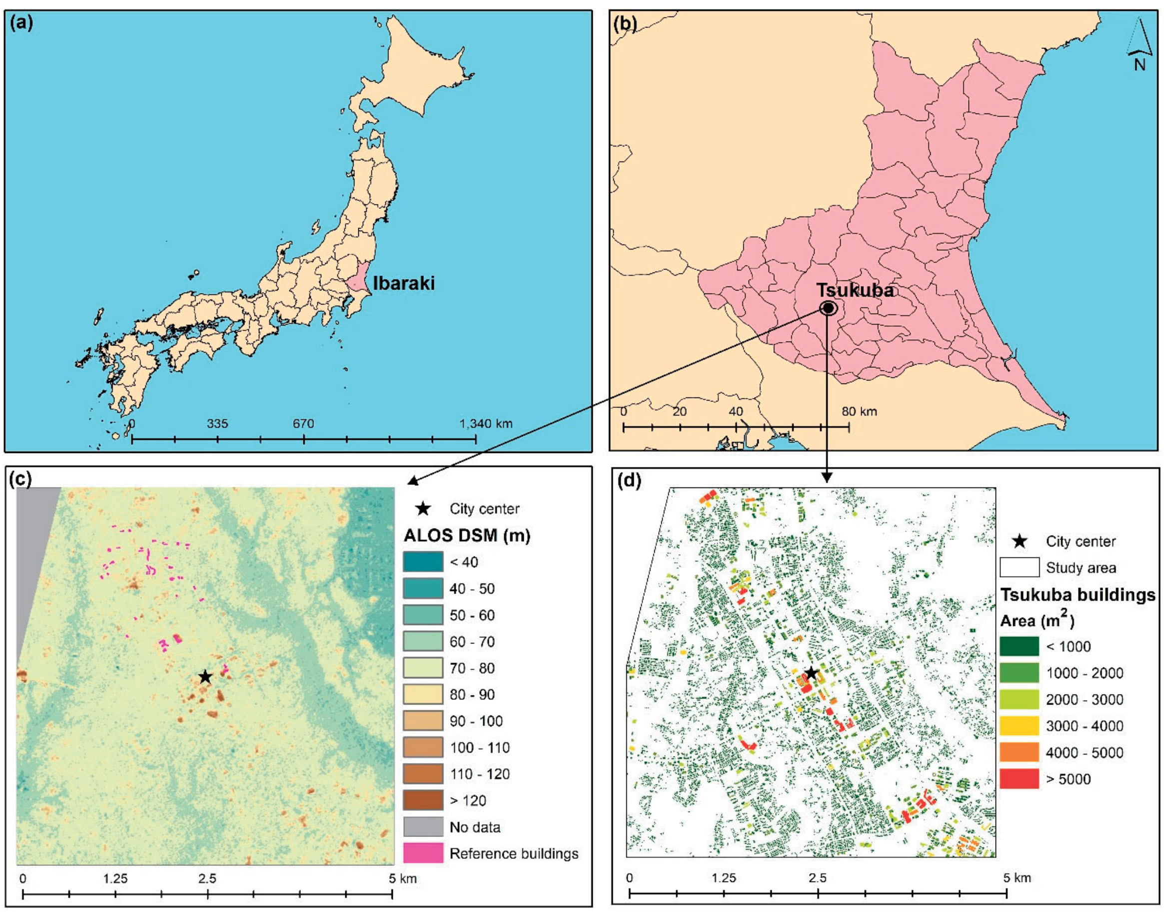

Fig. 1. Location map of the study area: (a) Japan; (b) Ibaraki Prefecture; (c) Advanced Land Observing Satellite panchromatic remote-sensing instrument for the stereo mapping digital surface model (ALOS PRISM DSM) (2011), and (d) building footprint based on the Geospatial Authority of Japan (2012).

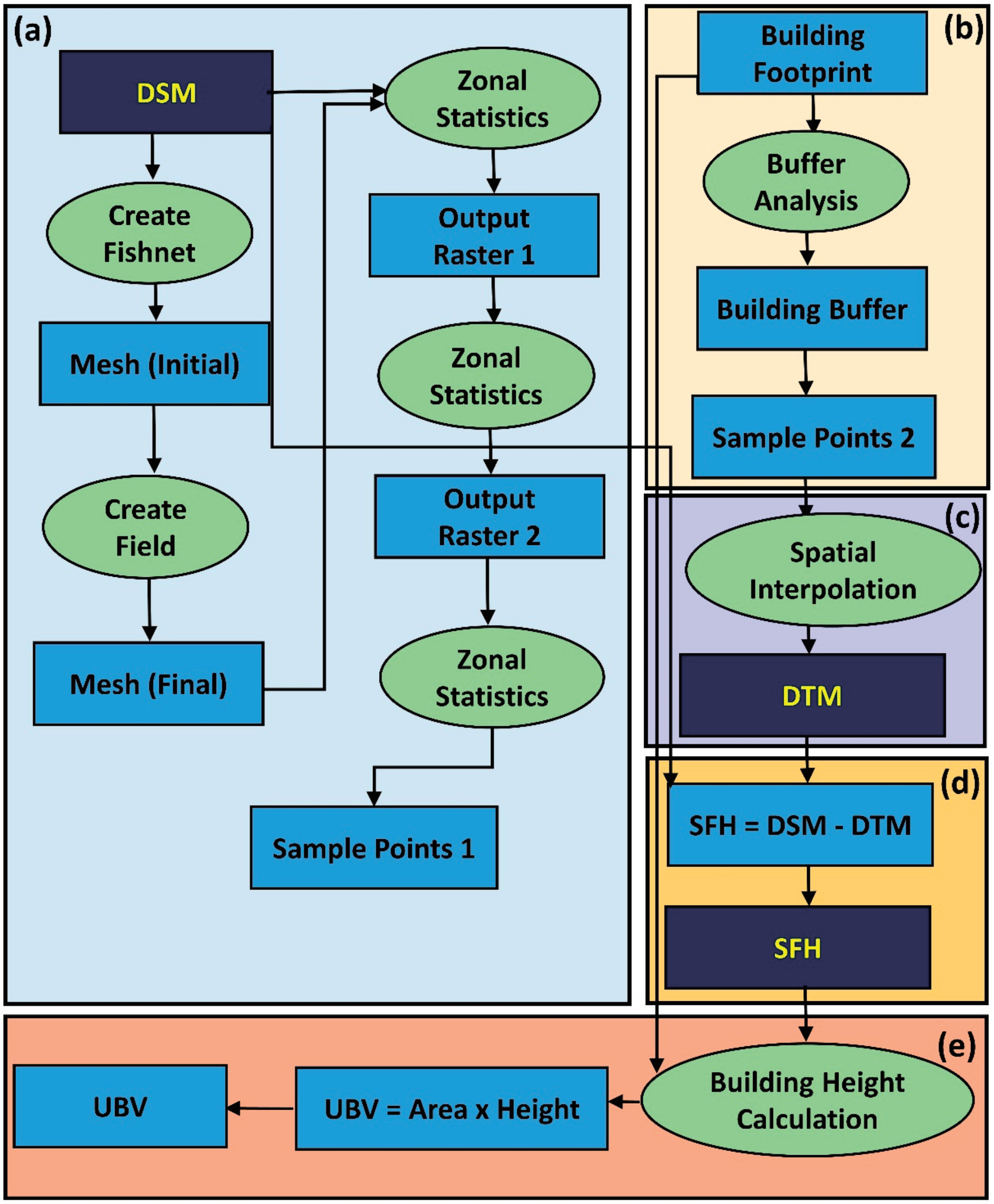

Fig. 2. The methodology adopted for extracting the surface feature height (SFH) based on the modified grid-based method: (a) identifying and extracting sample points from a DSM based on the grid-based method; (b) applying building buffer to remove the adjacent points; (c) interpolating DTM spatially; (d) extracting SFH; and (e) calculating building volume.

dense cities.

2. (Part b): Three types of building database were tested to find the best accurate building footprint estimation: "Google maps building footprint," "Zenrin footprint data," and "Building footprint by Geospatial Information Authority of Japan". After conducting the empirical analysis, we selected the data by "Geospatial Information Authority of Japan" as the most appropriate map. 23,091 buildings were used to create buffer distance of 5, 10 and 15 m from each building in the target area. The created buffer zone with the sample point was generated as shown in Fig. 2(a). The buffer distance of each building was used to remove the neighbor points in each building. Fig. 3 shows the way of selecting points created in Fig. 2(a). Finally, the points outside of each buffer zone were used to extract DTM.

3. (Part c): The minimum DSM value point outside of

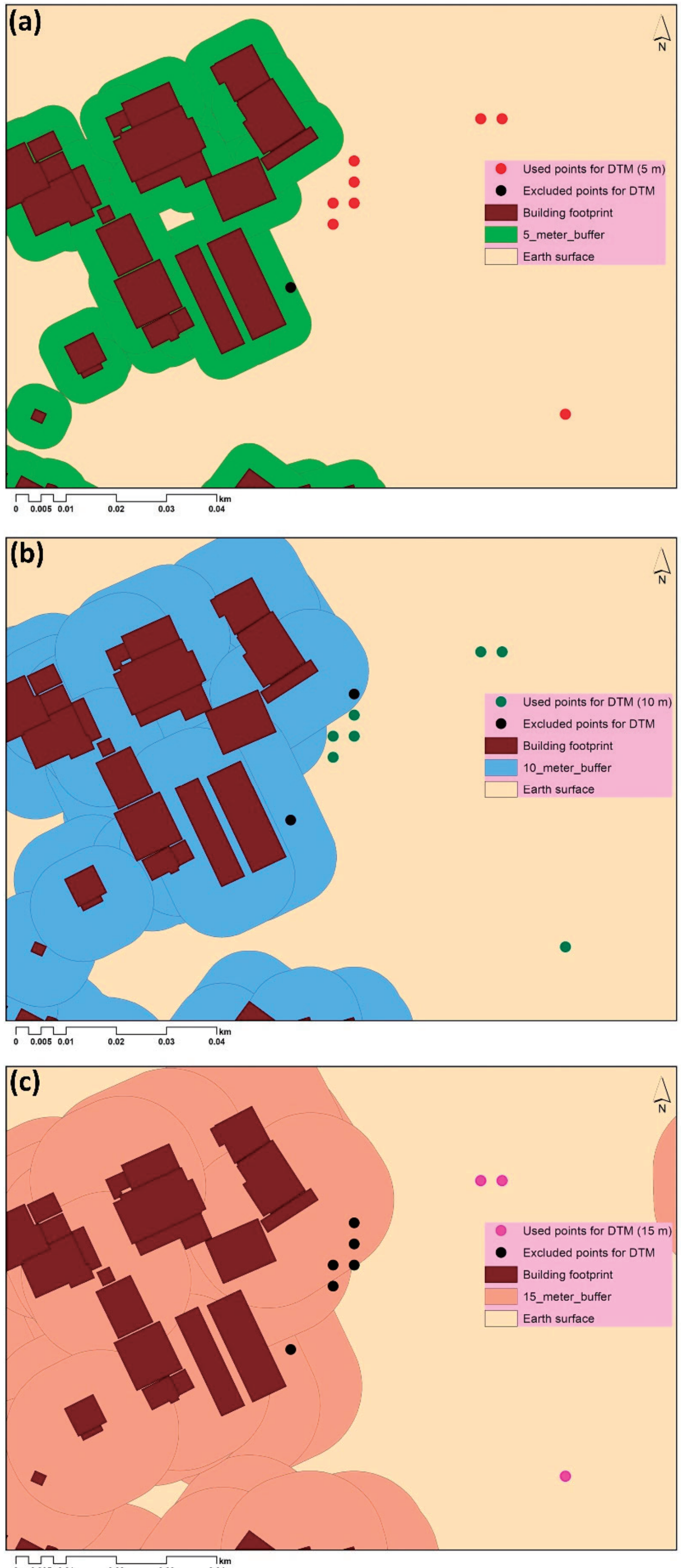

Fig. 3. Point used to extract DTM: (a) point used in 5 m buffer of each building; (b) point used in 10 m buffer of each building; and (c) point used in 15 m buffer of each building.

building footprint buffer zone was used to extract DTM by employing the empirical Bayesian Kriging surface interpolation method (Krivoruchko, 2012; Estoque *et al*., 2015; Gunarathna *et al*., 2016a; Gunarathna *et al*., 2016b; Kumari *et al*., 2018). Fig. 4 shows the extracted DTMs. Table 1 shows the number of points used to extract DTM.

4. (Part d): The SFH maps were made from the DSM and DTM which were generated by the "modified grid-based method."
5. (Part e): Building volume was extracted based on the area of building footprint and the height extracted by SFH. The buildings area less than one pixel (25 m^2) were excluded from UBV calculation (4,030 buildings).

We removed the lowest DSM value near the building based on the 5, 10 and 15 m buffer zone (Fig. 3). It helps to remove some errors including shadows.

2.4. SFH and building volume (BV) measurement

The SFH was derived by Eq. 1 (Estoque *et al*., 2015; Handayani *et al*., 2018a; Handayani *et al*., 2018b).

$$SFH_x = DSM_x - DTM_x \quad (1)$$

where SFH_x, DSM_x, and DTM_x are the surface feature height (m), digital surface model (m), and digital terrain model (m), respectively. Pixel x is a member of each feature class.

UBV is calculated by using Eq. 2.

$$UBV_x = A_x \times H_x \quad (2)$$

where UBV_x, A_x, and H_x are the building volume (m^3), building area (m^2), and building height (m), respectively in terms of building x.

3. Result and Discussion

3.1. Derived SFH maps

We have generated SFH with a spatial resolution of 5 m by using the four methods into grid size as 100 m and 200 m (Fig. 5). The extracted SFH 100 m ranged from 9.702 to 91.949, and the 200 m ranged from 13.293 to 93.889. The other six SFHs were extracted based on the proposed new method (Fig. 5). Table 2 shows details of extracted DTM in a different method.

3.2. Validating SFH maps

The 8 SFH maps were validated by comparing with the actual heights of 55 buildings which were measured by the fieldwork (Fig.1c). The predicted height was extracted by using zonal statistics available in ArcGIS. The method of calculating the building height is shown in Fig 6. There were several different roof types in the study area. RMSE was calculated by the observed heights and predicted heights (Fig. 7).

Though the past researches show that the use of the 200 m grid size provides the lowest RMSE in comparison with the other (Handayani *et al*., 2018a; Estoque *et al*., 2017), the 100 m grid size shows the lower RMSE than the 200 m in the present study. Thus, we conclude that the 100 m grid size is more usable for generating DTM based on the ALOS PRISM DSM in the low-dense city.

The validation of the SFH result shows that the proposed "modified grid-based method" provides the lowest RMSE. The buffer distance from 10 m of each building provides the lowest RMSE in the grid sizes of 100 m and 200 m. The new method provides the better result rather than the traditional grid-based method.

3.3. Calculating urban building volume

Based on the accuracy of the SFH in 10 m buffer zone method, the mean height of each building was extracted by using zonal statistics available in the ArcGIS. The SFH maps have a 5 m spatial resolution. Fig 8 shows the calculated UBV. The spatial distribution of the UBV helps to measure the urban intensity and spatial pattern of urban land use. The calculated UBV ranges between 17.29 to 322,946.58 m^3 with the mean UBV as 1,810.35 m^3. The combination of 2D and 3D approaches provides a comprehensive understanding of urban growth. Table 3 shows that 32.6% of the buildings belong to less than

Table 1. Number of points used to extract DTM in 100 m and 200 m.

Method	100 m	200 m
Grid based method (5×5 m)	5,455	1,127
5 m buffer	4,209 (1,246*)	858 (269*)
10 m buffer	3,589 (1,866*)	760 (367*)
15 m buffer	3,088 (2,367*)	682 (445*)

* Excluded points

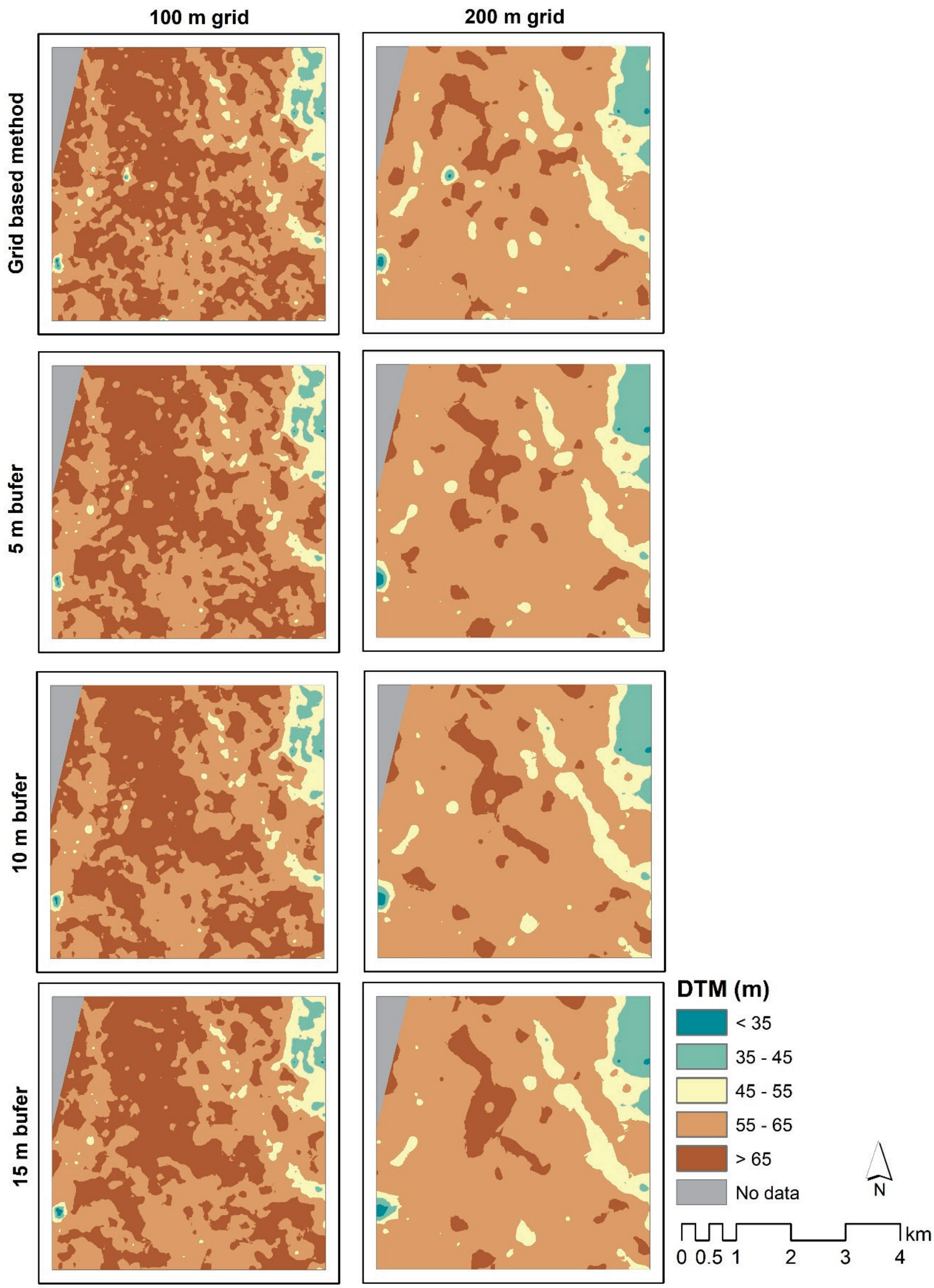

Fig. 4. Derived DTM based on the grid-based method and the modified grid-based method.

Note: The DSM map was captured on February 23, 2011.

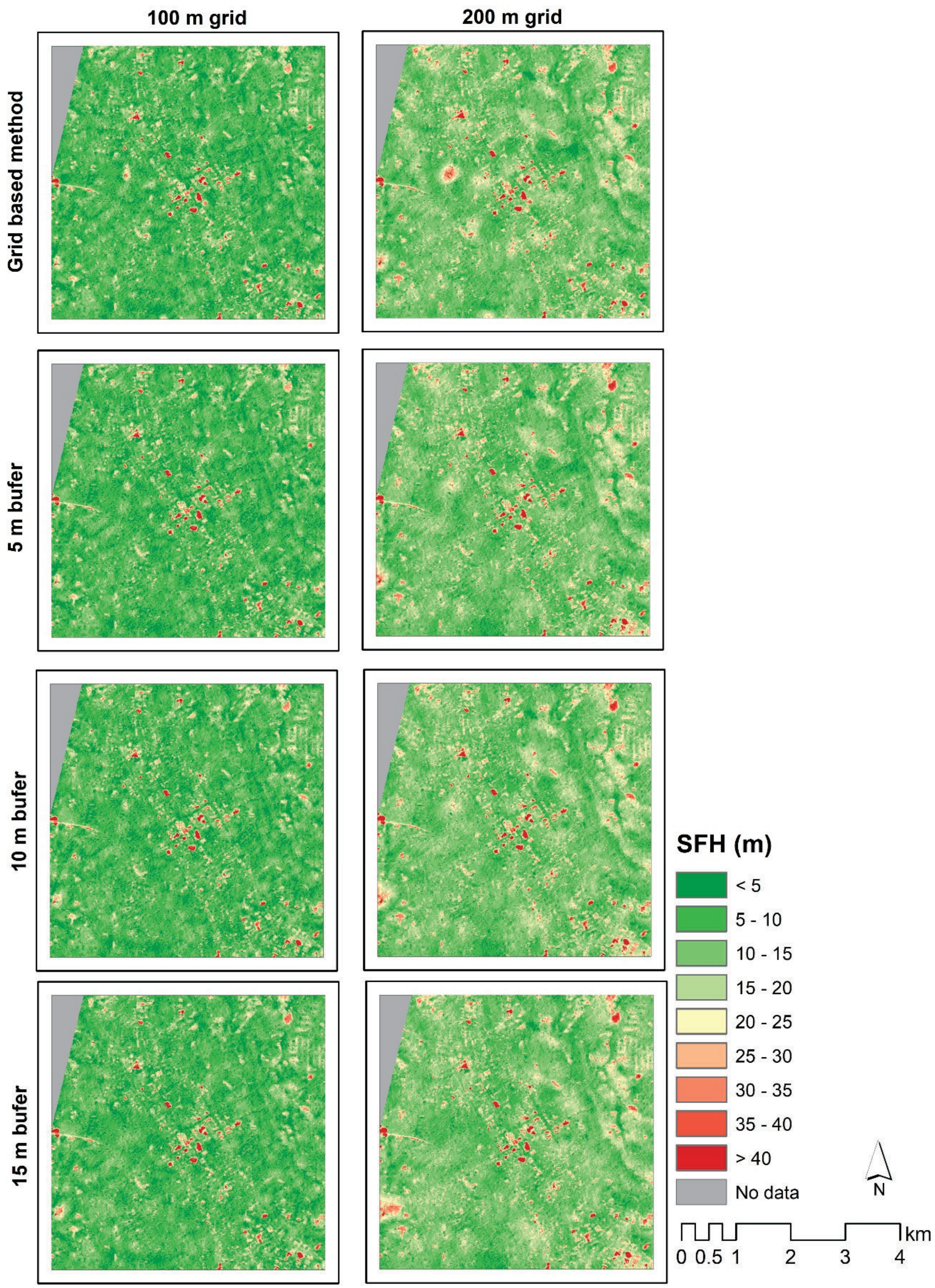

Fig. 5. Derived SFH based on the grid-based method and the modified grid-based method.

Note: The DSM map was captured on February 23, 2011.

Table 2. Details of extracted DTM in a different method.

Grid size	Method	Minimum (m)	Maximum (m)
100 m	Grid-based method	9.702	91.949
	5 m buffer	9.680	91.964
	10 m buffer	9.721	88.936
	15 m buffer	9.903	90.129
200 m	Grid-based method	13.293	93.889
	5 m buffer	13.137	93.704
	10 m buffer	13.355	91.034
	15 m buffer	13.440	90.907

Fig. 6. Measuring building heights by using SFH (Source: Google Street map, 2018).

<500 m^3 category. 28.2% of the buildings belong to 500 – 1000 m^3 category. 16.3% of the buildings belong to 1000 – 1500 m^3 category. Most of the large UBVs are located near the city center and northern and southeastern directions of Tsukuba (Ranagalage *et al*., 2018). Tsukuba has developed under the proper urban planning, and most of the urban subcenters were around the Tsukuba center. The spatial distribution of UBV can be used as a proxy indicator to understand the landscape pattern.

The result shows that the new DTM generation method is capable enough to minimize the RMSE error for calculating the height of each building. ALOS PRISM DSM is useful to generate DTM for low dense cities.

4. Conclusion

The purpose of this study was to develop a valuable method to efficiently extract DTM from ALOS PRISM DSM with the spatial resolution of 5 m. We generated DTM based on the “modified grid-based method” which was able to precisely measure the UBV with the lowest RMSE error. It is expected that the derived UBV helps to understand the changing urban landscape diversity. The UBV analysis focusing on both horizontal and vertical growth would be very valuable in sustainable urban planning and policy.

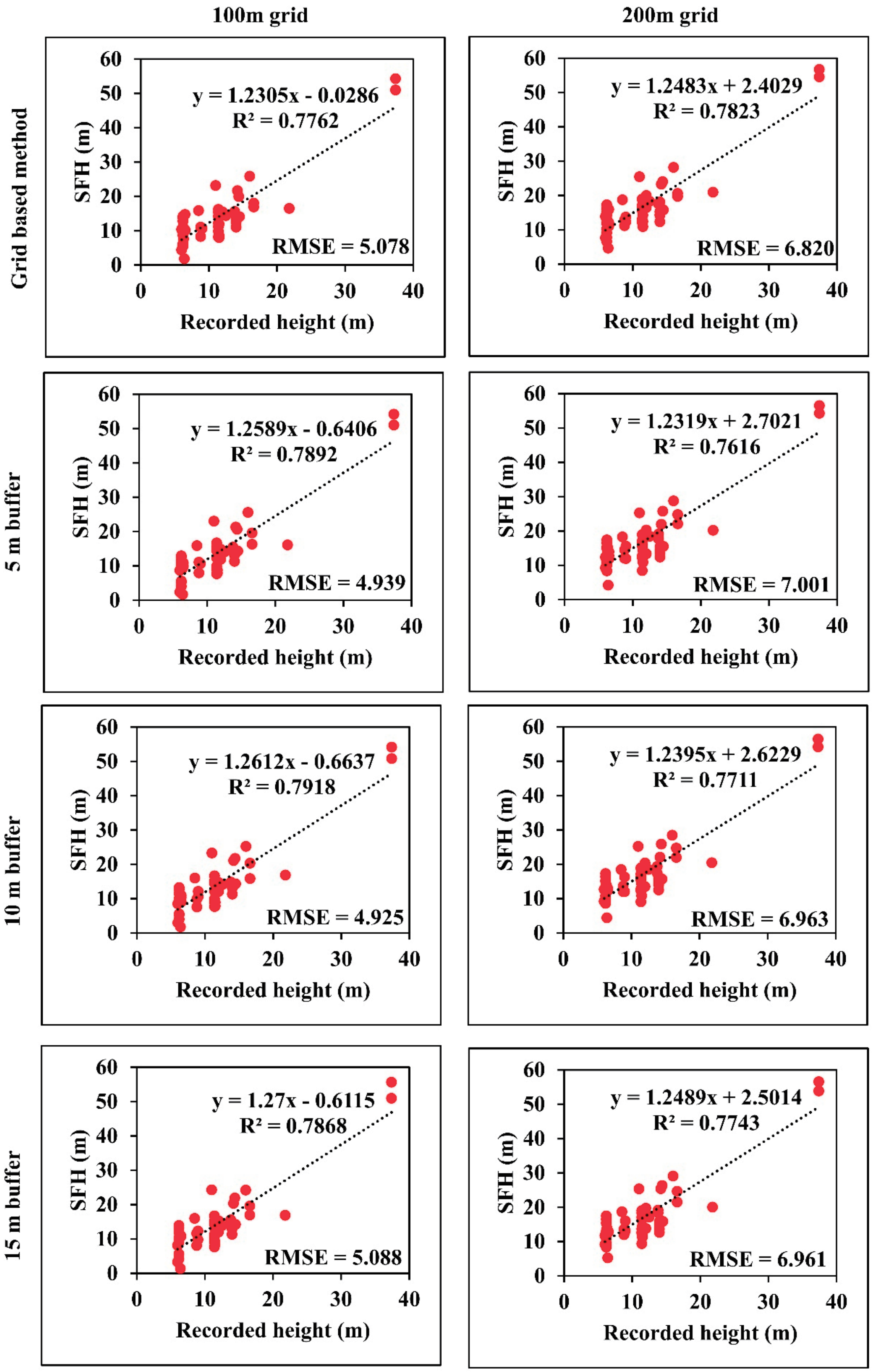

Fig. 7. Scatter plots of the recorded building heights and the extracted derived SFH based on the modified grid-based method.

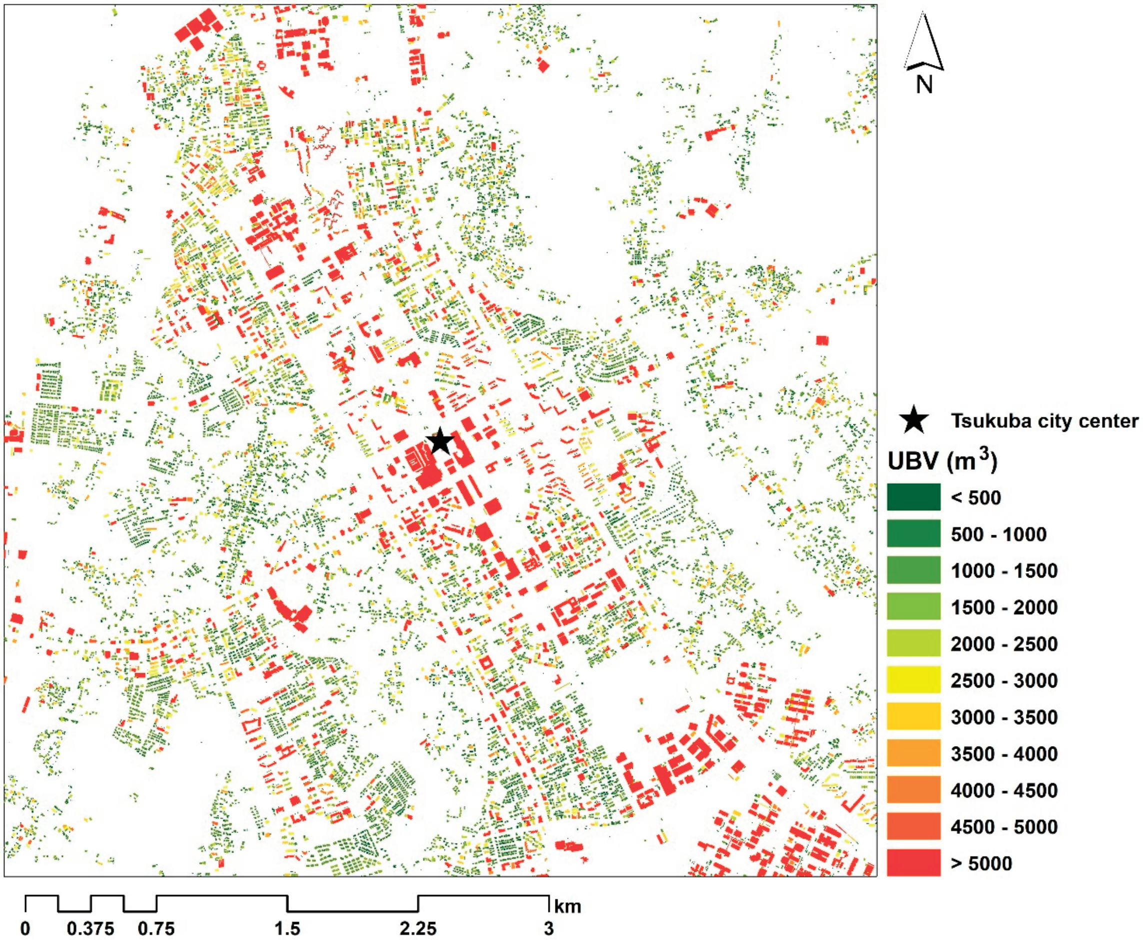

Fig. 8. Derived UBV based on the modified grid-based method (10 m buffer distance from building footprint).

Table 3: Number of points used to extract DTM in 100 m and 200 m in the study area.

UBV (m^3)	Number of buildings	%
< 500	6,215	32.6
500 - 1000	5,383	28.2
1000 - 1500	3,100	16.3
1500 - 2000	1,334	7.0
2000 - 2500	753	4.0
2500 - 3000	502	2.6
3000 - 3500	314	1.6
3500 - 4000	224	1.2
4000 - 4500	158	0.8
4500 - 5000	130	0.7
> 5000	948	5.0
Total	19,061	100.0

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