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ESTIMATION OF URBAN GROWTH USING TIME-SERIES LANDSAT SATELLITE IMAGES IN LIMA, PERU

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Abstract: In order to develop building inventory data for building damage assessment in Lima, Peru, distribution of urban growth is estimated by time-series analysis of satellite Landsat images. Spectral indices calculated from the images are used to evaluate changed areas from vegetated and bare ground areas to built-up areas. Threshold analysis is performed to difference of the indices between the multi-temporal images to identify the spatial distribution of the expansion of the built-up areas. The result shows that the older built-up areas are widely distributed in the central part of Lima and the newer built-up areas are expanded to the northern, southern and eastern suburban areas.

1. INTRODUCTION

Due to the rapid urban growth in developing countries, built-up areas have been dramatically expanded to suburban areas with poor ground conditions such as steep slope areas. In order to discuss seismic vulnerability of such urban areas, it is important to identify spatial distribution and its temporal change of the built-up areas. The identification of the age of the built-up areas could be also useful to estimate construction age of the buildings and to evaluate seismic performance of the buildings.

In developing countries, however, detailed building inventory data that includes construction age information has been rarely developed. Remote sensing technology would be powerful tool to easily identify spatial distribution of the built-up areas. Peru is one of the developing countries located in a zone of high seismicity. Since Lima, the capital of Peru, is prone to be struck by a large earthquake in near future, disaster preparedness such as building damage assessment should be enhanced in the urban areas. In this study, to develop building inventory data for the damage assessment in Lima, spatial growth of the urbanized areas is evaluated by time-series analysis of satellite Landsat images.

2. DATA USED

Figure 1 shows the land use map in Lima with 1/25,000 scale developed in 2004. Orange and green blocks indicate built-up and vegetated areas, respectively. The land use map is digitized and geo-referenced in the geographical information system. Each pixel of the map image is classified into three categories; built-up area, vegetated area and other area (bare grounds and roads). Figure 2 shows the distribution of the land use with the resolution of 30 m. Pink, green and gray pixels indicate built-up, vegetated and other areas, respectively. The built-up areas in Fig. 2 represent the current distribution of the urbanized areas.

In this study, the time-series satellite Landsat-TM (Thematic Mapper) images are used for the estimation of urban growth because large number of images has been stored since 1970s. After searching the database of the Landsat images (USGS 2012), we found an oldest cloud free image in Lima observed in 1987. In order to capture the expansion of the built-up areas after decades, we also searched another images observed about ten and twenty years after the oldest image and found cloud free images observed in 1998 and 2006. These three Landsat images are used in this study. Figure 3 and Table 1 show the characteristics of the images. As shown in Fig. 3, the western coastal area in Lima is covered with cloud in the 2006 image. The Landsat image observed in 2002 is supplementary used in the cloud cover area. The Landsat-TM data consists of seven band images that cover visible, near infrared, mid infrared and thermal spectral range. The spatial resolution of the images is 30 m.

From the comparison between the time-series Landsat images in Fig. 3, many vegetated areas and bare ground areas in the older images are changed to built-up areas in the newer images. In this study, the age of the built-up areas are estimated by identifying the changed areas from the vegetated and bare ground areas to the built-up areas in the Landsat images.

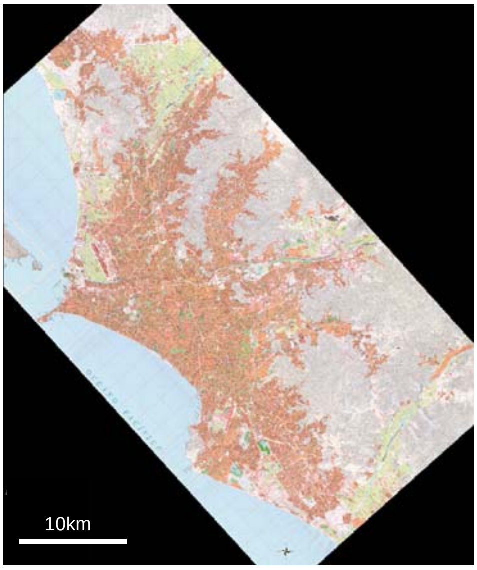

Fig. 1　Landuse map in Lima (2004)

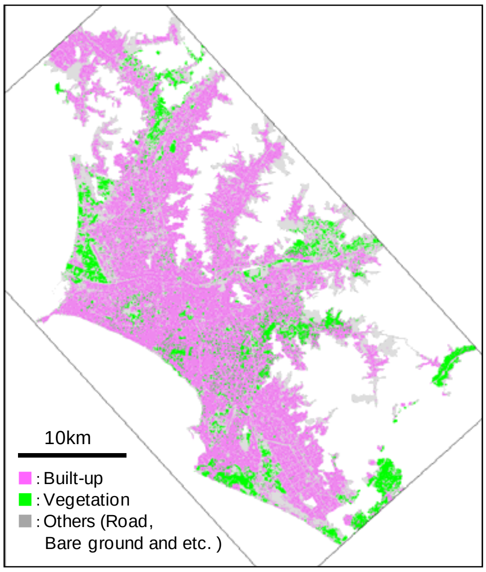

Fig. 2　Digitized landuse image

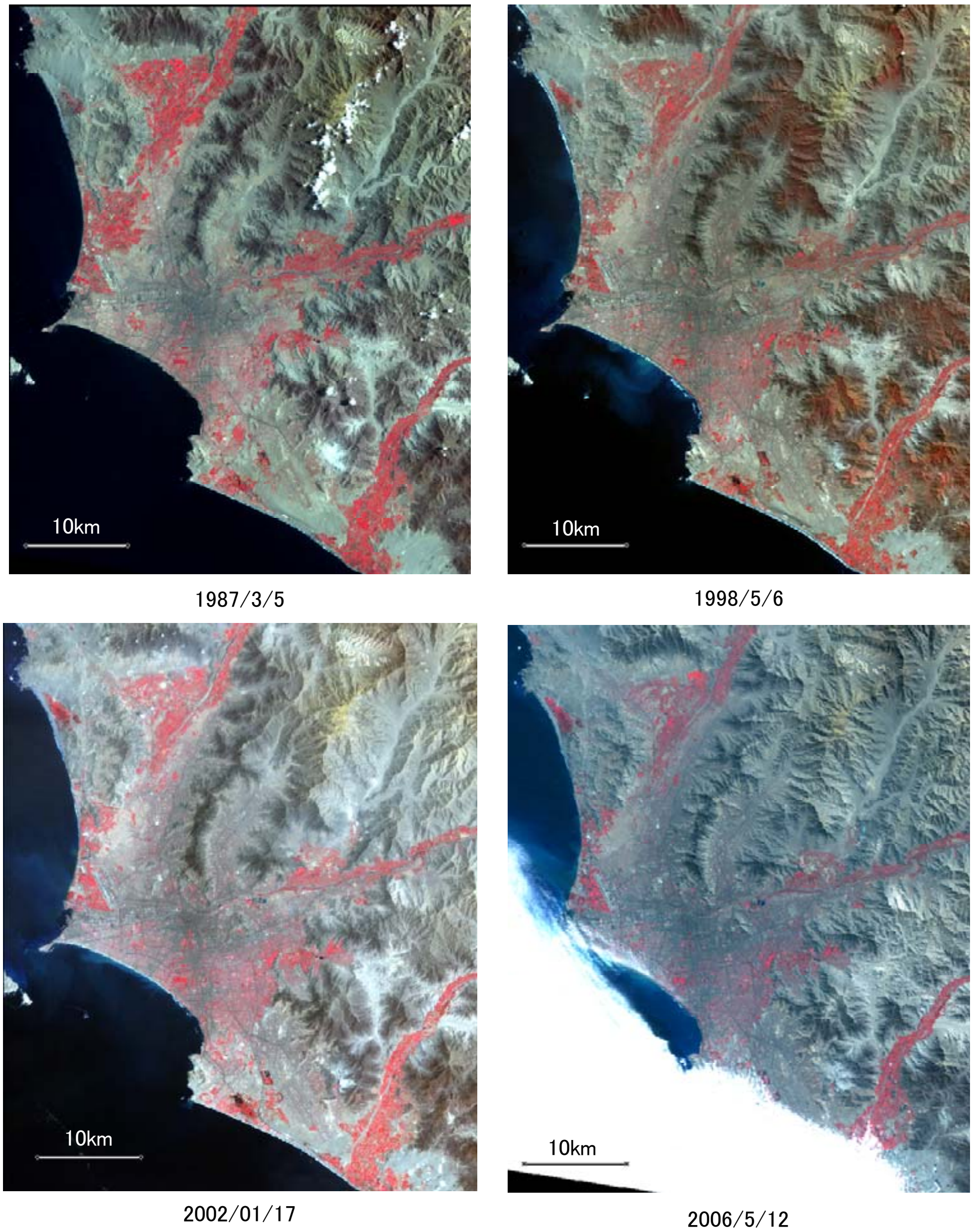

Fig. 3　Landsat images observed in 1987, 1998, 2002 and 2006 (False color composite)

Table 1 Characteristics of Landsat images used in this study

Satellite	Sensor	Date	Num. of Bands	Resolution
Landsat-5	Thematic Mapper (TM)	1987/3/5	7 bands	30 m
Landsat-5	Thematic Mapper (TM)	1998/5/6	7 bands	30 m
Landsat-5	Thematic Mapper (TM)	2002/1/17	7 bands	30 m
Landsat-5	Thematic Mapper (TM)	2006/5/12	7 bands	30 m

3. SPECTRAL INDEX CALCULATION

3.1 Evaluation of Vegetated Areas

Spectral indices calculated from combination of multi-band images have been widely used to evaluate vegetated and bare ground areas in remote sensing technology. NDVI (normalized difference vegetation index), one of the powerful indices to evaluate vegetated areas in satellite images, is calculated from the following equation.

$$NDVI = \frac{B4 - B3}{B4 + B3} \quad (-1 \le NDVI \le 1) \qquad (1)$$

Here, *B3* and *B4* indicate the digital number (DN) of the band 3 (red) and band 4 (near infrared) images, respectively. Higher NDVI values represent greater density of greenness. Figure 4 shows the distribution of NDVI calculated from the images. Figure 5 illustrates the close-up of the 2004 land use map and the 2006 NDVI image. As shown by arrows in the figure, the green areas in the land use map show high NDVI in the image, indicating that NDVI is useful to evaluate vegetated areas in the image.

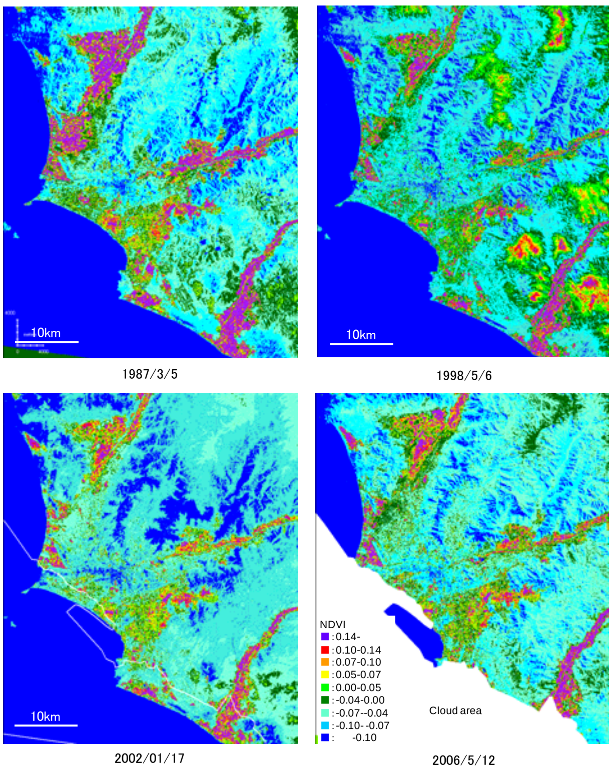

Fig. 4 NDVI images in 1987, 1998, 2002 and 2006

3.2 Evaluation of Bare Ground Areas

NDSI (normalized difference soil index) has been used as one of the spectral indices to evaluate bare ground areas from satellite images (Takeuchi and Yasuoka 2005). NDSI is also calculated from the combination of the multi-band images by the following equation.

$$NDSI = \frac{B5 - B4}{B5 + B4} \quad (-1 \le NDSI \le 1) \qquad (2)$$

Here, *B5* indicates the DN of the band 5 (mid infrared) image. Higher NDSI values would indicate greater possibility of bare ground in the image. Chen *et al.* (2010), however, pointed out that it is sometimes difficult to discriminate bare ground areas from built-up areas from only NDSI image because their spectral characteristics are similar each other in the near and mid infrared band images. In this study, other spectral indices are also calculated to evaluate bare ground areas.

$$NBI = \frac{B3 \times B5}{B4} \qquad (3)$$

$$NUI = \overline{B3} + \overline{B6} - \overline{B4} - \overline{B5} \qquad (4)$$

$$\overline{Bn} = \frac{Bn - Ave_{Bn}}{SD_{Bn}} \times 50 + 100 \quad (n = 3, 4, 5, 6)$$

NBI (new built-up index) proposed by Chen *et al.* (2010) is based on the characteristics that DNs of band 3 in bare ground areas are generally larger than those in built-up areas. Higher NBI values would indicate greater possibility of bare ground areas in the image. NUI (normalized urban index) proposed by Saito *et al.* (2002) is calculated based on the characteristics that DNs in built-up and bare ground area are higher in band 3 and 6 (thermal)

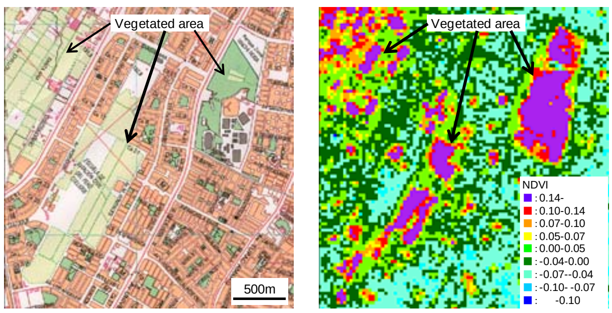

Fig. 5 Comparison of 2004 landuse map and 2006 NDVI image

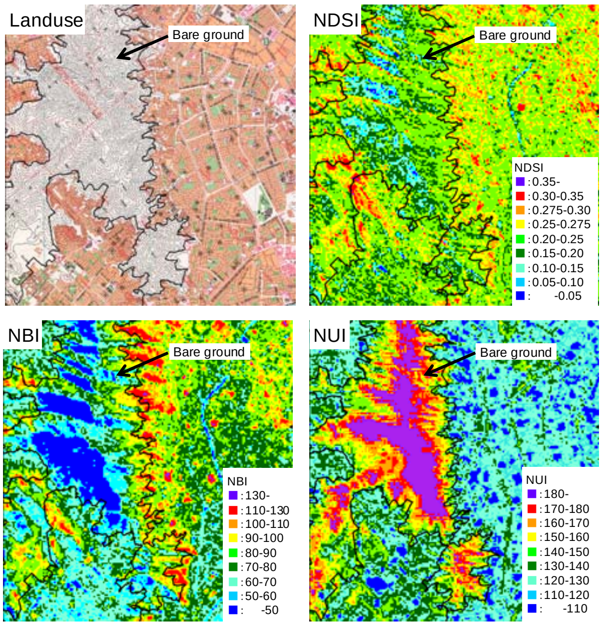

Fig. 6 Comparison of 2004 landuse map, NDSI, NBI and NUI images in 2006

than in band 4 and 5. NUI values in built-up and bare ground areas would be higher than in vegetated areas.

Figure 6 shows the distribution of the indices calculated from the 2006 Landsat image with the comparison of the 2004 land use map. Arrows in the figures indicate bare ground and mountain areas. The distribution of NDSI shows that NDSI in the bare ground areas is generally lower than that in the built- up areas. However, the boundary between the bare ground and the built-up areas could not be clearly identified in the NDSI image because many low NDSI pixels are distributed in the built-up areas. Also in the NBI image, it is difficult to identify the boundary between the bare ground and built-up areas because low NBI pixels are distributed not only in the bare ground areas but also in the built-up areas. On the contrary, in the NUI image, it is much easier to identify the boundary because NUI in the bare ground areas is much higher than that in the built-up areas. This may be because that the surface temperature in the bare ground is higher than that in the built-up areas and NUI is only the index based on the thermal band (band 6). In this study, the NUI image is used to evaluate bare ground areas. Figure 7 shows the distribution of NUI calculated from the Landsat images.

4. BUILT-UP AGE CLASSIFICATION

4.1 Methodology

The NDVI values are high in vegetated areas while they become lower in built-up areas changed from the vegetated areas. The NUI values are also high in bare ground areas while they become lower in newly developed built-up areas. Therefore, the differences of NDVI and NUI between the multi-temporal images are used to estimate the growth of the built-up areas.

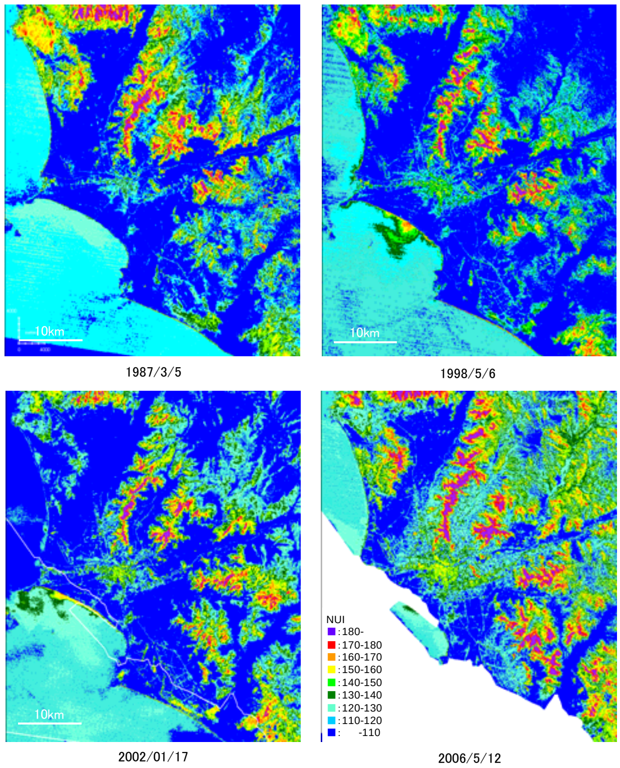

Fig. 7 NUI images in 1987, 1998, 2002 and 2006

In order to apply the method, validation data such as high-resolution images observed in the past and the present is necessary. Aerial photographs observed in 1984 are available in Lima. As shown solid line area in Fig. 8, the aerial photos are acquired in newly developed area located at the northern part of Lima. We assume that the 1984 aerial photos timely correspond to the 1987 Landsat image. The aerial photos are black-and-white images and the spatial resolution is approximately 20 cm. Recently, high-resolution satellite images are easily available. The satellite WorldView-2 (WV2) images observed in 2010 are used for the validation. The coverage of the 2010 WV2 images is shown in Fig. 8. We assume that the 2010 WV2 images timely correspond to the 2006 Landsat image. The spatial resolution is 50 cm.

Firstly, the built-up pixels are extracted from the 2004 land use map shown in Fig. 2 and only the built-up pixels are analyzed in the following procedure. The difference of NDVI and NUI between the 2006 and 1987 Landsat images is calculated for each pixel. Larger negative difference of the indices indicates greater possibility of the area where vegetation or bare ground is changed to built-up area.

Figure 9 shows the comparison of (a) the 1984 aerial photos, (b) the 2010 WV2 images and the distribution of the difference of (c) NDVI and (d) NUI. Purple and red color pixels in Fig. 9 (c) and (d) represent larger negative values of the difference of the indices. As shown in solid line polygons, training pixels are visually selected as changed areas. Green and orange line polygons represent the changed areas from the vegetated and bare ground areas to the built-up areas, respectively. Purple line polygons represent the built-up areas in all the images, indicating the old built-up areas. The distribution of NDVI difference shows that many purple and red color pixels are concentrated in the green polygons. The distribution of NUI difference also shows that many purple and red pixels are concentrated in the orange polygons.

Histograms of the NDVI and NUI difference are illustrated in Fig. 10 (a) and (b) by extracting the training pixels of the polygons in Fig. 9. Red and blue lines in the histograms indicate the pixels of the changed areas from the vegetated and bare ground areas to the built-up areas, respectively. Black lines indicate the pixels of the old built-up areas in all the images.

From Fig. 10(a), the difference of NDVI in the old built-up areas shows almost larger than -0.1 while the difference of NDVI in the changed areas from the vegetated areas are widely distributed from -0.6 to 0.0. In this study, the threshold value for the difference of NDVI is selected at -0.1 to discriminate the changed areas from the unchanged areas.

From Fig. 10(b), the difference of NUI in the old built-up areas shows larger than 10 while the difference of NUI in the changed areas from the bare ground areas are distributed from -60 to 40. In this study, the threshold value for the difference of NUI is selected at 10 to discriminate the changed areas from the unchanged areas.

Table 2 shows the result of the classification accuracy based on the threshold analysis proposed above. The table shows the number of pixels in each land use, the percentages of correct classification and mis-classification. From the result of the thresholding using the difference of NDVI, about 75% of the changed pixels in the vegetated areas are correctly classified. Almost 100% of the bare ground and the old built-up areas are classified. From the result of the thresholding using the difference of NUI, about 80% of the changed pixels in the bare ground areas are correctly classified. Almost 100% of the vegetated and old built-up areas are classified.

4.2 Result of Built-up Age Classification

Based on the threshold values examined in the previous section, the built-up age classification is performed using the time-series Landsat images. Figure 11 shows the flowchart of the classification. First, the built-up pixels are extracted from the 2004 land use map. The difference of NDVI and NUI between the 2006 and 1998 Landsat images is calculated for the built-up pixels. The threshold analysis is performed based on the threshold values. The pixels whose difference values are lower than the thresholds are classified to the newer built-up areas developed after 1998. The pixels whose difference values are higher than the thresholds are classified to the older built-up areas and analyzed in the following steps. The difference of NDVI and NUI between the 1998 and 1987 Landsat images is calculated for the older built-up pixels.

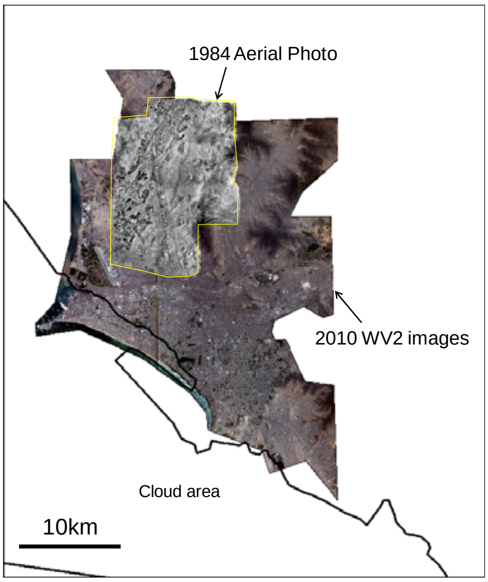

Fig. 8 Coverage of 1984 aerial photos and 2010 WV2 images

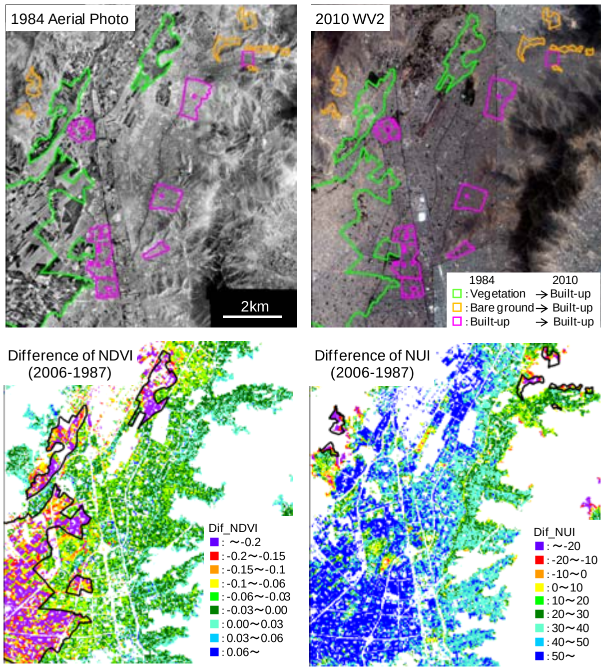

Fig. 9 Comparison of (a) 1984 aerial photo, (b) 2010 WV2 image, (c) difference of NDVI and (d) difference of NUI

The pixels whose difference values are lower than the thresholds are classified to the newer built-up areas developed between 1987 and 1998. The pixels whose difference values are higher than the thresholds are classified to the older built-up areas developed before 1987. In the cloud-cover areas of the 2006 image, same procedure is applied to the 2002 image instead of the 2006 image. Finally, the built-up age classification is estimated by combining the results.

Figure 12 shows the result of the built-up age classification. The pink, red and yellow pixels indicate the

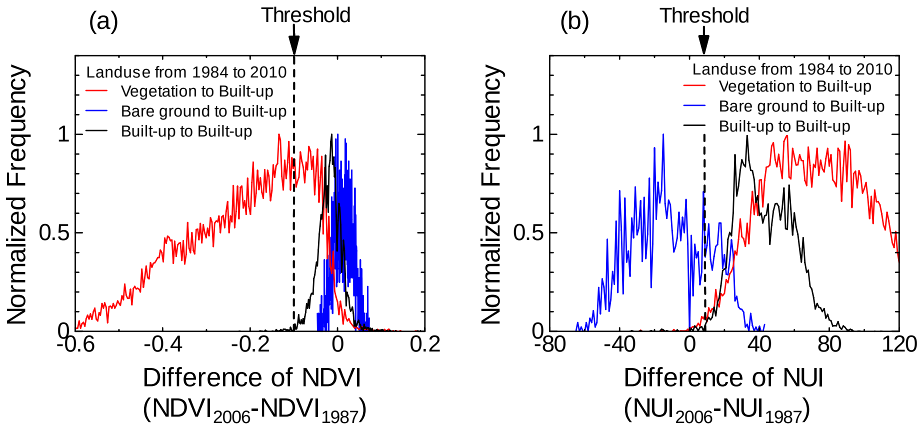

Fig. 10 Histograms of difference of NDVI and difference of NUI

Table 2 Classification accuracy of threshold by difference of NDVI and NUI

Landuse change from 1984 to 2010	Num. of Pixels	Threshold by Difference of NDVI			Threshold by Difference of NUI		
		Correctly classified (%)	Mis-classified (%)	Total (%)	Correctly classified (%)	Mis-classified (%)	Total (%)
Vegetation to Built-up	486,540	75.2	24.8	100.0	99.3	0.7	100.0
Bare ground to Built-up	30,105	100.0	0.0	100.0	80.5	19.5	100.0
Built-up to Built-up	149,859	99.5	0.5	100.0	99.3	0.7	100.0

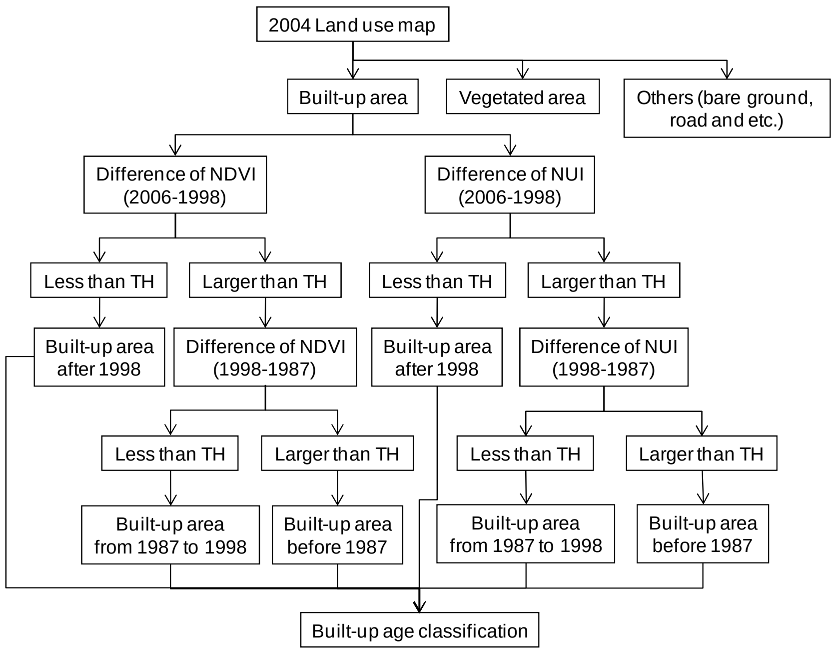

Fig. 11 Flowchart of built-up age classification using landuse map, NDVI and NUI images (TH: Threshold value)

built-up areas developed before 1987, between 1987 and 1998 and after 1998, respectively. Green and gray pixels represent vegetated areas and others, respectively. The result shows that most of the built-up areas in Lima had been developed before 1987. The newer built-up areas are expanded to the suburban areas in the northern, southern and eastern part of Lima.

Table 3 shows the number of pixels in each built-up area calculated from Fig. 12. The total area in each built-up area is also calculated from the mesh size of the Landsat images (30m x 30m). The total built-up area in Lima is about 1600 km2. About 70% of the total was developed before 1987. About 20% and 10% of the total were developed between 1987 and 1998, and after 1998, respectively.

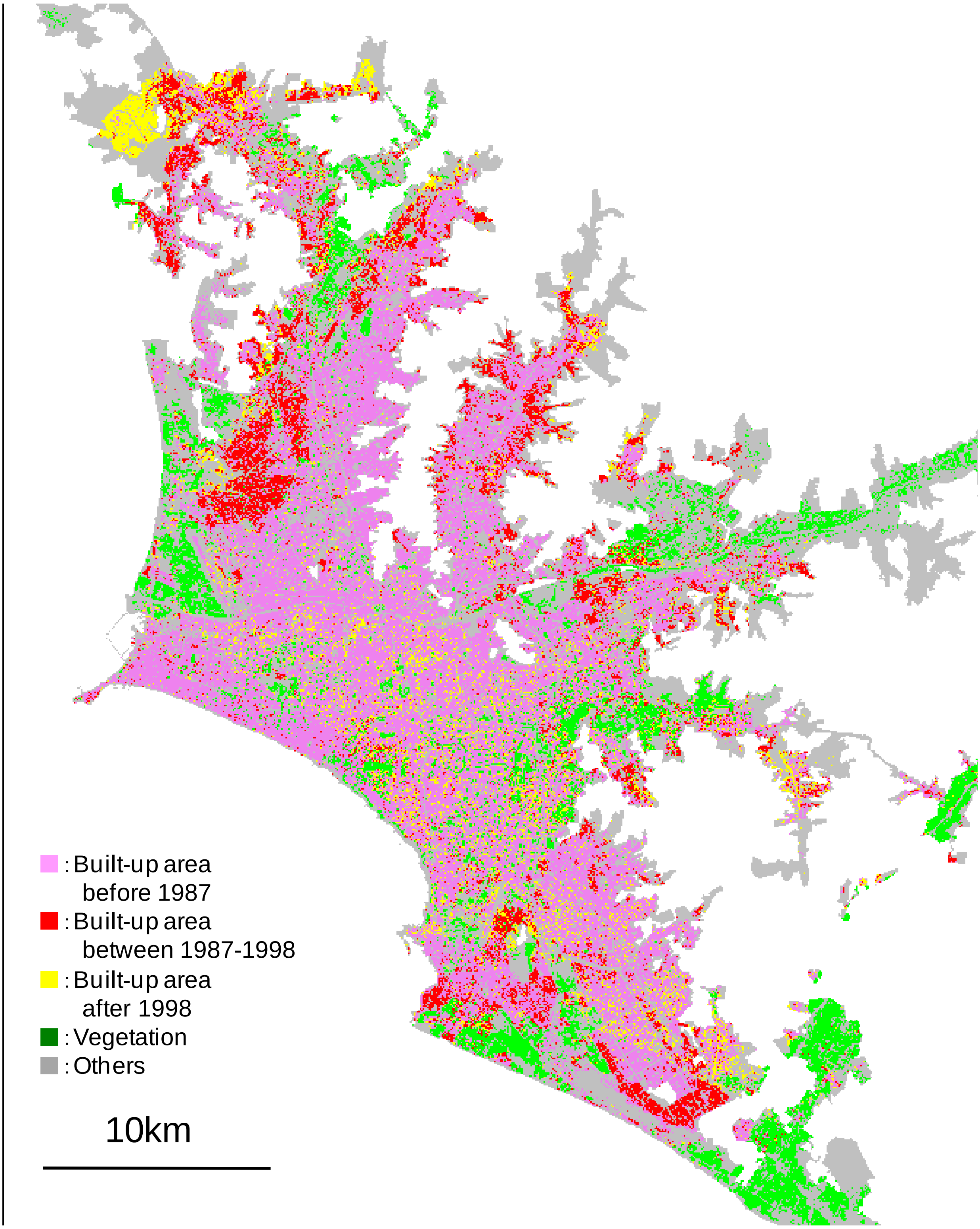

Fig. 12 Result of built-up age classification

Table 3 Number of pixels and area of each built-up area

Age	Num. of Pixels	Area (km^2)	Percent (%)
Built-up before 1987	1,192,567	1,073	68.1
Built-up between 1987-1998	314,830	283	18.0
Built-up after 1998	243,192	219	13.9
Total	1,750,589	1,576	100.0

5. CONCLUDING REMARKS

In order to develop the building inventory data in Lima, Peru, the distribution of the age of the built- up areas is estimated using the existing land use map and the time-series Landsat images. The changed areas from the vegetated and bare ground areas to the built-up areas are evaluated based on the spectral indices calculated from the images. The difference values of NDVI and NUI between the multi-temporal images are used to extract the changed areas. The threshold analysis is performed to estimate the spatial distribution of the built-up ages. The result shows that the older built-up areas before 1987 are widely distributed in Lima and the newer built–up areas are expanded to the suburban areas.

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