Souknilanh Keola, “Measuring Urbanization in ASEAN from Space” BRC Research Report, Bangkok Research Center, JETRO Bangkok / IDE-JETRO, 2018

Chapter 1

Urban Mapping from Space

Ryutaro Tateishi

Abstract

This article describes remote sensors and satellites used for urban mapping, and introduced available global land cover products. Urban maps in ASEAN region extracted from global land cover products are compared, and methods of urban mapping in these products are explained. Further, recent research of urban mapping are described by paper survey. There is almost 20-year history of global land cover mapping from space. Though many global land cover products are available, their mapping accuracies are not enough to know urban expansion. Further research is required for better global urban extent mapping.

Keywords: Remote Sensing, Land Cover, Urban Area

1. Satellite remote sensing used for land cover mapping or urban mapping

Remote sensing technology from satellite was widely recognized by the launch of Landsat-1 in 1972. Soon after that, various applications of land cover/land use mapping were tried. In most cases, urban (or “urban and built-up land”) was one of classes in legends of these maps. That is, urban mapping from space has started soon after 1972. Currently used four types of remote sensing for urban mapping are introduced here.

Daily/near-daily global observation

1-km resolution Advanced Very High Resolution Radiometer (AVHRR) on satellite, TIROS-N, was launched in 1978. TIROS-N series satellites were later called NOAA. The observed data by AVHRR on NOAA from April 1992 to March 1993 were globally mosaicked for global land cover mapping by IGBP-DISCover project. This is the first attempt of global land cover mapping from space.

Daily global observation from satellite like AVHRR is main type of sensor suitable for global land cover mapping. In addition to AVHRR, MODIS sensor (1-km resolution) was launched by NASA in 1999, and VEGETATION sensor (1-km resolution) was launched by the European Union in 1998. MERIS on ENVISAT was launched by European Space Agency (ESA) in 2012. It can observe the entire planet every 3 days (in equatorial regions) with the resolution of 300 meter.

Nighttime light observation

"Defense Meterological Satellte Programme (DMSP) platform was designed as a meterological satellite for the U.S. Air Force." "The DMSP OLS data were originally produced on mylar film and were not easily analyzed." "The digital DMSP archive was established in 1992 and has dramatically improved access to and utility of the DMSP OLS data." (Weng and Quattrochi 2006). The first DMSP weather satellite was launched in 1962. The detail of the history of DMSP is found in Hall (2001). In 1976, the first nighttime light image was observed by Operational Linescan System (OLS) on DMSP.

Radar observation

After 1990s, various radar missions from satellites have started. By European Space Agency (ESA), European Remote Sensing Satellite (ERS) 1 & 2 installed C band SAR were launched in 1991 and 1995, respectively. After that, ENVISAT installed Advanced Synthetic Aperture Radar (ASAR) was launched in 2002.

By Canada, RADARSAT 1 & 2 were launched in 1995 and 2007, respectively.
By Germany, TerraSAR-X with X band SAR was launched in 2007.
By Japan, ALOS installed PALSAR was launched in 2006, and ALOS-2/PALSAR-2 in 2014.

High resolution optical observation

High resolution optical observation with approximate ground resolution of 1 meter has started by IKONOS launched in 1999 by U.S. private company. After that, several high resolution optical sensors were launched by U.S. private companies such as: QuickBird in 2001, GeoEye-1 in 2008, WorldView-1, -2, -3, -4 in 2007, 2009, 2012, 2016, respectively.

2. Global land cover products

The first global land cover product from satellite was IGBP-DISCover using AVHRR data observed in 1992 and 1993 by mainly U.S. Geological Survey. In the U.S., University of Maryland developed another product, UMD-LC, used the same AVHRR data. After that, Boston University group funded by NASA developed several products using MODIS data; MODIS 1km LC, MODIS 500m LC.

The first European initiative to develop global land cover product was GLC2000 using SPOT VEGETATION data observed in 2000 by Joint Research Centre of European Commission. European Space Agency (ESA) developed global land cover product, GlovCover, using the 300m resolution MERIS sensor on board the ENVISAT satellite in 2 periods: December 2004 - June 2006 and January - December 2009.

The first Japanese initiative to develop global land cover product was GLCNMO using MODIS data observed in 2003 by Geospatial Information Authority of Japan, Chiba University and collaborating organizations. It is a part of products in Global Map project by national mapping organizations (or geospatial information authorities). They developed consecutive 3 versions of land cover products using MODIS data in 2003, 2008, and 2013.

A new type of global land cover data with 30 meter resolution, GlobLand30 (2000 and 2010), using Landsat data was developed by Chinese initiative. All the above global land cover products are summarized in Table 1.

Table 1 Global land cover products

3. Urban maps of ASEAN region in global land cover products

Most land cover maps include a class corresponding to urban. Table 2 shows their classes of each products in Table 1. In this section, urban maps of the Association of Southeast Asian Nations (ASEAN) region extracted from global land cover products are displayed in Figure 2 to Figure 13 and compared in Figure 14, 15, and 18. ASEAN consists of 10 countries: Indonesia, Malaysia, Philippines, Singapore, Thailand, Brunei, Cambodia, Laos, Myanmar, and Vietnam which are shown in Figure 1.

Table 2 Urban class in global land cover products

Figure 1 ASEAN countrie

Figure 2 Urban mapping of ASEAN region from IGBP-DISCover (1992-1993)

Figure 3 Urban mapping of ASEAN region from UMD-LC (1992-1993)

Figure 4 Urban mapping of ASEAN region from MOD12Q1V004 (2001)
MODIS 1km LC

Figure 5 Urban mapping of ASEAN region from MODIS-Collection5 (2001-2002)
Urban Extent

Figure 6 Urban mapping of ASEAN region from MCD12Q1 (2008)
MODIS 500m LC

Figure 7 Urban mapping of ASEAN region from GLC2000

Figure 8 Urban mapping of ASEAN region from GlobCover (2004-2006)

Figure 9 Urban mapping of ASEAN region from GlobCover (2009)

Figure 10 Urban mapping of ASEAN region from GLCNMO (2003)

Figure 11 Urban mapping of ASEAN region from GLCNMO (2008)

Figure 13 Urban mapping of ASEAN region and 5 cities from GlobLand30 (2000 and 2010)

Figure 14 shows comparison of urban areas of ASEAN region in different global land cover products. MODIS-Collection5 (2001-2002) Urban Extent, MCD12Q1 (2008)=MODIS 500m LC, and GLCNMO (2013) have relatively large urban areas. Three products by European initiative have relatively small urban areas. It is difficult to find change of urban areas in ASEAN from Figure 14 (lower) in temporal order because of poor accuracies of products.

Figure 15 shows comparison of urban areas of Thailand in global land cover products in temporal order. Variation of urban areas among products is large, so it is difficult to find changes. In order to investigate smaller area, we selected Bangkok region as one of large cities in ASEAN. Figure 16 shows urban extent of Bangkok city from “Atlas of urban expansion” (Angel 2016) which includes urban extent of 200 global sample cities. Next, local administrative boundaries including the whole urban extent of Bangkok city are selected as shown in Figure 17. Then urban areas of Bangkok, within the region of Figure 17, were extracted from global land cover products. Figure 18 shows their comparison including “Atlas of urban expantion” in Bangkok in temporal order. Urban extent in “Atlas of urban expantion” was produced using Landsat data (30m resolution) while global land cover products in Figure 18 were produced using 300m to 1km resolution satellite data. Therefore the former one is more reliable than the latter.

Figure 14 Comparison of urban areas of ASEAN region in global land cover products
upper: displayed in the order of Amarican, Eropean, and Japanese initiative
lower: displayed in the order of the year of map contents

Figure 15 Comparison of urban areas of Thailand in global land cover products
displayed in the order of the year of map contents

Figure 16 Urban extent of Bangkok city
Source: Atlas of urban expansion (Angel 2016)

Figure 17 Local administrative boundaries including Bangkok urban extent

Figure 18 Comparison of urban areas of Bangkok in global land cover products and “Atlas of urban expansion”, displayed in the order of the year of map contents

4. Methods of urban mapping in global land cover products

This section describes methods how urban or artificial surfaces were mapped in global land cover products in Table 1.

4.1 IGBP-DISCover (1992-1993)

The general classification method is unsupervised classification based on monthly Normalized Difference Vegetation Index (NDVI) composites of Advanced Very High Resolution Radiometer (AVHRR) data from April 1992 to March 1993. However, urban class, “Urban and Built-Up” was mapped from Digital Chart of the World (DCW).

“Thus, the required urban land cover data came from the populated places’ data layer in the Defense Mapping Agency’s DCW (Danko 1992). This data layer was derived from 1:1 000 000 scale maps and is therefore at a compatible resolution. A significant limitation of the DCW urban data is that they are drawn from maps of varying ages, ranging from the 1960s to 1980s. Typically the data from the rapidly urbanizing developing world are from the oldest sources. ” (Loveland et al.

2000)

4.2 UMD-LC (1992-1993)

The general classification method is decision tree method which consists of hierarchy of pair-wise class trees. Metrics employed include minimum annual red reflectance, peak annual Normalized Difference Vegetation Index (NDVI), and minimum channel three brightness temperature of AVHRR. Satellite data used are the same as 4.1. “Urban and built-up” was obtained from the Digital Chart of the World (Danko 1992) similarly to 4.1.

4.3 MCD12Q1V004 (2001) = MODIS 1km LC

The primary classification algorithm is decision tree (C4.5). The satellite data used was MODIS data. 1373 training sites distributed globally were interpreted using Landsat data. Land cover legend is the same as IGBP-DISCover . The project was made by NASA grant.

4.4 MODIS Collection5 (2001-2002) = MODIS 500m Urban Extent

Schneider et al. (2009) produced global urban extent map using MODIS 500m data by decision tree algorithm with region-specific parameters. An accuracy assessment based on sites from a stratified random sample of 140 cities shows that the new map has an overall accuracy of 93% (k =0.65) at the pixel level.

4.5 MCD12Q1 (2008) = MODIS 500m LC

Friedl et al.(2010) described the mapping method of MODIS 500m LC (MODIS Collection 5 Global Land Cover). MODIS 500m data were classified by ensemble decision tree method which is ensemble of ten boosted decision trees. Five different land cover classification systems were applied: IGBP 17 classes, UMD 14 classes, LAI/FPAR 10 classes, BGC (biome classification) 8 classes, PFT(plant functional type) 12 classes. Urban was classified by the similar method to “4.4 MODIS 500m Urban Extent” by the same producer.

4.6 GLC2000

European Commission’s Joint Research Centre coordinated 30 international research groups to map global land cover using VEGETATION sensor data on-board SPOT 4. Global area was divided into multiple regions where each research group has responsibility to classify. Classification methods applied were independent region by region. For example, some region was mapped by supervised method while another region by unsupervised method.

4.7 GlobCover

“The spectral classification consists of a supervised and an unsupervised classification. The supervised classification aims at identifying land cover classes that are not well represented, i.e. urban and wetland areas. The pixels classified through this process are masked and an unsupervised classification is then applied on the remaining pixels to create clusters of spectrally similar pixels.” (GLOBCOVER 2009)

That is, “urban” was classified by supervised method with training data.

4.8 GLCNMO (2003)

14 classes out of 20 classes were derived by supervised classification using 1km MODIS data in 2003. Training data were collected from Landsat images, MODIS NDVI seasonal change patterns, Google Earth, Virtual Earth, existing regional maps, and expert’s comments. The remaining six classes (urban, tree open, mangrove, wetland, snow/ice, and water) were classified independently.

Urban areas were extracted using ORNL's LandScan population data, MODIS/NDVI data, and DMSP/OLS data. Common areas after threshold processing for these three data were assigned as urban areas (Kasimu and Tateishi 2008). The main input data are population data. MODIS/NDVI data were used to exclude large green areas such as parks in populated areas. In addition, DMSP/OLS was used to exclude villages in developing countries with large populations.

4.9 GLCNMO (2008) and (2013)

The general classification method was similar to that of GLCNMO (2003) with some refinements. The primary source data were 23-period, 16-day composite, 7-band, 500-m MODIS data in 2008.

Urban was mapped using LandScan 2008 population data, DMSP-OLS nighttime light data, constructed impervious surface area (ISA) data, and MODIS NDVI data. The thresholding method was applied to extract urban. The values of thresholding for each parameter were decided separately in three economic levels based on the Gross Domestic Product (GDP) per capita.

In GLCNMO (2013), urban was mapped using LandScan population data in 2012, DMSP-OLS nighttime light data in 2012, Impervious Surface Area (ISA) data in 2010, and MODIS

NDVI data in 2013. As a result of evaluation of urban area in Eurasia with references of Landsat and Google Earth imagery, overall accuracy of 94% was obtained (Alsaaideh et al. 2017).

.

4.10 GlobLand30 (2000 and 2010)

The satellite data used for the mapping were 30m resolution Landsat TM/ETM+ for 2000 and 2010, Chinese HJ-1 satellite for 2010, MODIS NDVI time series data. 10 land cover types were classified: water bodies, wetland, artificial surfaces, cultivated land, forest, shrubland, grassland, bareland, permanent snow and ice, tundra. “Artificial surfaces” are defined as urban areas, roads, rural cottages and mines. The general classification method was an integration of pixel- and object-based methods with knowledge. Pixel-based method includes Support Vector Machine, and object-based method includes percentage thresholding.

For the mapping of artificial surfaces, supervised pixel-based classifier (Support Vector Machine) was used for both spectral and textural data. After that, segmentation was performed at multiple scales. Then artificial surfaces were identified by the ratio of area coverage within an object (percentage thresholding). Finally classification results at different scales were combined and verified by manual editing based on visual comparison with Google Earth image and other reference data (Chen et al. 2015).

5 Recent research of urban mapping from space

In this section, representative studies are introduced from the view point of remotely sensed data types: high resolution optical data, radar data, and nighttime light data.

5.1 Use of high resolution optical data

Early study to use high resolution optical data for urban mapping was made by Thomas et al. (2003). They used airborne sensor data by ADAR 5500 digital multispectral scanner at a 1- to 2-m ground sampling distance (GSD) resolution observed the city of Scottsdale, Arizona during July 1999. Four band image data were classified to 5 classes: water, bare ground, vegetation, pavement, rooftop. Three classification approaches were compared and the best one was found as the image segmentation classification incorporating classification tree analysis with texture, shape, and contextual information.

Huang et al. (2014) proposed multi-index learning (MIL) method for urban mapping using high resolution images such as GeoEye-1, QuickBird, WorldView-2, and ZY-3. Multi-kernel support vector machine (SVM) was applied using Primitive indices (PI) and Variation indices (VI). PI consists of morphological building index (MBI), morphological shadow index (MSI), and normalized difference vegetation index (NDVI). VI consists of spectral and spatial indices by 3D wavelet transformation (3D-WT). Roads, Grass, Buildings, Soil, Shadow, Trees, and Water body were classified by the proposed method. It was found to be promising by the comparison with some existing methods.

Hamedianfara and Shafria (2015) proposed object-based image analysis (OBIA) for three subsets of a WorldView-2 (WV-2) image after image segmentation was proposed to classify 10 intra-urban land cover classes: metal roofs, medium-tone concrete roofs, dark-tone concrete/asbestos roofs, roads, grass, trees, shadow, swimming pool, pond/river, shadow. OBIA rule sets were decided using spectral, spatial, and textural features as well as several spectral indices.

5.2 Use of radar data

Pacfici et al. (2008) reported the outcome of data fusion contest organized by the IEEE Geoscience and Remote Sensing Data Fusion Technical Committee. The data used for the contest were European Remote Sensing satellites (ERS) 1 & 2 and Landsat 5 & 7. Land use/land cover classes in and around an urban area for the contest were 5 classes: City center, Residential areas, Sparse buildings, Water, and Vegetation. The committee found the best algorithm was a Neural Network (NN) approach with pre- and post-processing.

Ban et al. (2015) developed KTH-Pavia Urban Extractor for global urban mapping. The data used was ENVISAT Advanced Synthetic Aperture Radar (ASAR) C-VV data with 30 meter resolution for 10 cities. The developed method was based on Local Indicators of Spatial Association (L.I.S.A.) including Moran index, Geary index and Getis-Ord index and Grey Level Co-occurrence Matrix (GLCM) variance and correlation textures as described in detail in Gamba et al.(2015). Ban et al. (2015) compared the result of urban extraction with GlobCover and MODIS 500m and found their method was better.

Niu et al.(2016) proposed a contextual mapping approach for urban land-cover mapping using multitemporal RADARSAT-2 fine-beam PolSAR (pixel spacing: 4.7 m × 5.1 m) and RADARSAT-2 ultra-fine-beam C-HH SAR (pixel spacing:1.6 m × 1.6 m) data. “This approach has been developed based on a contextual stochastic expectation maximization (SEM) framework (Niu and Ban 2012) using a spatial variant finite mixture model (FMM) and an adaptive Markov random field (MRF). A texture enhancement has been employed in the SEM iterations. Based on the SEM result, a rule-based approach is applied using the object features and spatial relationships to further extract roads, streets, and parks” (Niu et al. 2016). In this study, the northern rural–urban fringe of Greater Toronto area, Canada, was selected as the study area. 13 land-use/land-cover classes including high-density residential area (HD), low-density residential area (LD), industry commercial area (Ind.), construction site (Cons.), major road, street, park, golf course, forest, water, pasture, and two types of crops were classified in the experiment. The results showed potential of the use of SAR data in detailed urban mapping.

5.3 Use of nighttime light data

Zhou et al. (2014) developed a cluster-based method to map urban extent using Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) nighttime stable light (NTL) data. The developed method consists of five steps: data preprocessing, urban cluster segmentation, logistic model development, threshold estimation, and urban extent delineation. The threshold was estimated based on urban cluster size and overall nightlight magnitude in the cluster. Using this method, they created a new global 1km urban extent map for the year 2000 (Zhou et al. 2015). The produced global urban extent data can be requested to the author.

Guo et al.(2017) developed a method to map fractional Impervious surface area (ISA) at cell size of 250m x 250m using DMSP-OLS and Moderate Resolution Imaging Spectroradiometer (MODIS) normalized difference vegetation index (NDVI) data. The developed method was a support vector regression approach based on the relationship between a newly proposed index called normalized impervious surface index (NISI) and Landsat-derived ISA data. The NISI is derived from DMSP-OLS data and MODIS NDVI data.

5.4 Review papers of urban mapping

Wentz et al. (2014) reviewed urban remote sensing science: mapping urban area, urban indices, and modeling. In mapping section, urban extent, urban composition, population, surface temperature, and air quality are discussed. In indices section, biophysical indices and social and economic indices are discussed. Examples of biophysical indices are vegetation or green indices, normalized difference water index (NDWI), normalized difference built-up index (NDBI), normalized difference impervious surface index (NDISI), index-based built-up index (IBI), normalized difference impervious surface index (NDISI), and vegetation adjusted nighttime lights urban index (VANUI). In modeling section, urban climate, urban hydrology, urban land change and expansion, and social and economic modeling are discussed.

Liu et al. (2014) indicated different definitions of urban land. “urban area” that is delineated by administrative boundaries, “built-up area” that is dominated by artificial surfaces, and “impervious surface area” that is devoid of life. Twelve estimates of the global urban land based on different definitions and data sources were compared. They are:

- Worldwatch cities’ area (WWCA)
- Generalized approximation of urban land area (GAULA)
- Global Urban Land Cover in 2010 (GULC2010)
- MODIS Urban Land Cover 500-m (MOD500)
- History Database of the Global Environment V3.1-2010 (HYDE3.1-2010)
- Demographia World Urban Areas 2012 (DWUA2012)
- World Bank Urban Area 2000 (WBUA2000)
- Global Land Cover Product 2009 (GlobCover2009)
- Global Land Cover 2000 (GLC2000)
- Global Impervious Surface Area in 2010 (IMPSA2010)
- Gamba and Herold’ estimate of global urban area (GHGUA)
- Global Rural–Urban Mapping Project (GRUMP)

5.5 Others

Shao et al. (2016) produced 23-year (1993 to 2015) urban impervious surface mapping in Wuhan using Landsat data. The method used was random forest algorithm with a set of decision trees. Each decision tree was independently created by two thirds of the training samples, and the remaining one-third was put into use to estimate the out-of-bag (OOB) error. The final classification was taken via majority voting. Three indices from Landsat were used as parameters for decision trees: the normalized difference vegetation index (NDVI), the modified normalized difference water index (MNDWI), and the biophysical composition index (BCI) derived from Tasseled Cap Transformation.Huang et al. (2016) produced fractional urban cover maps in 2001 and 2010 at 250 m spatial resolution for cities in China using MODIS and stable nighttime lights observations from DMSP/OLS data. The method used was Random Forest regression models with calibration information derived from Landsat data. In the background section of the paper by Huang et al. (2016), some general information about urban mapping is introduced: definition of urban, remote sensing types for urban mapping, introduction of nine global datasets with urban information. Firstly, there are two types of definition of urban; Sociodemographic definition and Physical definition. Sociodemographic definition uses geopolitical, demographic, and socioeconomic criteria. Physical definition is based on mount of impervious surface such as buildings, roads, runways, and other facilities. Secondly, there are three types of remote sensing used for urban mapping; optical, thermal, and radar. Thirdly, three datasets focuses on urban cover; MODIS 1 km Urban Land Cover, MODIS 500 m Urban Land Cover, Global Rural-Urban Land Mapping Project (GRUMP). Four datasets include urban class; Vector Map (VMap) Level 0, Global Land Cover 2000 (GLC2000), GlobCover, European Space Agency Climate Change Initiative (ESA CCI) Land Cover. Two datasets have fractional urban cover; Global Impervious Surface Area Cover (IMPSA) and History Database of the Global Environment (HYDE3). Seven of these use remote sensing and none is updated regularly.

6. Summary

In the latter half of 1970s, after the launch of Landsat-1, land cover/land use mapping using 80m resolution Landsat MSS data has started. “Urban and built-up” class was included in the classification. That was the first urban mapping using digital satellite data from space. In 1990s, globally mosaicked AVHRR data were used for global land cover mapping. However, at that time, urban class was mapped using not AVHRR but the existing digital map data, Digital Chart of the World (DCW), because of poor accuracy in the case of AVHRR. The first global urban mapping from satellite data was by the use of MODIS data after 2000.

In 2000s, urban mapping was made by not only daily/near daily global observation data such as MODIS but also other types of satellite data such as DMSP/OLS nighttime light data, ERS SAR data and others. Also, high resolution optical data such as Geoeye-1, WorldView-2 were used for local urban mapping.

Table 3 shows the summary of urban mapping. There are three types of urban mapping: urban extent map, land cover map including urban class, intra-urban map. Urban extent map shows only urban area while intra-urban map is a classified map of urban components such as buildings, streets, and trees. Global urban mapping is usually land cover map or urban extent map while local urban mapping is usually intra-urban map. In both global and local cases, supervised classification method is used because urban is too heterogeneous to apply unsupervised classification which requires similar data values for the same class. Therefore the key point of successful urban mapping is how to collect better representative training data for urban or intra-urban classes.

There is almost 20 years history in global land cover mapping from space. However their mapping accuracies are not too high to compare time series maps. Therefore, urban extent mapping (urban specific mapping) is suitable to know urban changes in global case.

Table 3 Summary of urban mapping from space

<References>

Alsaaideh, B., R. Tateishi, D. X. Phong, N. T. Hoan, A. Al-Hanbali & X. Bai, 2017, New urban map of Eurasia using MODIS and multi source geospatial data, Geo-spatial information science, Vol.20, no.1, 29-38

Angel, S. et al., Atlas of Urban Expansion – 2016 Edition, Volume 1: Areas and Densities, New York: New York University, Nairobi: UN-Habitat, and Cambridge, MA: Lincolin Institute of Land Policy

Ban, Y., A. Jacob, P. Gamba, 2015, Spaceborne SAR data for global urban mapping at 30m resolution, ISPRS Journal of Photorammetry and Remote Sensing, 103, 28-35

Bartholome´, E. and Belward, A. S., 2005, GLC2000: a new approach to global land cover mapping from Earth observation data, International Journal of Remote Sensing 26: 1959–1977.

Chen, J., J. Chen, A. Liao, X. Cao, L. Chen, X. Chen, C. He, et al., 2015, Global Land Cover Mapping at 30 M Resolution: A POK-based Operational Approach, ISPRS Journal of Photogrammetry and Remote Sensing 103: 7–27.

Danko, D. M., 1992, The Digital Chart of the World Project. Photogrammetric Engineering and Remote Sensing, 58, 1125–1128.

Friedl, M. A., D. K. McIver, J. C. F. Hodges, X. Y. Zhang, D. Muchoney, A. H. Strahler, C. E. Woodcock, et al., 2002, Global Land Cover Mapping from MODIS: Algorithms and Early Results, Remote Sensing of Environment 83: 287–302.

Friedl, M. A., D. Sulla-Menashe, B. Tan, A. Schneider, N. Ramankutty, A. Sibley, and X. Huang, 2010, MODIS Collection 5 Global Land Cover: Algorithm Refinements and Characterization of New Datasets, Remote Sensing of Environment 114: 168–182.

Gamba, P., M. Aldrighi, M. Stasolla, 2011, Robust extraction of urban area extents in HR and VHR SAR images, IEEE J. Select. Top. Appl. Earth Observ. Remote Sens. 4(1), 27-34

GLOBCOVER 2009 Product description and validation report 18/02/2011 UCLouvain & ESA Team

Guo, W., D. Lu, and W. Kuang, 2017, Improving Fractional Impervious Surface Mapping Performance through Combination of DMSP-OLS and MODIS NDVI Data, Remote Sensing, 9, 375; doi:10.3390/rs9040375

Hall, R. C., 2001, A history of the military polar orbiting meteorological satellite program, Office of the historian national reconnaissance office

Hamedianfara, A. and H. Z. M. Shafria, 2015, Detailed intra-urban mapping through transferable OBIA rule sets using WorldView-2 very-high-resolution satellite images, International Journal of Remote Sensing, Vol.36, No.13, 3380-3396

Hansen, M. C., R. S. Defries, J. R. G. Townshend, and R. Sohlberg, 2000, Global land cover classification at 1 km spatial resolution using a classification tree approach, International Journal of Remote Sensing 21: 1331–1364.

Huang, X, A. Schneider, and M. A. Friedl, 2016, Mapping sub-pixel urban expansion in China using MODIS and DMSP/OLS nighttime lights, Remote Sensing of Environment, 175, 92-108

Huang,X., Lu,Q., Zhang,L., 2014, A multi-index learning approach for classification of high-resolution remotely sensed images over urban areas, ISPRS Journal of Photorammetry and Remote Sensing, 90, 36-48

Kasimu, A. and Tateishi, R., 2008, GLCNMO global urban mapping, validation and comparison with existed global urban maps, Journal of the Remote Sensing Society of Japan, 28 (5) 427-440.

Kobayashi, T., R. Tateishi, B. Alsaaideh, R. C. Sharma, T. Wakaizumi, D. Miyamoto, B. Xiulian, et al., 2017, Production of Global Land Cover Data - GLCNMO2013, Journal of Geography and Geology 9:1-15.

Leroy M., P. Bicheron, C. Brockmann, U. Krämer, B. Miras, M. Huc, F. Ninô, P. Defourny, C. Vancutsem, D. Petit, V. Amberg, B. Berthelt, O. Arino and F. Ranera, 2006, GlobCover: a 300 m global land cover product for 2005 using ENVISAT MERIS time series, ISPRS Commision VII Mid-Term Symposium: Remote Sensing: from Pixels to Processes, Enschede (NL), May 2006

Liu, Z., C. He, Y. Zhou, J. Wu, 2014, How much of the world’s land has been urbanized, really? A hierarchical framework for avoiding confusion, Landscape Ecology. DOI 10.1007/s10980-014-0034-y

Loveland, T. R. and Belward, A. S., 1997, The IGBP-DIS global 1 km land cover data set, DISCover: first results, International Journal of Remote Sensing 18: 3289– 3295.

Loveland, T. R., B. C. Reed , J. F. Brown , D. O. Ohlen , Z. Zhu , L. Yang & J. W. Merchant, 2000, Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data, International Journal of Remote Sensing, 21:6-7, 1303-1330, DOI: 10.1080/014311600210191

Niu, X., and Y. Ban, 2012, An Adaptive Contextual SEM Algorithm for Urban Land Cover Mapping Using Multitemporal High-Resolution Polarimetric SAR Data, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 5 (4): 1129–1139.

Niu, X., Y. Ban & Y. Dou, 2016, RADARSAT-2 fine-beam polarimetric and ultra-finebeam SAR data for urban mapping: comparison and synergy, International Journal of Remote Sensing, Vol.37, No.12, 2810-2830.

Pacfici, F., F. D. Frate, W. J. Emery, P. Gamba and J. Chanussot, 2008, Urban Mapping Using Coarse SAR and Optical Data: Outcome of the 2007 GRSS Data Fusion Contest, IEEE Geoscience and Remote Sensing Letters, Vol. 5, No. 3, 331-335

Schneider, A., M. A. Friedl, and D. Potere, 2009, A New Map of Global Urban Extent from MODIS Satellite Data, Environmental Research Letter 4: 1–11.

Shao, Z., Y. Zhang, W. Zhou, 2016, Long-term monitoring of the urban impervious surface mapping using time series Landsat imagery: A 23-year case study of the city of Wuhan in China, The 4th International Workshop on Earth Observation and Remote Sensing Applications, 4-6 July 2016, Guangzhou, China

Tateishi, R., B. Uriyangqai, H. Al-Bilbisi, M. Ghar, J. Tsend-Ayush, T. Kobayashi, A. Kasimu, et al., 2011, Production of Global Land Cover Data – GLCNMO, International Journal of Digital Earth 4: 22–49.

Tateishi, R., N. T. Hoan, T. Kobayashi, B. Alsaaideh, G. Tana, and D. X. Phong, 2014, Production of Global Land Cover Data – GLCNMO2008, Journal of Geography and Geology 6: 99–122.

Thomas,N., C. Hendrix, and R.G. Congalton, 2003, A Comparison of Urban Mapping Methods Using High-Resolution Digital Imagery, Photogrammetric Engineering & Remote Sensing Vol. 69, No. 9, 963–972

Weng, Q. and D. A. Quattrochi (Ed.), 2006, Urban Remote Sensing, CRC Press (cited from page 292)

Wentz, E. A., S. Anderson, M. Fragkias, M. Netzband, V. Mesev, S. W. Myint, D. Quattrochi, A. Rahman and K. C. Seto, 2014, Supporting Global Environmental Change Research: A Review of Trends and Knowledge Gaps in Urban Remote Sensing, Remote Sensing, 6, 3879-3905

Zhou, Y., S. J. Smith, C. D. Elvidge, K. Zhao, A. Thomson, M. Imhoff, 2014, A cluster-based method to map urban area from DMSP/OLS nightlights, Remote Sensing of Environment, 147, 173-185

Zhou,Y., S. J. Smith, K. Zhao, M. Imhoff, A. Thomson, B. Bond-Lamberty, G. R. Asrar, X. Zhang, C. He and C. D. Elvidge, 2015, A global map of urban extent from nightlights, Environmental Research Letters, 10, 054011

Table 1 Global land cover products

Product name	Access site	Reference
1- IGBP-DISCover (1992 and 1993)	National Aeronautics and Space Administration (NASA), USGS http://edc2.usgs.gov/glcc/glcc.php (Using data accessed and saved in 2014)	Loveland, T. R. and Belward, A. S., 1997, The IGBP-DIS global 1 km land cover data set, DISCover: first results, International Journal of Remote Sensing 18: 3289– 3295.
2- UMD-LC (1992-1993)	Global Land Cover Facility (GLCF), UMD Land Cover Classification, UMD LC product: http://glcf.umd.edu/data/landcover/data.shtml (Using data accessed and saved in 2014)	HANSEN, M. C., R. S. DEFRIES, J. R. G. TOWNSHEND, and R. SOHLBERG, 2000, Global land cover classification at 1 km spatial resolution using a classification tree approach, International Journal of remote sensing 21: 1331–1364.
3- MOD12Q1V004 (2001) = MODIS 1km LC	National Aeronautics and Space Administration (NASA), USGS, Land Processes Distributed Active Archive Center (LP DAAC), MCD12Q1product: https://lpdaac.usgs.gov/products/modis_products_table/mcd12q1	Friedl, M. A., D. K. McIver, J. C. F. Hodges, X. Y. Zhang, D. Muchoney, A. H. Strahler, C. E. Woodcock, et al., 2002, Global Land Cover Mapping from MODIS: Algorithms and Early Results, Remote Sensing of Environment 83:287–302.

	(Using data accessed and saved in 2014)	
4- MODIS-Collection5 (2001-2002) = MODIS 500m Urban Extent	http://landcoverchange.com/home/data/ (Using data accessed and saved in 2014)	Schneider, A., M. A. Friedl, and D. Potere, 2009, A New Map of Global Urban Extent from MODIS Satellite Data, Environmental Research Letter 4: 1–11.
5- MCD12Q1 (2008) = MODIS 500m LC	National Aeronautics and Space Administration (NASA), USGS, Land Processes Distributed Active Archive Center (LP DAAC), MCD12Q1product: https://lpdaac.usgs.gov/products/modis_products_table/mcd12q1	Friedl, M. A., D. Sulla-Menashe, B. Tan, A. Schneider, N. Ramankutty, A. Sibley, and X. Huang, 2010, MODIS Collection 5 Global Land Cover: Algorithm Refinements and Characterization of New Datasets, Remote Sensing of Environment 114: 168–182.
6- GLC2000	The European Commission's science and knowledge service, Global Land Cover 2000 (GLC2000): http://forobs.jrc.ec.europa.eu/products/glc2000/glc2000.php	BARTHOLOME´, E. and BELWARD, A. S., 2005, GLC2000: a new approach to global land cover mapping from Earth observation data, International Journal of Remote Sensing 26: 1959–1977.
7- GlobCover (2004-2006) and (2009)	ESA's global land cover map, the European Space Agency (ESA),	http://due.esrin.esa.int/page_globcover.php Leroy M., P. Bicheron, C. Brockmann,

	GlobCover product: http://www.esa.int/Our_Activities/Observing_the_Earth/Space_for_our_climate/ESA_global_land_cover_map_available_online	U. Krämer, B. Miras, M. Huc, F. Ninô, P. Defourny, C. Vancutsem, D. Petit, V. Amberg, B. Berthelt, O. Arino and F. Ranera, 2006, GlobCover: a 300 m global land cover product for 2005 using ENVISAT MERIS time series, ISPRS Commision VII Mid-Term Symposium: Remote Sensing: from Pixels to Processes, Enschede (NL), May 2006 GLOBCOVER 2009 Product description and validation report 18/02/2011 UCLouvain & ESA Team
8- GLCNMO (2003) (2008) (2013)	https://globalmaps.github.io/glcnmo.html http://www.cr.chiba-u.jp/databases/GLP/database-GLP.html	Tateishi, R., B. Uriyangqai, H. Al-Bilbisi, M. Ghar, J. Tsend-Ayush, T. Kobayashi, A. Kasimu, et al., 2011, Production of Global Land Cover Data – GLCNMO, International Journal of Digital Earth 4: 22–49. Tateishi, R., N. T. Hoan, T. Kobayashi, B. Alsaaideh, G. Tana, and D. X. Phong, 2014, Production of Global Land Cover Data – GLCNMO2008, Journal of Geography and Geology 6: 99–122. Kobayashi, T., R. Tateishi, B. Alsaaideh, R. C. Sharma, T. Wakaizumi, D. Miyamoto, B. Xiulian, et al., 2017, Production of Global Land Cover Data - GLCNMO2013, Journal of Geography

		and Geology 9:1-15.
9- GlobLand30 (2000 and 2010)	http://www.globallandcover.com/GLC30Download/index.aspx	Chen, J., J. Chen, A. Liao, X. Cao, L. Chen, X. Chen, C. He, et al., 2015, Global Land Cover Mapping at 30 M Resolution: A POK-based Operational Approach, ISPRS Journal of Photogrammetry and Remote Sensing 103: 7–27.

Table 2 Urban class in global land cover products

Global land cover product	Class corresponding to urban
1- IGBP-DISCover (1992 and 1993)	Urban and built-up
2- UMD-LC (1992-1993)	Urban and built-up
3- MOD12Q1V004 (2001) = MODIS 1km LC	Urban and built-up
4- MODIS-Collection5 (2001-2002) Urban extent	-
5- MCD12Q1 (2008) = MODIS 500m LC	Urban and built-up
6- GLC2000	Artificial surfaces and associated areas
7- GlobCover (2004-2006) and (2009)	Artificial surfaces and associated areas
8- GLCNMO (2003), (2008), and (2013)	Urban
9- GlobLand30 (2000 and 2010)	Artificial surfaces

Figure 1 ASEAN countries

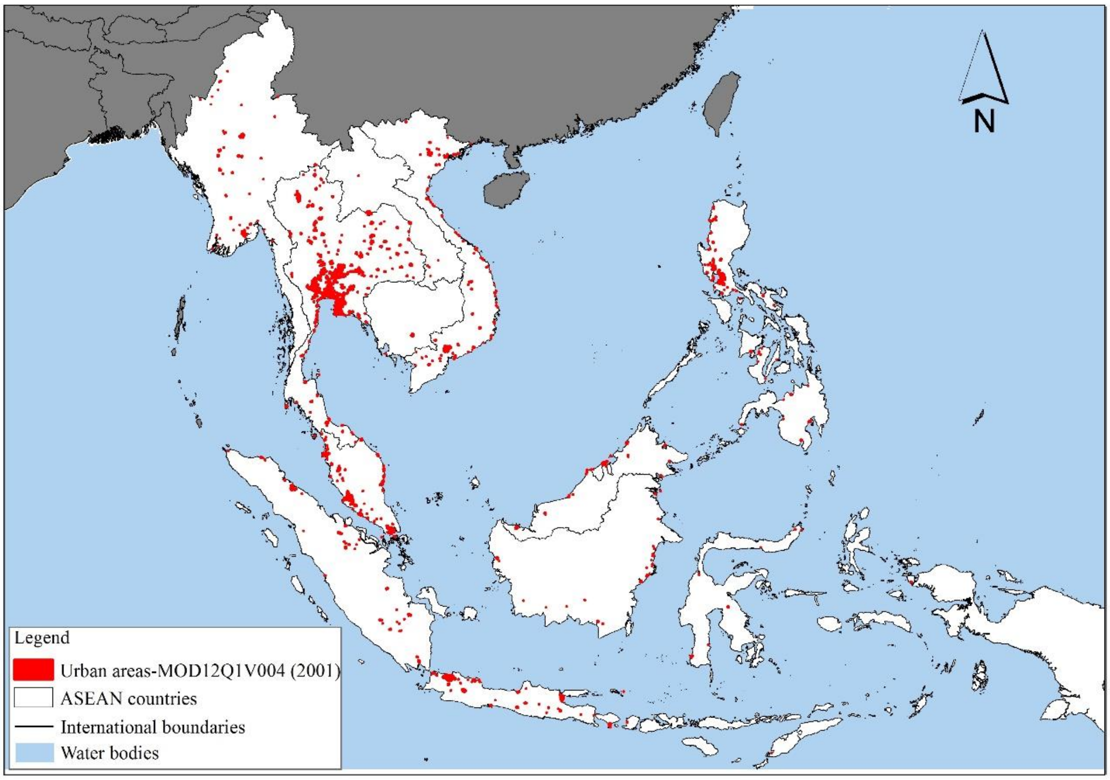


Figure 2 Urban mapping of ASEAN region from IGBP-DISCover (1992-1993)

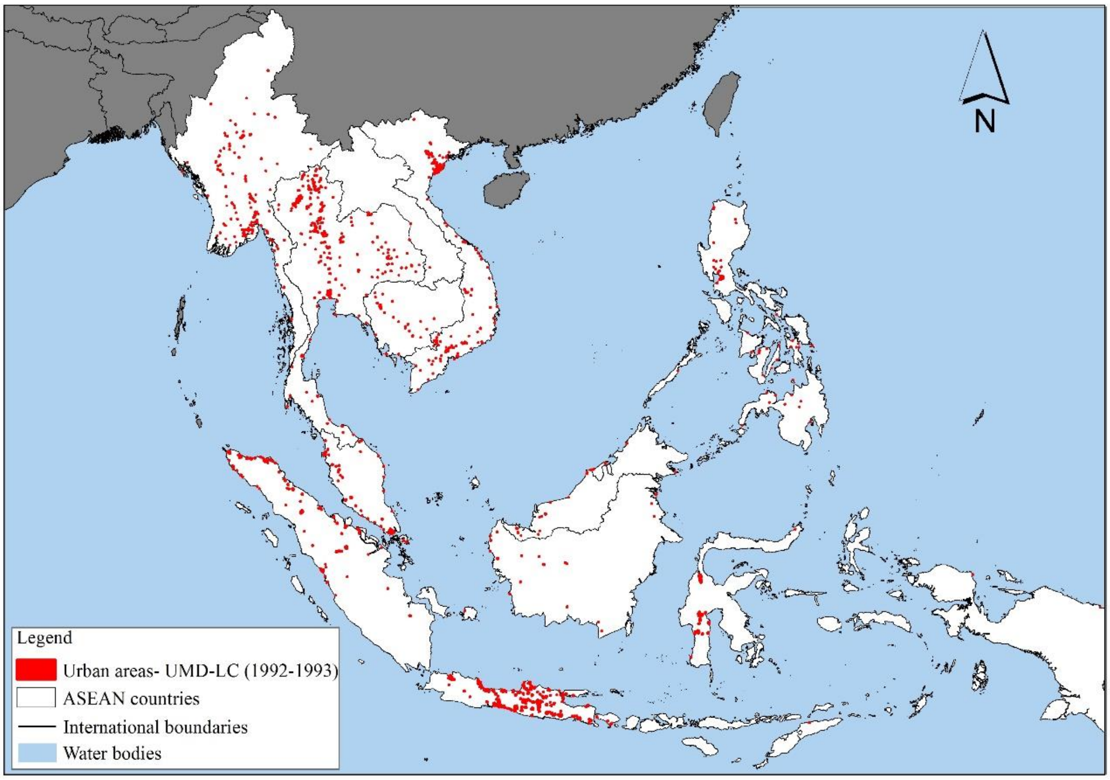


Figure 3 Urban mapping of ASEAN region from UMD-LC (1992-1993)

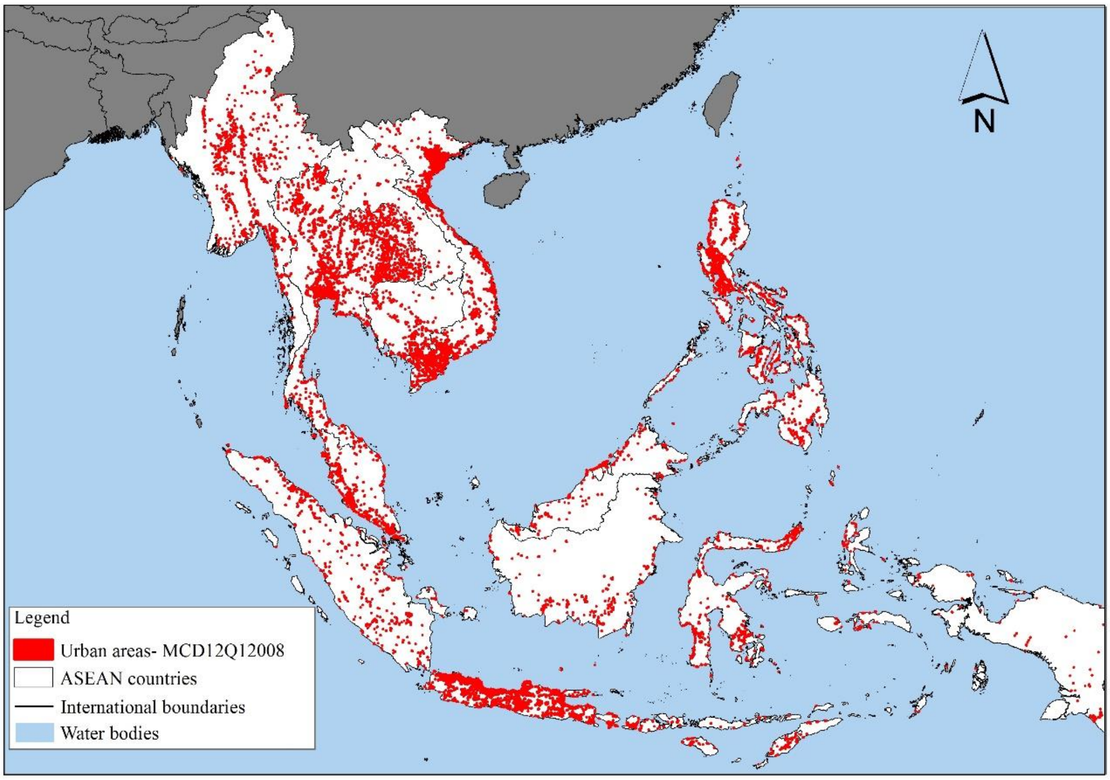


Figure 4 Urban mapping of ASEAN region from MOD12Q1V004 (2001)
MODIS 1km LC

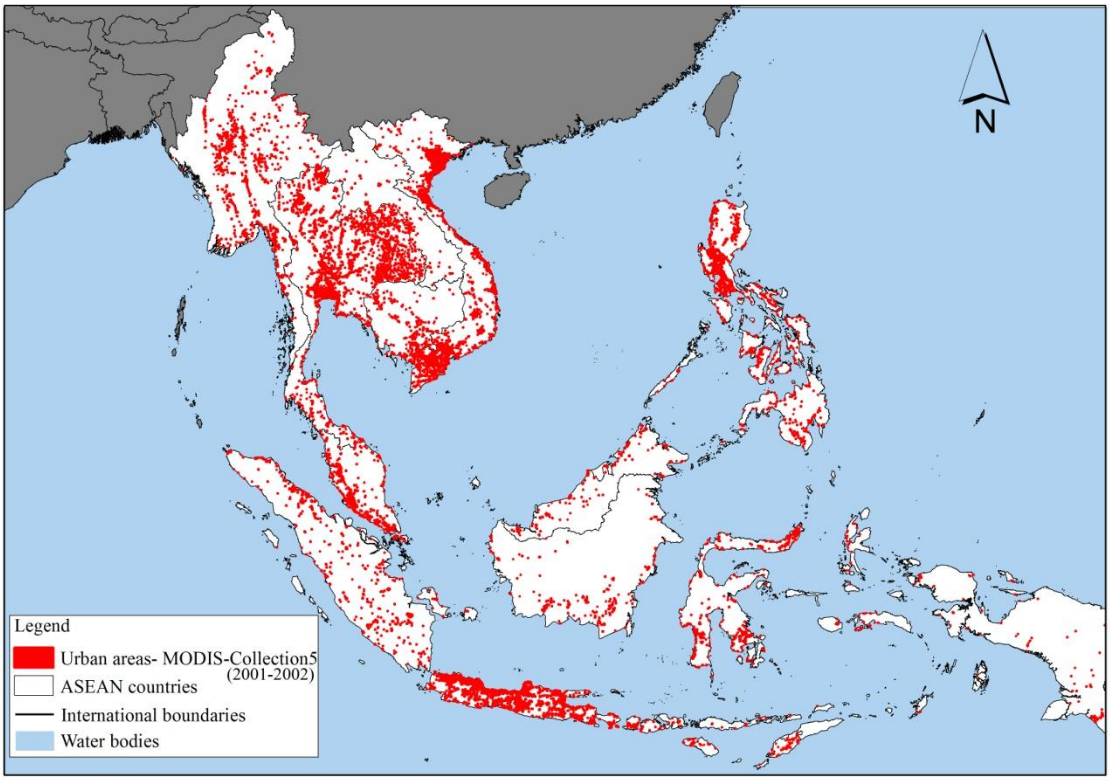


Figure 5 Urban mapping of ASEAN region from MODIS-Collection5 (2001-2002) Urban Extent

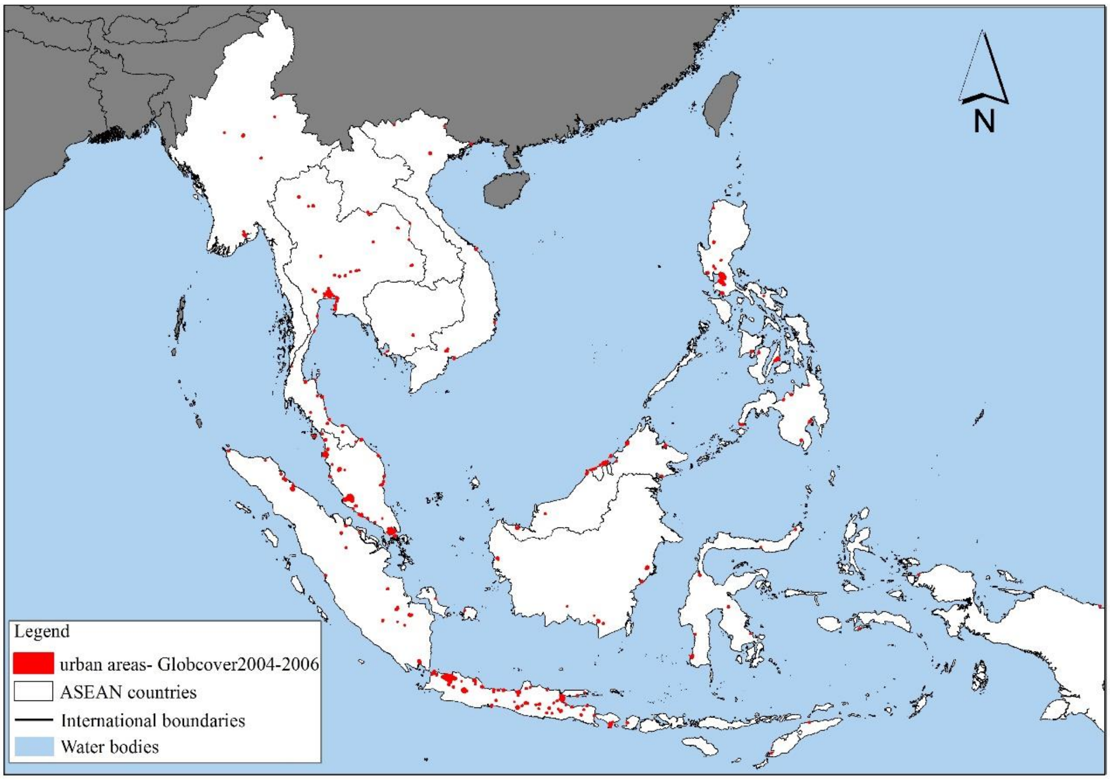


Figure 6 Urban mapping of ASEAN region from MCD12Q1 (2008)

MODIS 500m LC

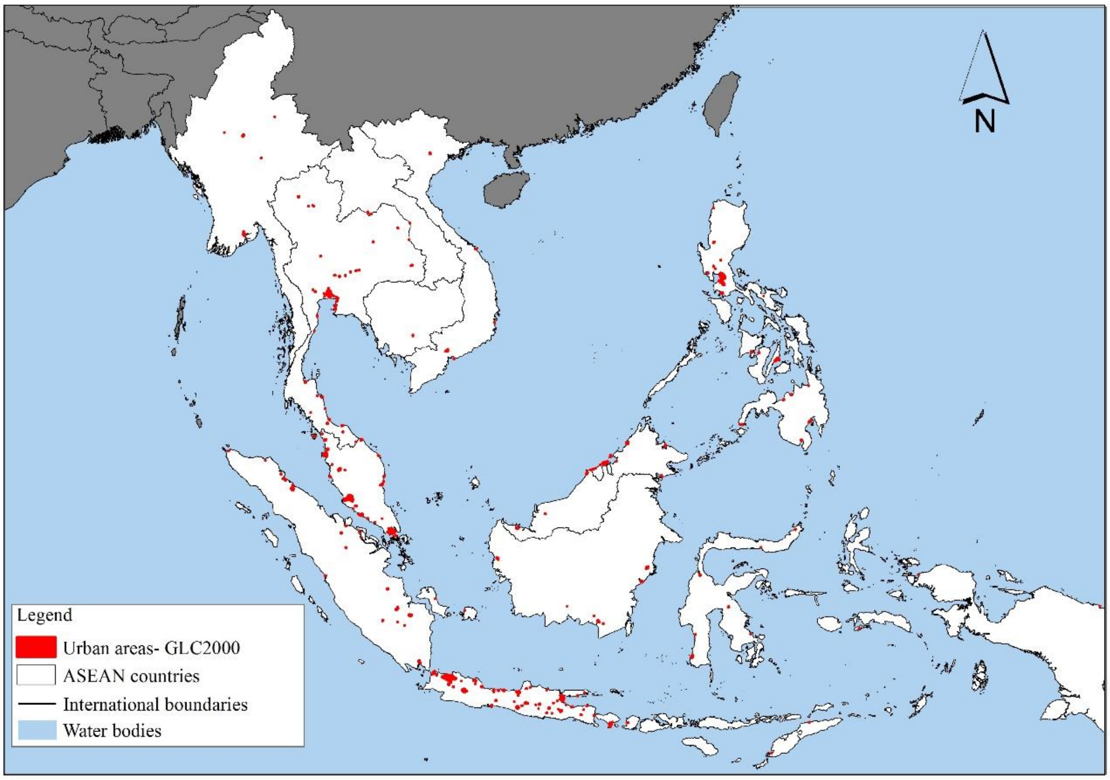


Figure 7 Urban mapping of ASEAN region from GLC2000

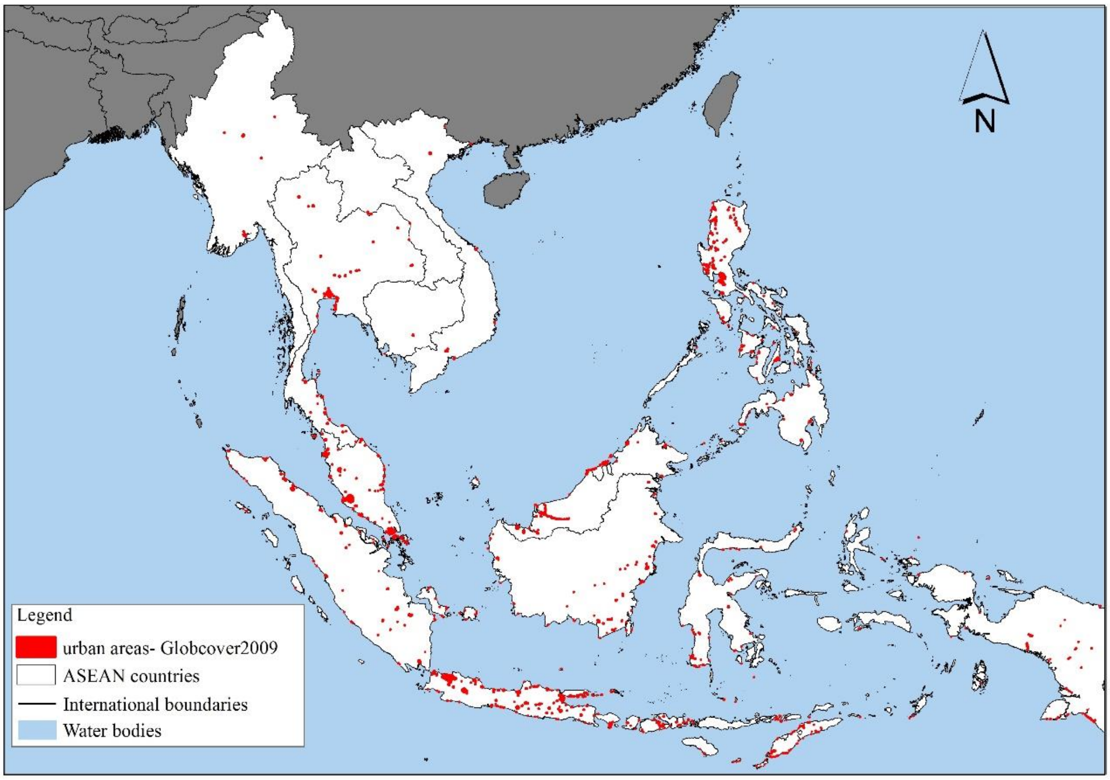


Figure 8 Urban mapping of ASEAN region from GlobCover (2004-2006)

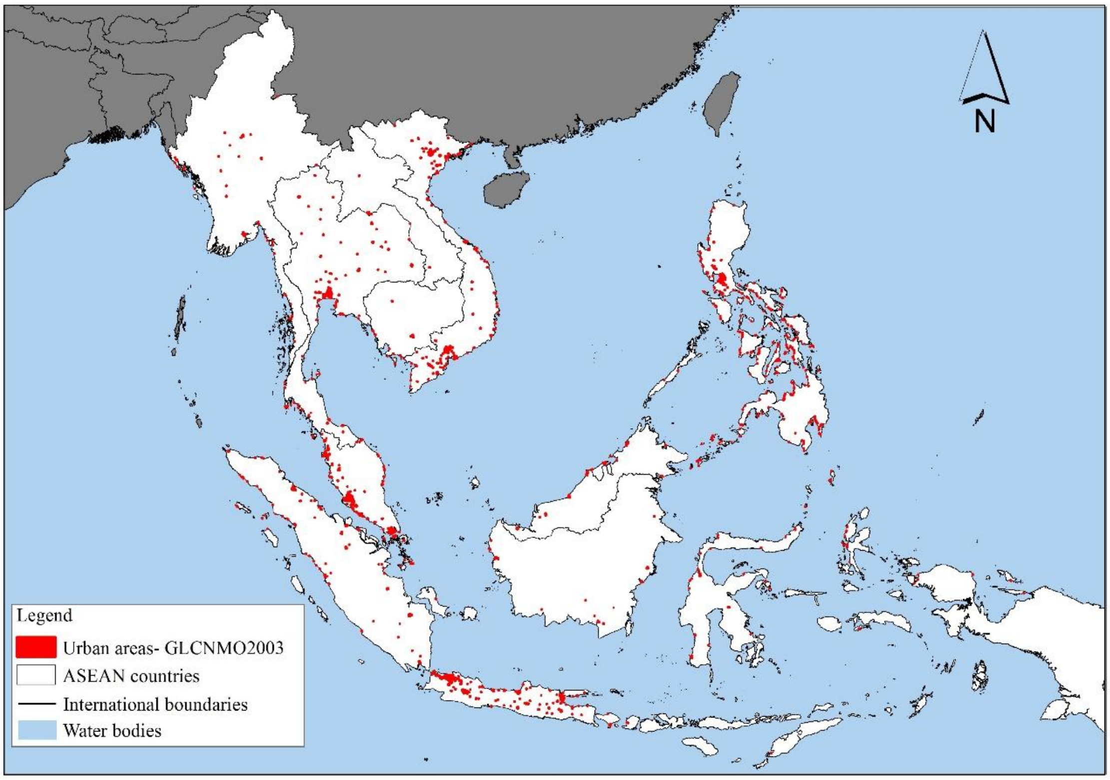


Figure 9 Urban mapping of ASEAN region from GlobCover (2009)

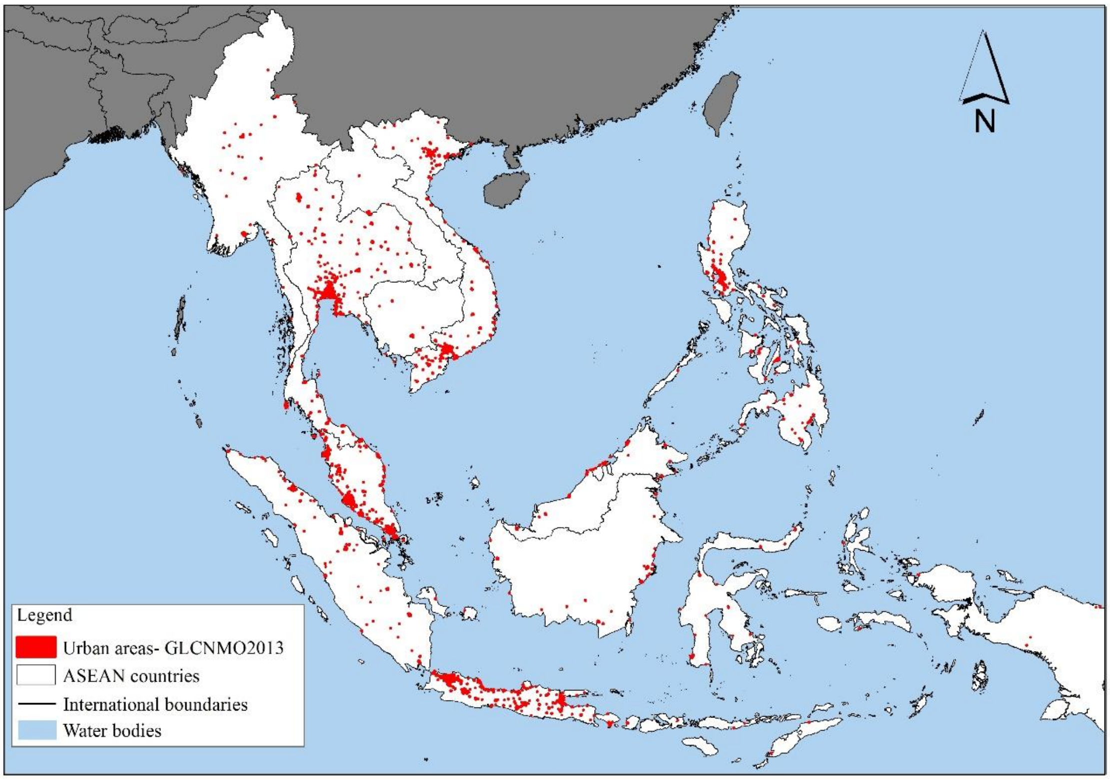


Figure 10 Urban mapping of ASEAN region from GLCNMO (2003)

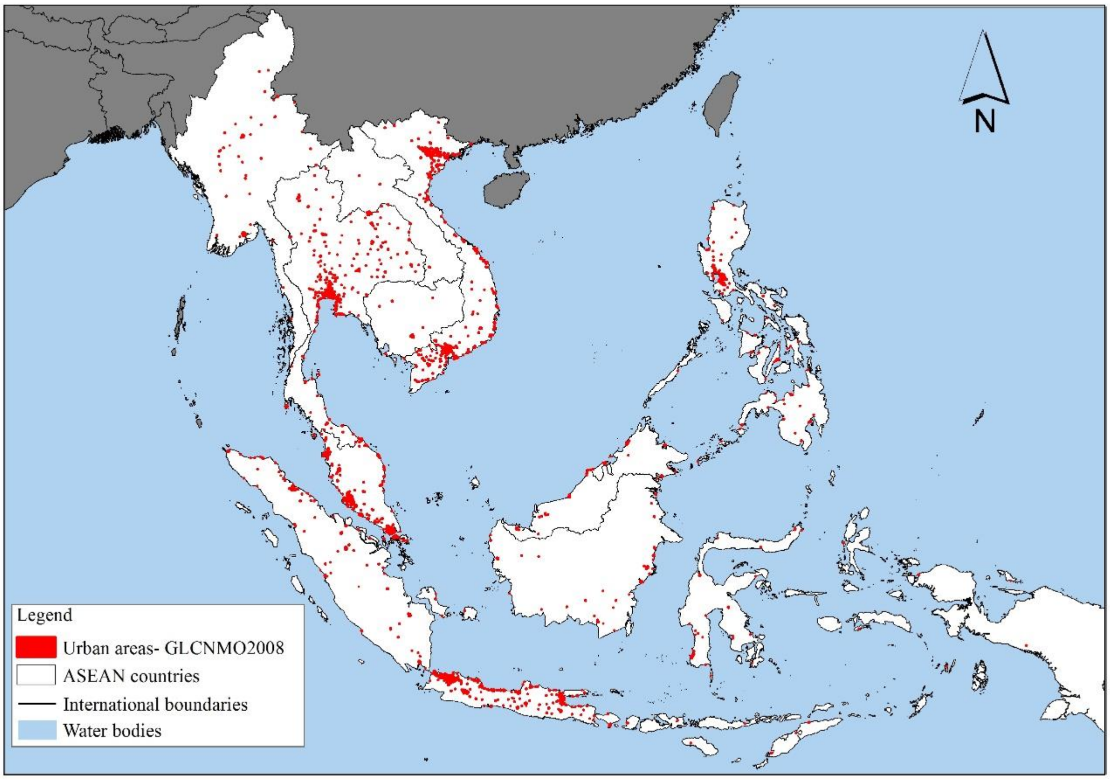
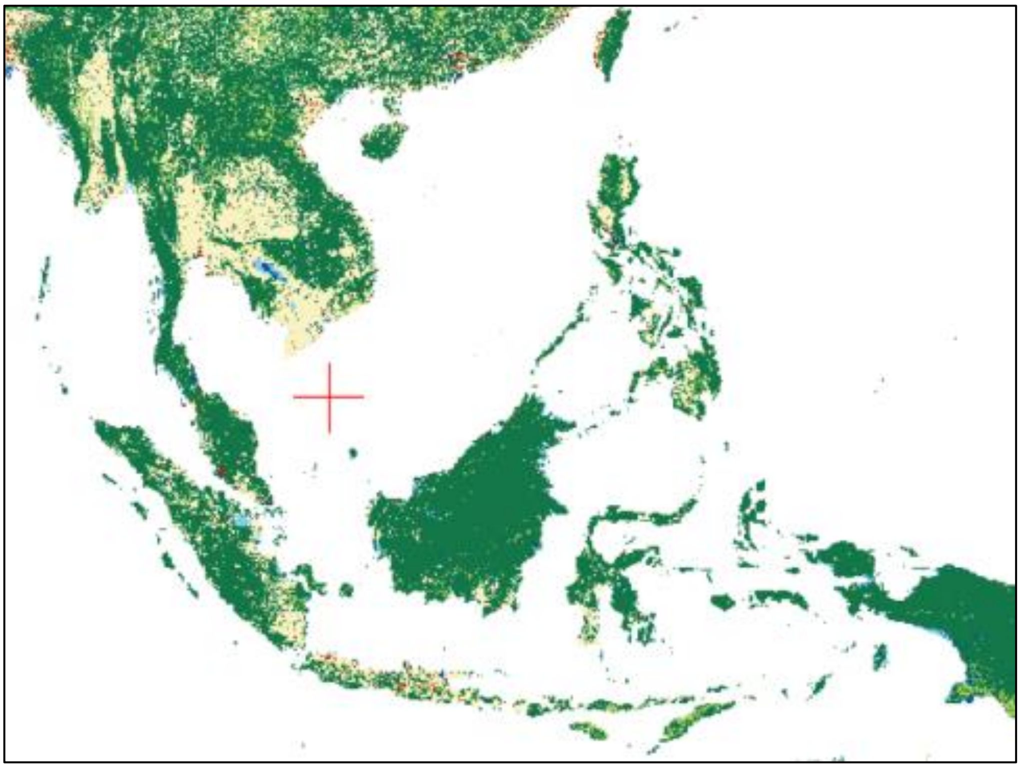
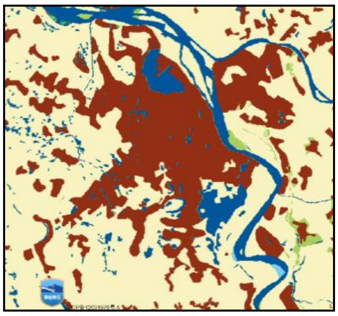
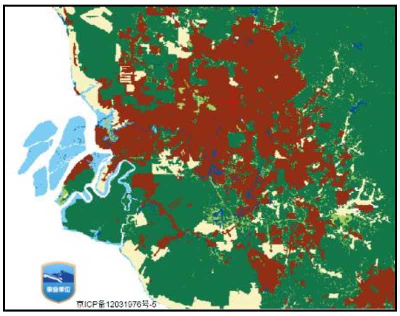


Figure 11 Urban mapping of ASEAN region from GLCNMO (2008)

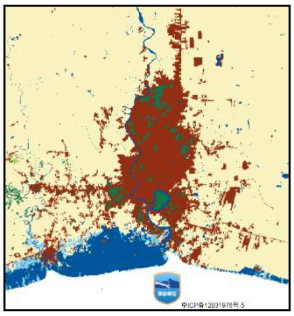




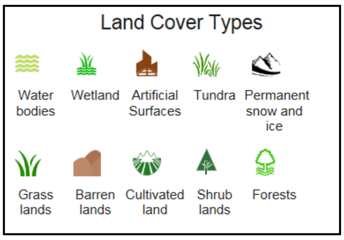
Hanoi city-



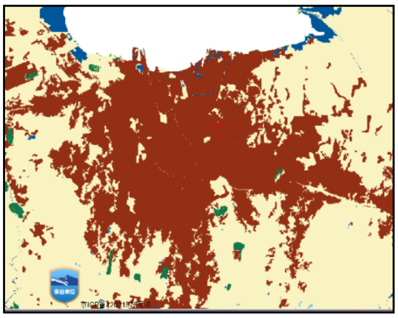
Kuala Lumpur city-



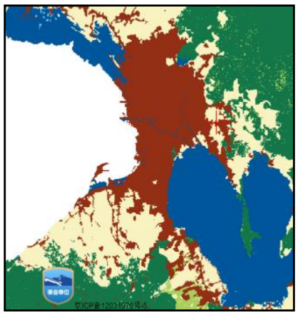
Bangkok city- Thailand



GLOBLAND30: http://www.globallandcover.com/GLC30Download/index.aspx

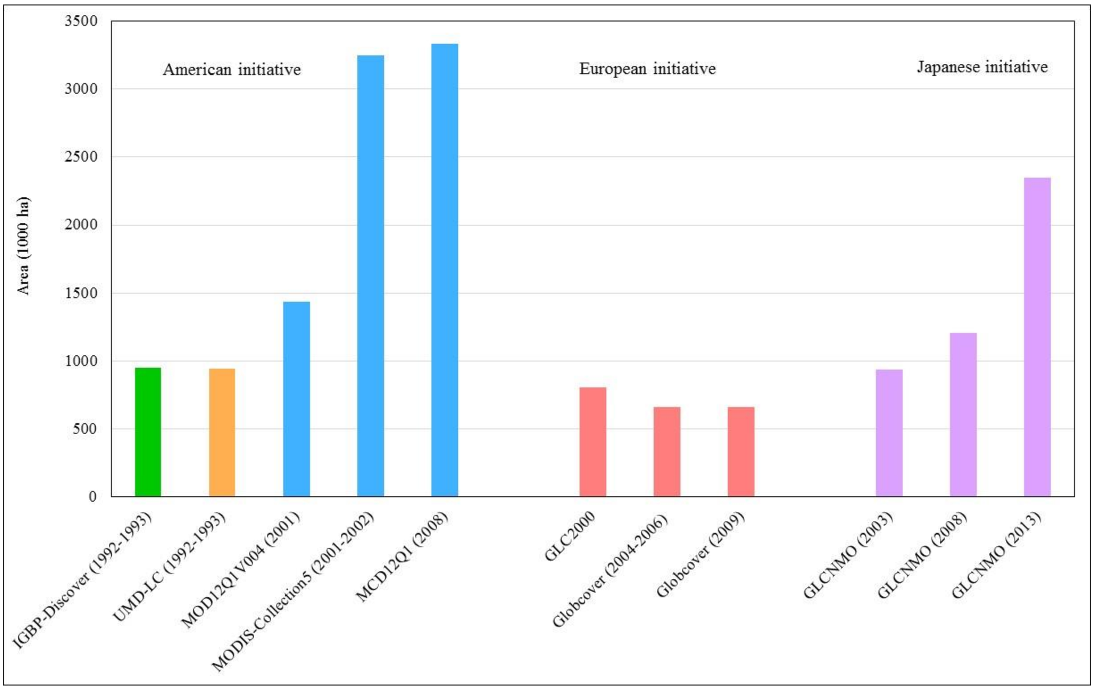


Jakarta city-



Manila city-

Figure 13 Urban mapping of ASEAN region and 5 cities from GlobLand30 (2000 and 2010)



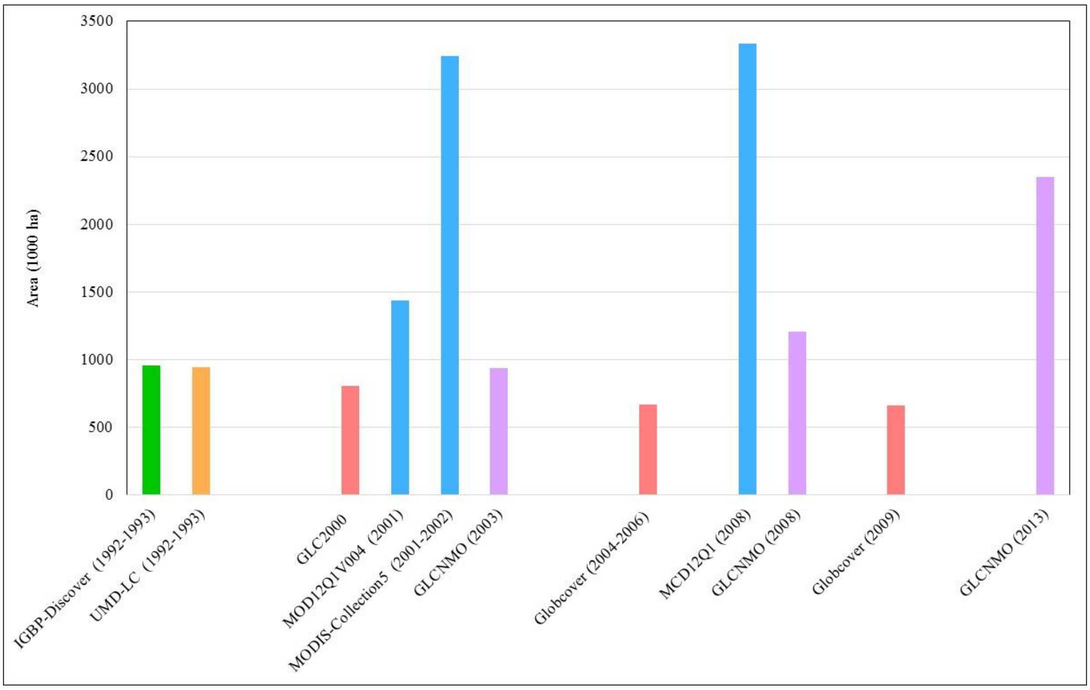


Figure 14 Comparison of urban areas of ASEAN region in global land cover products

upper: displayed in the order of Amarican, Eropean, and Japanese initiative

lower: displayed in the order of the year of map contents

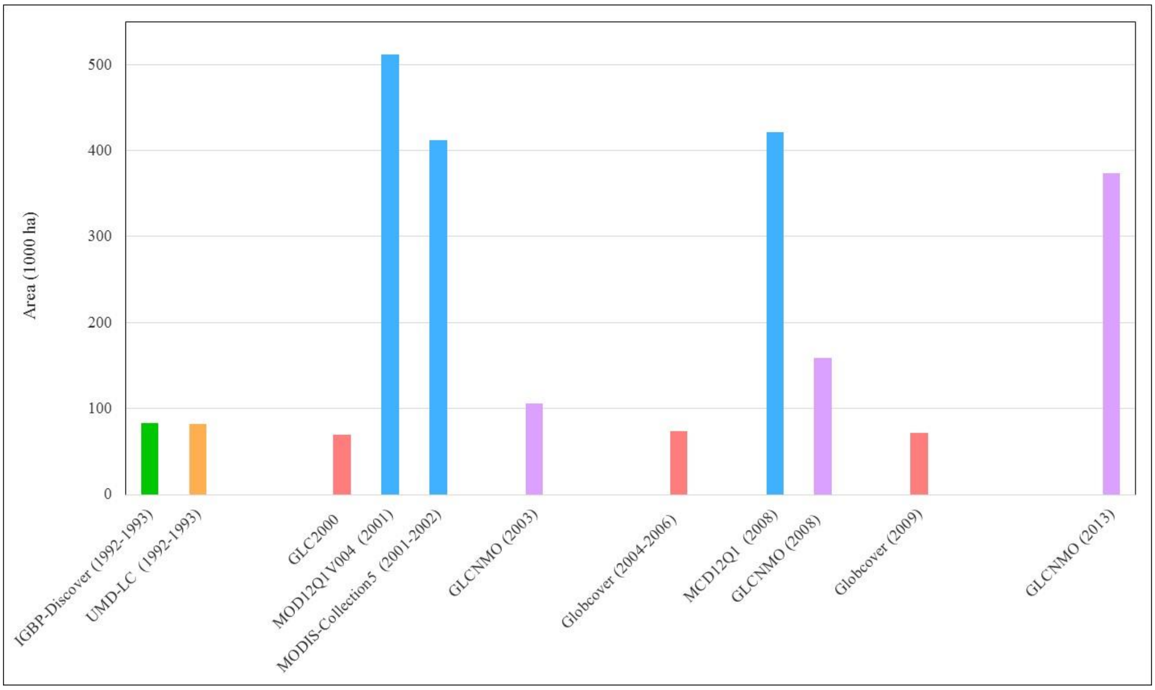


Figure 15 Comparison of urban areas of Thailand in global land cover products displayed in the order of the year of map contents

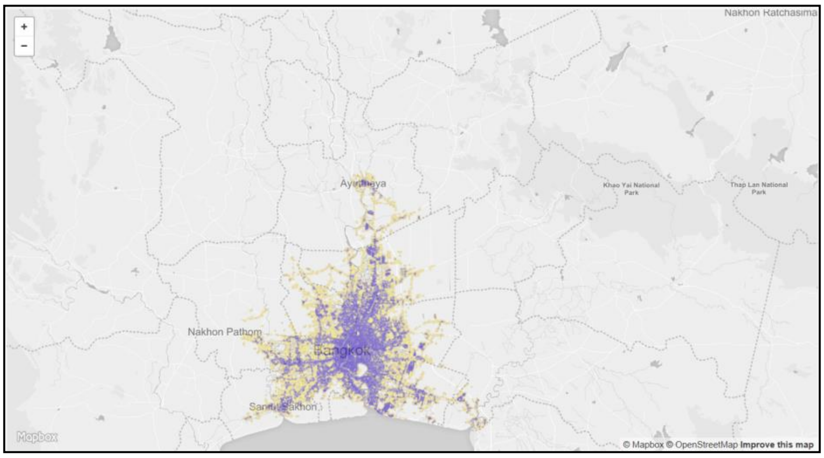


Figure 16 Urban extent of Bangkok city

Source: Atlas of urban expansion (Angel 2016)

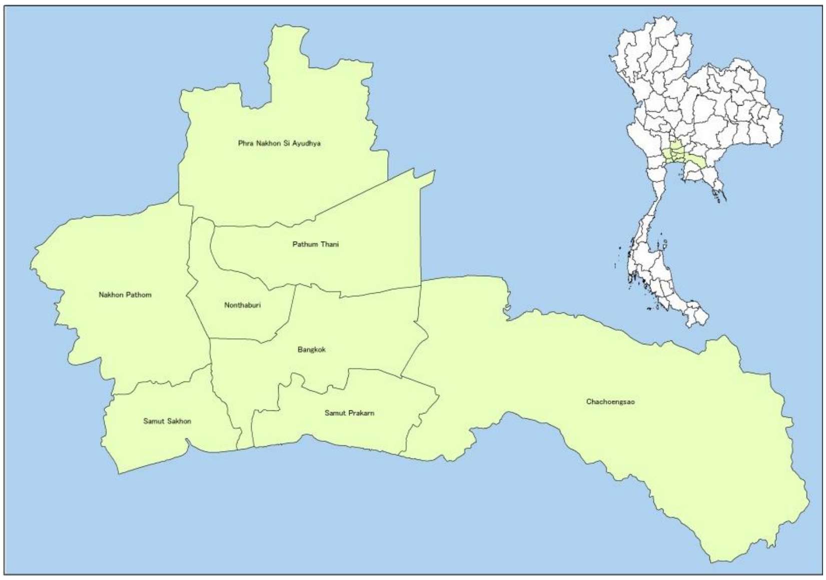


Figure 17 Local administrative boundaries including Bangkok urban extent

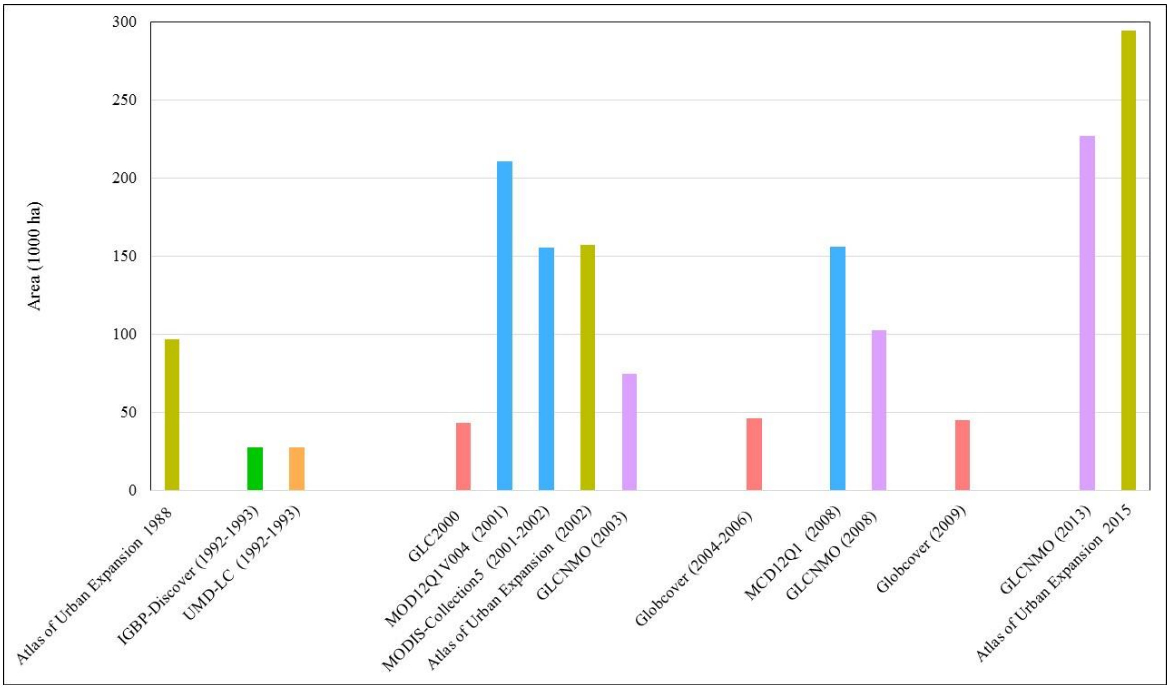


Figure 18 Comparison of urban areas of Bangkok in global land cover products and “Atlas of urban expansion”, displayed in the order of the year of map contents

Table 3 Summary of urban mapping from space

Mapping area	Local (one or several cities)	Global (or national, regional)
Resolution	1-30 m (mainly 1-10 m)	30 m – 1 km (mainly 250- 500 m)
Mapping type	- Intra-urban map (ex. roof types, roads, trees, water)	- Urban class in land cover map - Urban extent
Sensor types	- High resolution optical sensor - High resolution radar sensor - Landsat type sensor	- Daily/near-daily global observation sensor (ex. MODIS) - Nightlight observation sensor (ex. DMSP/OLS) - Radar - Landsat type sensor
Mapping methods	Supervised classification - Decision tree - Random forest - Support vector machine - Thresholding - Neural network - Others (All require training data)	