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LETTER

A new urban landscape in East–Southeast Asia, 2000–2010

A Schneider[1], C M Mertes[1], A J Tatem[2,3], B Tan[4], D Sulla-Menashe[5], S J Graves[6], N N Patel[7], J A Horton[1], A E Gaughan[8], J T Rollo[1], I H Schelly[1], F R Stevens[8] and A Dastur[9]

[1] Center for Sustainability and the Global Environment, Nelson Institute for Environmental Studies, and Department of Geography, University of Wisconsin-Madison, USA
[2] Department of Geography and Environment, University of Southampton, UK
[3] Fogarty International Center, National Institutes of Health, Bethesda, Maryland, USA
[4] NASA Goddard Space Flight Center/Science Systems and Applications Inc., Lanham, Maryland, USA
[5] Department of Earth and Environment, Boston University, Boston, Massachusetts USA
[6] School of Forest Resources and Conservation, University of Florida-Gainesville, USA
[7] Department of Geography and Geoinformation Science, George Mason University, Fairfax, Virginia, USA
[8] Department of Geography and Geosciences, University of Louisville, Kentucky, USA
[9] World Bank, Washington DC, USA

E-mail: aschneider4@wisc.edu

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Abstract

East–Southeast Asia is currently one of the fastest urbanizing regions in the world, with countries such as China climbing from 20 to 50% urbanized in just a few decades. By 2050, these countries are projected to add 1 billion people, with 90% of that growth occurring in cities. This population shift parallels an equally astounding amount of built-up land expansion. However, spatially-and temporally-detailed information on regional-scale changes in urban land or population distribution do not exist; previous efforts have been either sample-based, focused on one country, or drawn conclusions from datasets with substantial temporal/spatial mismatch and variability in urban definitions. Using consistent methodology, satellite imagery and census data for >1000 agglomerations in the East–Southeast Asian region, we show that urban land increased >22% between 2000 and 2010 (from 155 000 to 189 000 km^2), an amount equivalent to the area of Taiwan, while urban populations climbed >31% (from 738 to 969 million). Although urban land expanded at unprecedented rates, urban populations grew more rapidly, resulting in increasing densities for the majority of urban agglomerations, including those in both more developed (Japan, South Korea) and industrializing nations (China, Vietnam, Indonesia). This result contrasts previous sample-based studies, which conclude that cities are universally declining in density. The patterns and rates of change uncovered by these datasets provide a unique record of the massive urban transition currently underway in East–Southeast Asia that is impacting local-regional climate, pollution levels, water quality/availability, arable land, as well as the livelihoods and vulnerability of populations in the region.

1. Introduction

We have entered the urban era: cities now form the basis of the human experience for the majority of the Earth's population (UN 2012). Cities today must meet the needs of growing populations and expanding economies, while at the same time minimizing their environmental impacts (Grimm *et al* 2008, Montgomery 2008). Expansion of built-up land is often the most direct environmental impact associated with urban growth, with far-reaching implications for climate, hydrology, and biogeochemical cycles that extend beyond municipal boundaries (Seto *et al* 2010). While remote sensing has proven especially useful for characterizing broad-scale land changes, detailed monitoring of urban land use change remains costly and challenging due to the highly heterogeneous nature of cities, the spectral similarity between new urban land and other land cover types, and the lack of cloud-free data in locations where estimates are most needed (e.g. tropics, Mertes *et al* 2015). As a result, there has been little information on the building boom

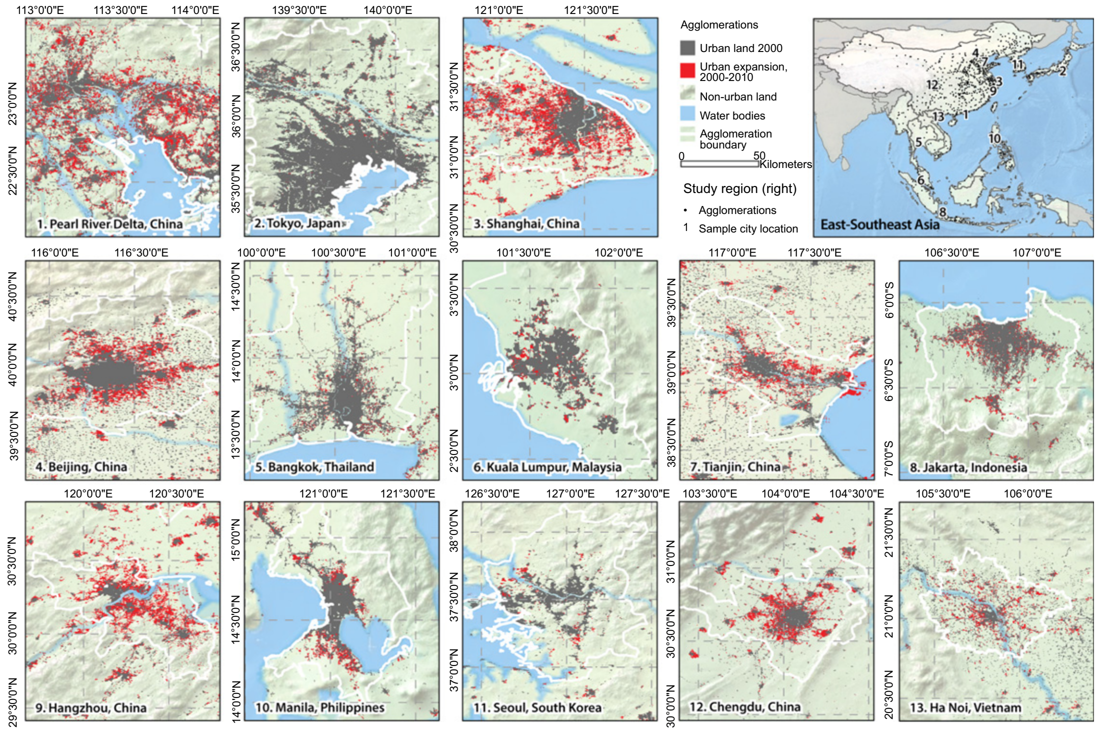

Figure 1. Maps of urban land extent and urban expansion for 13 of the 30 largest urban agglomerations in East–Southeast Asia. Agglomerations are labeled by largest city (see table A5 for a list of cities within each agglomeration). Note that the scale is held constant across all urban agglomerations.

that is accompanying population growth in many developing countries (China, India, etc) other than case-study analysis of individual cities (Schneider and Woodcock 2008, Angel *et al* 2011), or country-level assessments (Liu *et al* 2005, Wang *et al* 2012). Comparing urban populations has also been notoriously difficult due to differences in census timing, data availability/quality, and most critically, the considerable variability in how cities are defined, whether by population threshold, functional area, or administrative boundaries (Cohen 2004). One of the few studies reporting transnational urban land and population trends concluded that cities are universally spreading out and declining in density (Angel *et al* 2005). While there is evidence to contradict this in East Asia (Murakami *et al* 2005, Bagan and Yamagata 2012), there has been no systematic way to compare trends across cities, nations, or regions.

To describe urban trajectories across East and Southeast Asia[10] systematically, we characterize urban extent and urban expansion 2000–2010 using Moderate Resolution Imaging Spectroradiometer (MODIS) satellite observations (Mertes *et al* 2015). In these maps, urban land refers to places dominated by the 'built environment', which includes all non-vegetative, human-constructed elements (e.g. roads, buildings) with >50% coverage of a landscape unit (here, a 250 m pixel). We synthesize this information with population density maps developed using demographic data at the finest administrative unit available and empirically-tested population-land cover relationship-based methods (Tatem *et al* 2007). To address the issue of comparability, we conduct our analysis of regional urbanization trends using the urban agglomeration as the unit of analysis. We perform a comparative analysis to understand within-nation and across-nation trends in East–Southeast Asia (figure 1, A1) recognizing that such a regional approach cannot account for each city's circumstances or individual drivers/impacts. Our results likely produce a conservative estimate of urban change in the region, and may differ from 'official' statistics (World Bank 2015) as a result of necessary choices regarding definitions, spatial scale, and data sources. Our aim is not to replace national estimates, but to offer a consistent approach for regional comparability of all cities >100 000 in the region.

2. Background

Great strides have been made to map population distribution using consistent data and methods (Balk *et al* 2006, Tatem *et al* 2007), but they depict population as measured at one point in time, and at best adjust only for changing population growth rates at the country level. Similarly, urban maps from remote sensing data have been limited to either static

[10] East Asia includes China (including Hong Kong SAR, Macao SAR), Taiwan, Japan, Mongolia, North Korea, South Korea; Southeast Asia includes Brunei Darussalam, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, Timor-Leste, Vietnam.

global maps that sacrifice detail to provide areal coverage (Potere *et al* 2009), or local maps of metropolitan growth that forego coverage in favor of spatial detail (Seto *et al* 2010). Moreover, of the many global urban maps now available (Elvidge *et al* 2007, Schneider *et al* 2009), none characterize changes in urban land.

Recent comparative work on urbanization has found a middle ground by focusing on local maps (typically 30 m resolution) for a sample of cities (Seto *et al* 2011, Angel *et al* 2012, Taubenbock *et al* 2012, Schneider and Mertes 2014). These studies point to several key findings: (1) cities in developing countries are consistently smaller or more compact than those in developed nations (Huang *et al* 2007, Schneider and Woodcock 2008); (2) developing country cities typically undergo some decrease in population density in the core during their development trajectory (Murakami *et al* 2005); and (3) cities are declining in density (Angel *et al* 2011, 2012).

Although they represent advances in our empirical understanding of urbanization, these studies (and their conclusions) suffer from several limitations. Many rely on a limited very city sample (Murakami *et al* 2005, Taubenbock *et al* 2012); most exclude small-and medium-sized cities (100 000-1 million) where the majority of new growth is taking place (UN 2012). Definitional issues also jeopardize comparability: nearly all utilize municipal boundaries to clip the city extent, making it nearly impossible to compare trends across places. In addition, administrative divisions often under-bound the built-up extent, so new growth in fringe areas is not captured. Finally, many studies rely only on population or remote sensing, failing to connect the two to provide a complete picture of urban trends meaningful for environmental assessment, land use planning, and regional policy implementation.

3. Methods

3.1. Satellite-based maps of urban expansion

To establish potential locations of urban land, the study extent was first established by synthesizing all contemporary city point data (table A1) with a c. 2000 map of urban extent developed from MODIS 500 m data (Schneider *et al* 2009, 2010). The MODIS 500 m urban extent map has been shown to have the highest locational accuracy of available maps and a zero omission rate for cities globally (Potere *et al* 2009). Where city points did not align with the MODIS map or vice versa, the locations were manually checked against Google Earth data and adjusted. The final study extent was created by categorizing the identified urban patches into small, medium, and large classes according to their spatial extent and population, and buffering by 5, 25, and 100 km respectively to include potential areas of urban and peri-urban growth (Webster 2002).

Urban expansion 2000–2010 was mapped in two steps, beginning with delineation of the c. 2010 urban extent. A probability surface of urban land was developed from three years of 500 m MODIS imagery (table A2) and training samples for urban and non-urban areas photo-interpreted using very high resolution (VHR) Google Earth imagery (1–4 m resolution). A separate probability surface based on vegetation characteristics of urban and non-urban areas was produced from 250 m MODIS enhanced vegetation index (EVI) data (Tan *et al* 2011) and integrated with the 500 m probabilities according to Bayes' Rule (Mertes *et al* 2015).

To detect change, we assume all urban expansion 2000–2010 to be unidirectional and occur within the mapped 2010 urban extent. We again exploit EVI data in a multi-date composite technique (annual maximum for each year, 2001–2010) by stacking all images for classification with a boosted decision tree (Quinlan 1993) to map (a) stable urban areas; and (b) areas that were developed 2000–2010. This approach relies on the assumption that any conversion from a non-urban land cover to developed land is detectable through changes in vegetation content (Schneider *et al* 2010, Mertes *et al* 2015).

The final maps were assessed for accuracy using a two-tiered approach. The 2010 urban map was first assessed using a stratified random sample of 6528 sites 0.132 km^2 in size, and the maps of urban expansion were assessed using a separate random sample of 2086 sites (0.06 km^2, to align with the 250 m resolution). Test sites were assessed within Google Earth against VHR data in a double-blind assessment by a team of photo-interpretation analysts, and labeled as urban/non-urban land (tier one), or urban land/urban expansion 2000–2010 (tier two) according to the >50% built-up threshold (note that the 50% threshold is used throughout to maintain consistency with previous urban remote sensing efforts). Overall accuracy measures for the maps were calculated by comparing the maps against the test sites. The results indicate that map accuracies for urban extent (tier one) range between a maximum of 93% to a minimum of 79% for each country, and for urban expansion (tier two), between 91% and 70%, confirming their suitability for this analysis (Mertes *et al* 2015).

3.2. Population density maps

Human population census data and corresponding administrative boundaries at the finest level available were obtained from multiple recent censuses in each nation (table A3). If they did not align with the c. 2000 and 2010 time points, the population data were adjusted forward or backward using inter-censal growth rates and linear estimation methods. High resolution census data were then used to establish population densities for each time point (2000, 2010) on a biome-by-biome basis for each land cover type in the region, following previous WorldPop (www.worldpop.org.uk) mapping approaches (Tatem *et al* 2007, Gaughan *et al* 2013). These population densities were then used as weights to distribute the population across the raster cells, an approach that has been shown to produce more accurate disaggregations than previous approaches that rely on disaggregation to very coarse data (nighttime lights data) or areal weighting alone (Linard *et al* 2010, 2013, Gaughan *et al* 2013). After synthesizing all population data with land cover information and built-up extent to map population density, we count only the population cells fully contained within the built-up area. With this approach, we avoid the problems common to urban population data, including the lack of data at disaggregated scales, country-dependent definitions and delineations of urban versus rural that lead to drastically different population estimates, and changes in census geographies that require adjustment so measures reflect true population growth/decline rather than differences due to changes in administrative boundaries (Cohen 2004).

3.3. Analysis

We defined an urban agglomeration as the extended area comprising the built-up area of a central place (i.e. a city) and any suburbs or small cities linked by continuous urban land (UN 2012). To delineate agglomerations for this analysis, we collected the most detailed administrative boundary data available (typically county or finer) for c. 2010, to reflect the most recent units used for governing. We then assigned any administrative unit containing part of the contiguous built-up area of the city to its agglomeration, so that the agglomeration boundary is made up of one or more official administrative units. This was repeated for each city >100 000 persons, resulting in 1036 agglomerations across 17 countries (figure A1). For each agglomeration, we estimated the built-up extent for 2000 and 2010 from the satellite-based maps, as well as the 2000 and 2010 urban population within the built-up extent from the population density maps. The 1036 agglomerations were then stratified into five categories (UN 2012) based on their 2010 agglomeration population: >10 million; 5–10 million; 1–5 million; 500 000–1 million; and 100 000–500 000.

To understand regional urbanization trends within the 30 largest agglomerations, we also conducted a separate analysis measuring urban expansion for all established cities within the administrative core, within the urban agglomeration defined by the built-up extent, and directly adjacent or near the urban agglomeration boundary (within 120 km of each agglomeration's center, following distance recommendations from the peri-urbanization literature, Webster *et al* 2002). For this analysis, we followed convention in urban geography, and standardized the study extent for each small city using adaptive radial zones (5, 10, 15 km) based on 2010 population size (Dietzel *et al* 2005, Seto and Fragkias 2005).

4. Results

4.1. Regional and country-level results

Across the region, the total net increase in urban land area was >34 000 km^2 from 2000 to 2010, expanding from 155 000 to 189 000 km^2. While urban land area increased >22%, urban populations climbed >31%, adding 231 million persons in just ten years (from 738 to 969 million). The rapid pace of population change is clear in the average rates of change for each country (table A4): cities in the region grew annually at 2.8%, with Malaysia, Vietnam, Cambodia, and Laos all observing rates well above this average (4.0–7.8%). In contrast, the rates of change for urban land average 2.0% annually, with only China, the Philippines, Cambodia, and Laos having rates above this level (2.2–3.2%).

The results suggest that urban population growth has outpaced land expansion, a trend we measure explicitly using urban density. Here we estimate persons per square kilometer of built-up land since the conventional measure, persons per square kilometer within an administrative region, does not account for the vastly different sizes of municipal boundaries. While the results show a great degree of variability (figure 2), there are two common trends across nations: (a) urban densities are high (mean 2010, 5850 persons/km^2), and (b) urban densities increase 15–30% from 2000 to 2010, adding between 270 and 2020 persons/km^2 in ten years. Although on average, urban densities are decreasing in China (from 6150 to 5290 persons/km^2 across 677 cities), there is considerable variability here as well: roughly half of Chinese agglomerations are decreasing in density, while the remaining half witnessed no change or an increase in urban density, similar to other agglomerations in the region.

4.2. City-level results: the view from above

More than one-third of all urban land and urban population in East–Southeast Asia falls into 30 large agglomerations (figure 3). By 2010, the Pearl River Delta agglomeration climbed to >41 million inhabitants and 6970 km^2 of urban land, surpassing Tokyo (31 million persons, 5570 km^2 urban land) as the largest urban agglomeration on Earth. An additional 12 of the top agglomerations are located in China, including Shanghai and Beijing, with 3480 and 2720 km^2 of urban land, and populations of 24 and 16 million persons, respectively, in 2010. China also contains the agglomerations with the greatest urban land expansion, 2000–2010, with a median increase of 463 km^2, compared to a median of 217 km^2 for all 30 cities. The Chinese agglomerations have witnessed

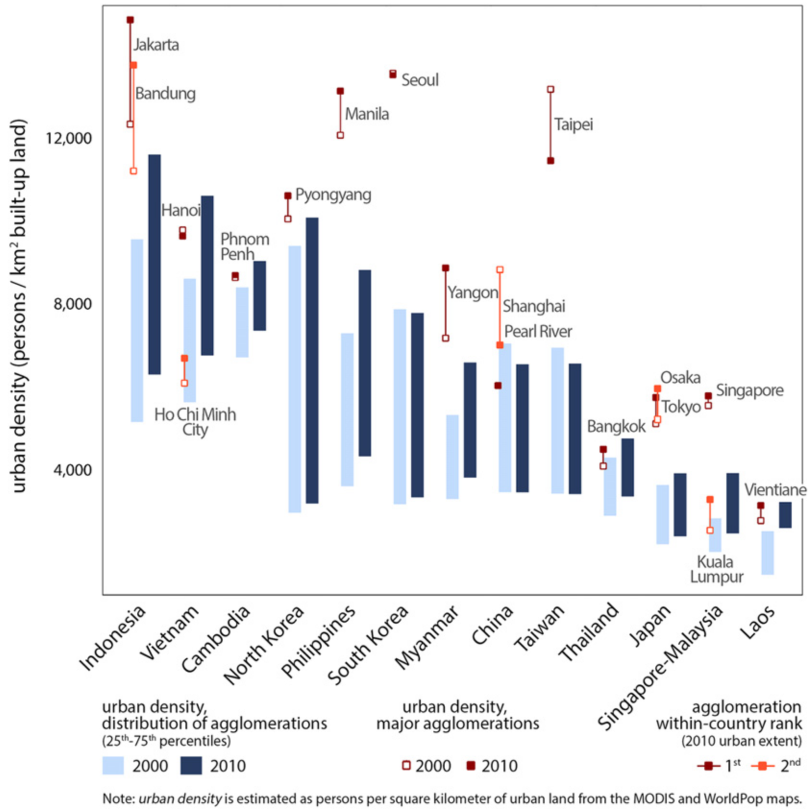

Figure 2. Country-and city-level urban densities in East–Southeast Asia. On average, the majority of urban agglomerations in the region are becoming more dense, as shown in the box plots for urban densities (population/km^2 of built-up land, 25th–75th percentiles) for 14 countries, 2000 and 2010 (not shown: Brunei, Mongolia, Timor-Leste). For comparison, the urban densities for 18 large agglomerations are included.

significant population increases as well, adding a median 2.5 million persons to each large agglomeration during the last decade. Several large agglomerations outside of China have major population increases (Tokyo, Jakarta, Manila), but not surprisingly, none have the scale of new development witnessed in China.

The growth of these 'mega-agglomerations' is not the whole story, however. The region has an additional 101 large agglomerations, each with populations between 1 and 5 million persons, totaling >207 million. Although rates of expansion in these areas are on par with the 30 large agglomerations (>3%), the average rates of population increase surpass those of the top 30, at >3.4%. These trends are also apparent in agglomerations 100 000–1 million: small cities in Myanmar, Indonesia, Vietnam and the Philippines, especially, have added population without much expansion (figure 4). Nearly all trajectories are headed in the same general direction, with an average increase of 970 persons/km^2 for the 2000–2010 period.

4.3. City-level results: governance and policy perspectives

While the agglomeration provides a consistent way to compare metropolitan areas since they are defined by built-up extent, many agglomerations are comprised of a large number of independently-governed cities. For instance, the Manila agglomeration has 17 cities in its administrative core (where resources and planning are concentrated) and another 15 cities on the outskirts. Alternatively, many large agglomerations have a small core area governed as one unit, with expansion that spills into the jurisdiction of nearby county-or city-level governments (e.g. Shanghai, Seoul, Hanoi). To understand how cities within an agglomeration view and govern themselves, we measure urban expansion for all established cities within 120 km of the city core for the top 30 agglomerations. Here we delineate each core according to its 2010 municipal area, and standardize the size of each small city extent using adaptive radial zones corresponding to each city's 2010 population.

On average, >60% of 2010 urban land and >71% of new development 2000–2010 are located outside the core administrative area, but within the urban agglomeration defined by this study (figure 5). The results also highlight three distinct urban typologies for large agglomerations: (1) a core surrounded by rapidly growing cities, with expansion rates that decline with distance (e.g. Hangzhou, Guangzhou, Chengdu, Jakarta); (2) a core with numerous nearby cities, but with limited growth due to geophysical factors (e.g. Manila, Bangkok, Kuala Lumpur); and (3) a

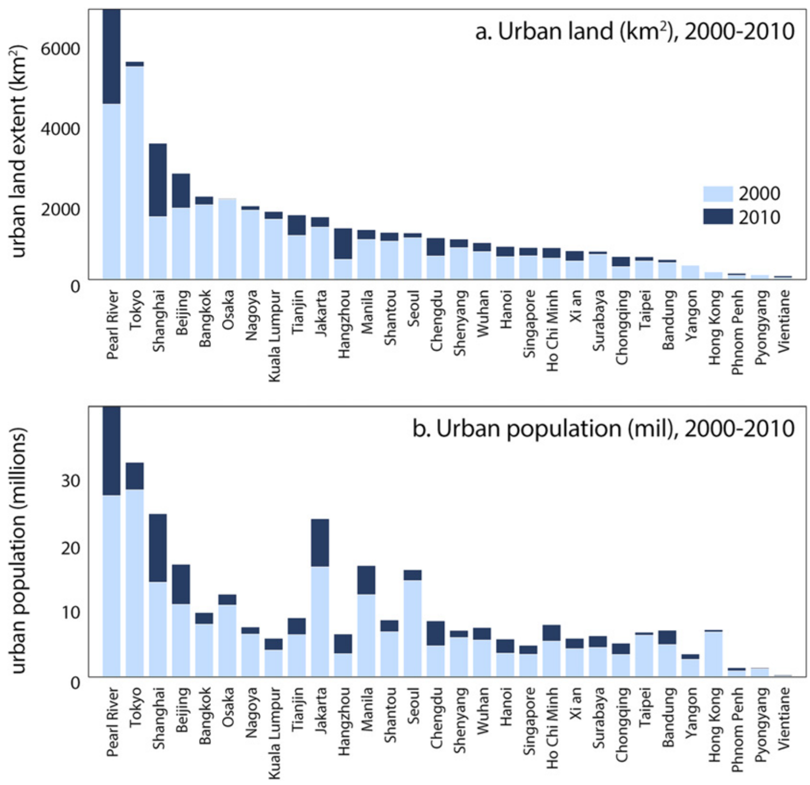

Figure 3. Amounts of (a) urban land and (b) urban population, 2000–2010, for 30 large urban agglomerations in East–Southeast Asia. The figures illustrate the 26 agglomerations with the largest 2010 populations (all >5 million), and four capital cities included for regional representation (Yangon, Phnom Penh, Pyongyang, Vien-tiane). Agglomerations are labeled by largest city (see table A5).

core with few nearby cities (Hanoi, Bangkok). Some of these latter areas are witnessing peri-urbanization (expansion up to 100 km from the core, Kontgis *et al* 2014), but this trend may not be fully captured in satellite-based estimates or census data due to its small, patchy nature.

5. Discussion and conclusions

This research presents new evidence that East–Southeast Asia is undergoing unprecedented urbanization and urban expansion, coincident with well-established trends of rapid industrialization, economic growth, and globalization. These results were generated using directly comparable, spatially-detailed datasets derived from multiple sources of remote sensing and disaggregated census data, with close attention to how urban land, urban expansion, urban population and agglomeration boundaries were defined and operationalized. When the factors limiting comparative urban analysis are addressed, the results reveal that urban agglomerations across East Asia are experiencing increasing urban densities. While these trends are not surprising for some scholars and local experts, they do contradict established empirical work that shows—with similar attention to consistency in data and definitions but with results modeled using static c. 2000 urban maps—that cities are universally declining in density (Angel *et al* 2011, 2012).

The trend toward increasing urban densities is clear in nearly all countries, and at multiple scales. At the country level, Japan and South Korea lead the region with highly urbanized populations (80–90%) spread across multiple large urban agglomerations covering 3–5% of each country's land area. Although growth has tapered off in these countries, their aggregate urban densities are still climbing. On average, population growth rates for large, middle-income countries (China, Indonesia, the Philippines, Thailand) are high (3.5%) relative to their average rates of urban expansion (2.6%). Cities of all sizes are growing in these countries, with higher rates of population growth for small cities than for large agglomerations during the last decade. China is clearly a unique case, however. At the country level, Chinese cities appear to be decreasing in density, a result that is expected given the central government's planning and policy initiatives focused on small cities outside major metropolitan areas (Lin 1999). Results at the city level reveal that half of all Chinese cities have urban densities that increase or remain unchanged.

East–Southeast Asia is also home to several low or low-middle income countries with 30% of their total populations living in urban areas, including Vietnam, Myanmar, Laos, and Cambodia. During the last decades, these countries have witnessed major shifts from predominantly subsistence agrarian economies to increasingly commercialized agriculture, leading to rapid urbanization of rural populations (Hall

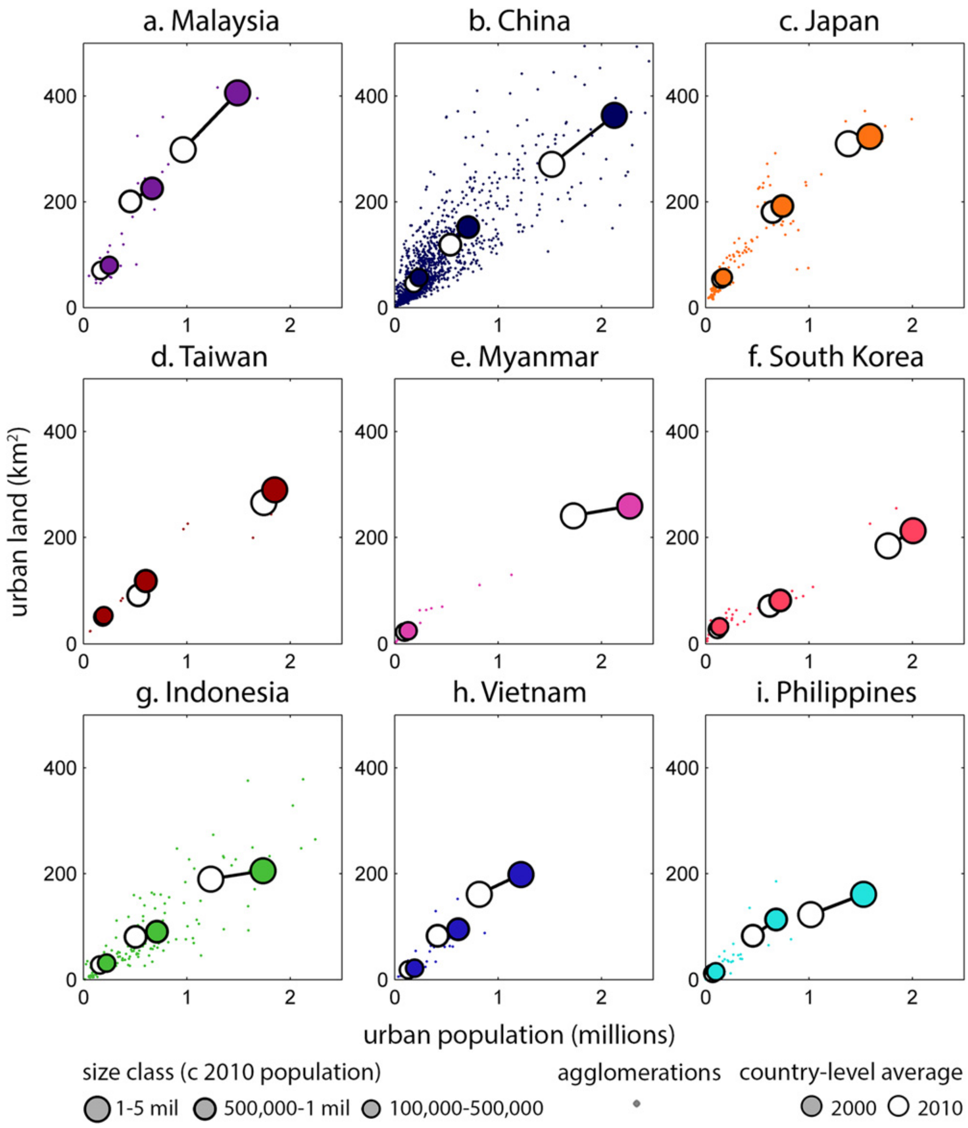

Figure 4. Mean urban land and urban population, 2000–2010, for agglomerations 100 000–5 million (not shown due to lack of cities in these size classes: Brunei, Cambodia, Laos, Mongolia, North Korea, Singapore, Thailand, Timor-Leste).

et al 2011). The rates of urban population growth at the country level average 4.6% annually, primarily due to the extraordinary growth of just a few large cities (>1 million). Ho Chi Minh City, Hanoi, Yangon, and Vientiane, for example, have all witnessed rapid population growth, adding an average 1.4 million persons, 2000–2010. The results here reveal limited urban expansion, though, which has led to an average increase in urban density of 870 persons/km^2.

Finally, this work also examines how differences in administrative boundaries and urban definitions impact how we characterize, monitor, and understand urban change. We defined 30 large agglomerations by contiguous urban land, but evaluated rates/amounts of growth within the core administrative area and for the individual cities comprising these agglomerations (figure 5). Most administrative cores contain multiple cities on average, while an additional 2–21 cities exist within the built-up area of the agglomeration, but outside the jurisdiction of the core. It is in these outer cities where the majority of urban growth is concentrated. From these results, we therefore conclude that cities as they are experienced on the ground (i.e. contiguous built-up regions) are often not the same as how they are governed. Given rising urban densities, continued expansion, and a lack of coordinated governance, the question for governments and planners becomes whether adequate services, infrastructure, housing, and employment are available or can be provided to incoming populations.

There are several potential sources of uncertainty in this study that should be noted. With respect to the remote sensing data, the 250 m pixel size combined with the population threshold of 100 000 makes it difficult to capture all small settlements. In China, Indonesia, and Vietnam, villages are spectrally distinct and sufficiently large (>1 km^2), and disaggregated population data are available. Accordingly, they are well-mapped with our methods (figure 1). In Laos, Cambodia, and North Korea, villages are small and comprised

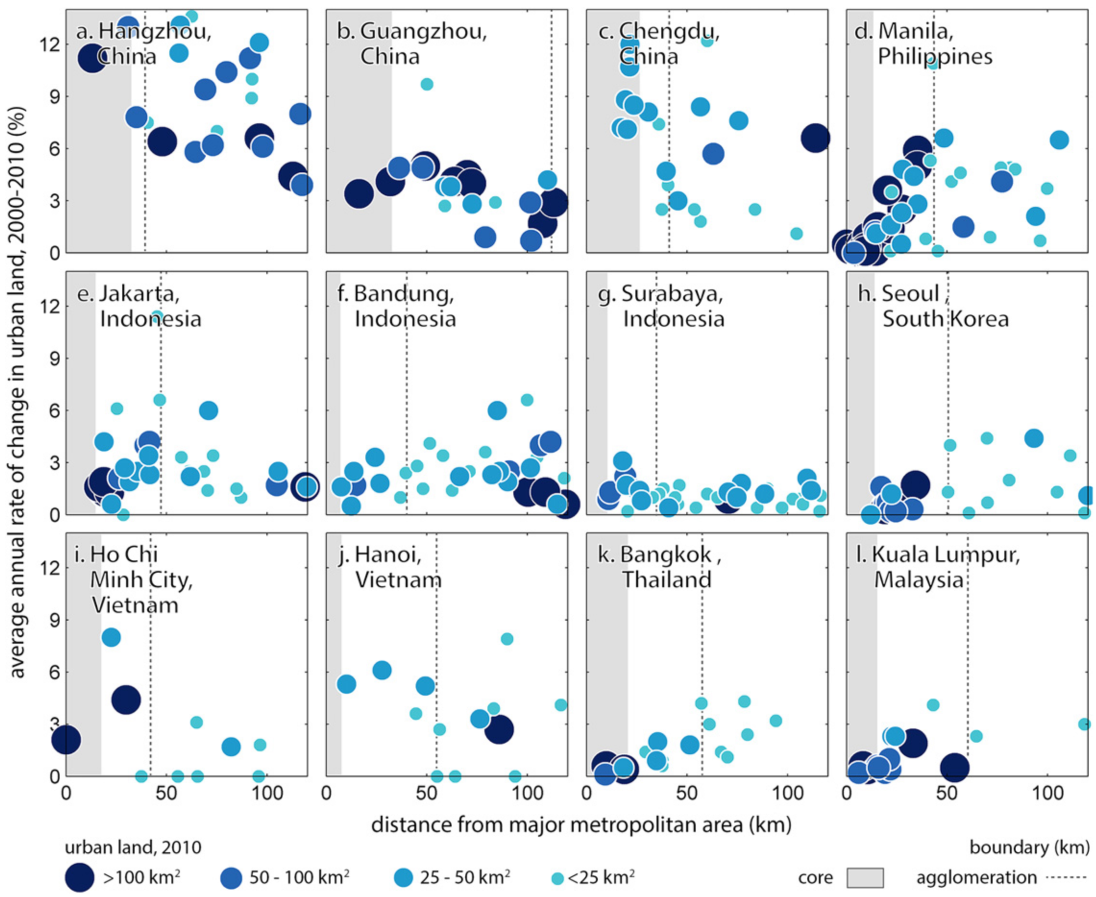

Figure 5. Scatter plots illustrating the size and growth rates of small and mid-sized cities located within the administrative core (gray area), within the urban agglomeration defined by the built-up extent (left of the dashed line), or directly adjacent or near the urban agglomeration boundary (right of the dashed line). A sample of results for 12 of the 30 largest agglomerations is shown here. Urban agglomerations are labeled by largest city (see table A5 for a list of cities within each agglomeration).

of local materials that are spectrally similar to surrounding land cover types. These countries have no reliable village population estimates, and consequently, the results may under-report urban land or growth. On average, the total land area and population of these settlements is a fraction of the urban extent and urban population in each country, and should therefore have a limited effect on interpreting the results of this study. Finally, the urban extent does not include low-density settlements (e.g. 30–40% built-up), although these areas may function as urban space. If we relax the 50% threshold, higher rates and amounts of urban land would be likely.

One additional area of uncertainty is related to the availability of population data. Locations with less-than-ideal data include Malaysia, Thailand, Laos, Myanmar, and North Korea (table A3); results for these countries should be considered in light of this bias. In addition, population estimates have greater uncertainty when the administrative unit is large relative to urban extent, and rural populations within the unit are dense (Hay *et al* 2005). In these areas (e.g. Indonesia), population densities may be overestimated. Finally, the approach here does not capture growth within existent urban areas, including redevelopment or vertical growth. The lack of within-city monitoring remains a critical limitation of both population data sources and remote sensing for land use planning. New datasets (crowd sourcing, social media, etc) and advances in radar/lidar have the potential to significantly change how we monitor urban change (Frolking *et al* 2013, Tsou *et al* 2013).

Urban growth has increased in scope, scale, and complexity in recent decades, and has become one of the most important challenges of the 21st century. The urban expansion and urban growth datasets[11] presented here provide a valuable, practical, and consistent way to monitor a broad range of issues, including impacts to local-regional climate (Kaufmann *et al* 2007), pollution levels (Grimm *et al* 2008), water quality/availability (McDonald *et al* 2011), arable land (Lambin and Meyfroidt 2011) as well as the livelihoods and vulnerability of populations in the region (Solecki *et al* 2011). These datasets are unique in that they represent the first comprehensive mapping of urban expansion and growth for all cities >100 000 in East–Southeast Asia, and they also form the basis of ongoing work to examine land and population trends globally for all cities and agglomerations.

[11] All datasets are publically available at www.landcoverchange.com.

While uncertainties may always be present no matter the data source, spatially-and temporally-detailed maps of urban expansion and population growth based on the best available data are nevertheless critical for researchers, urban planners, land managers, and government officials interested in a sustainable urban future.

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Appendix

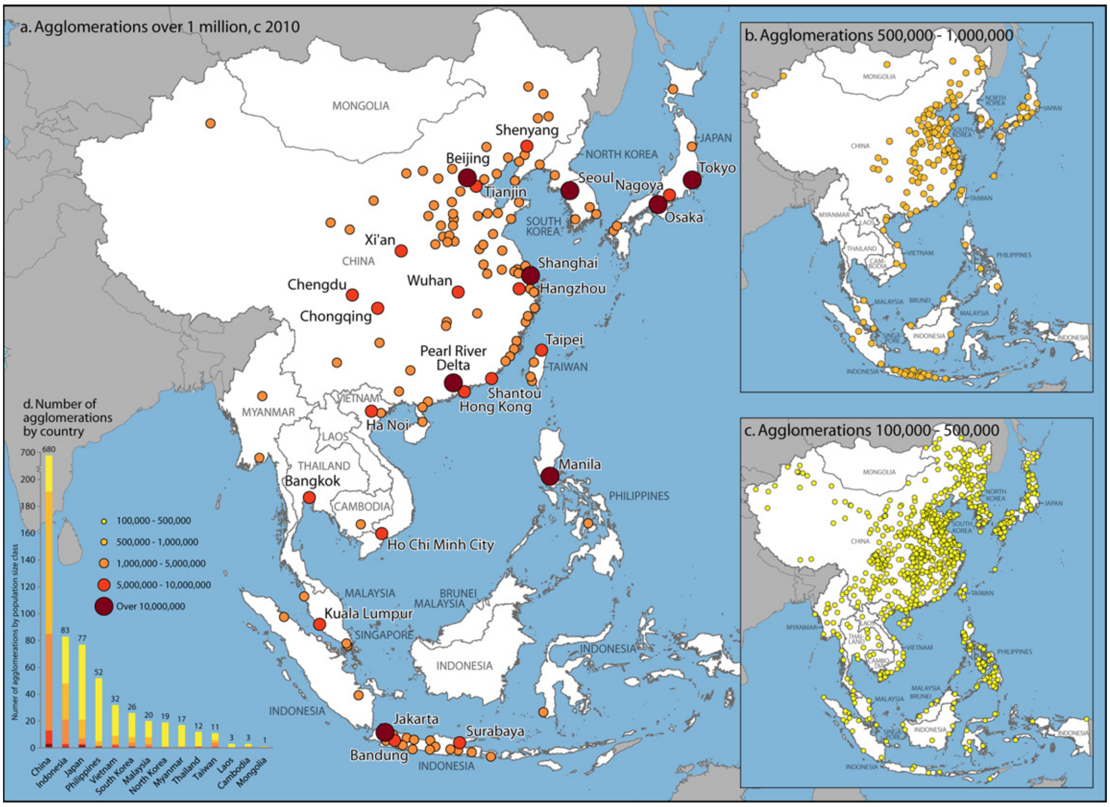

Figure A1. The distribution of urban agglomerations assessed in this research, including (a) 131 agglomerations >1 mil, (b) 164 cities between 500,000 and 1 mil, and (c) 741 cities between 100,000 and 500,000 persons. The number of agglomerations in each population size category is shown by country in (d).

Table A1. City point and raster datasets used to define the study extent for satellite image processing of urban expansion, as well as to define the 1036 urban agglomerations used for analysis.

Location	Dataset	Producer	Citation	Notes
Global	GRUMP city points	CIESIN, IFPRI, CIAT	Center for International Earth Science Information Network (CIESIN), Columbia University, International Food Policy Research Institute (IFPRI), World Bank, Centro Internacional de Agricultura Tropical (CIAT) 2004 *Global Rural-Urban Mapping Project (GRUMP): Settlement points (2000)* http://sedac.ciesin.columbia.edu	Point dataset of 67,935 cities, towns and settlements.

Table A1. (Continued.)

Location	Dataset	Producer	Citation	Notes
Global	Urban agglomerations with >750,000 inhabitants, 2011	UN Department of Economic and Social Affairs Population Division	United Nations (UN) Department of Economic and Social Affairs Population Division 2013 *Urban agglomerations with >750,000 inhabitants in 2011* http://esa.un.org/unup/GIS-Files/gis_1.htm	Point dataset of 633 cities >750,000 persons.
Global	Universe of cities	Angel, Lincoln Institute of Land Policy	Angel S 2012 *Planet of Cities* (Cambridge, MA: Lincoln Institute of Land Policy Publications	Point dataset of 3,943 cities >100,000 persons.
China	Chinese city point data	Chinese Academy of Sciences	Chinese Academy of Sciences 2011 *City points* Beijing, China	Point dataset of 664 cities.
Global	Google Earth populated places	Google	Google Earth Pro v7.1. 2013 *Layers: populated places* http://www.google.com/earth	City point location used to verify, geolocate, and update city points.
Global	MODIS 500 m map of global urban extent	University of Wisconsin-Madison	Schneider A, Friedl M, Potere D 2010 Mapping urban areas globally using MODIS 500m data: New methods and datasets based on urban ecoregions *Remote Sens Environ* **114** 1733-1746 http://sage.wisc.edu	Map of 88,578 urban patches >1 km^2 used to verify, geolocate, and update city points.

Table A2. Remote sensing data sources used to map urban extent and urban expansion, 2000-2010.

Location	Dataset	Producer	Citation	Spatial resolution
East Asia	MODIS 500 m nadir BRDF-adjusted reflectance, 7 spectral bands, 8-day composites (MCD43A2, MCD43A4)	NASA MODIS Land Team, Boston University	Schaaf C B *et al* 2002 First operational BRDF albedo nadir reflectance products from MODIS *Remote Sens. Environ.* **83** 135-148	500 m
East Asia	MODIS 250 m enhanced vegetation index 8-day annual and tiled products (MOD09Q1G_EVI)	NASA Goddard Space Flight Center	Gao F, Morisette J, Wolfe R, Ederer G, Pedelty J, Masuoka E, Myeneni R, Tan B, Nightingale J 2008 An algorithm to produce temporally and spatially continuous MODIS-LAI time series *IEEE Geoscience Remote S* **5** 60-64 Tan B, Morisette J, Wolfe R, Gao F, Ederer G, Nightingale J, Pedelty J 2011 An enhanced TIMESAT algorithm for estimating vegetation phenology metrics from MODIS data *IEEE J Sel Top App* **4** 361-371	250 m
Global	Training exemplar database	Boston University, University of Wisconsin-Madison	Friedl, M., *et al.* 2009 MODIS Collection 5 global land cover: algorithm refinements and characterization of new datasets *Remote Sens. Environ.* **114** 168-182 Schneider A, Friedl M, Potere D 2010 Mapping urban areas globally using MODIS 500m data: New methods and datasets based on urban ecoregions *Remote Sens. Environ.* **114** 1733-1746 Mertes C M, Schneider A, Sulla-Menashe D, Tatem A, Tan B 2014 Detecting change in urban areas at continental scales with MODIS data *Remote Sens. Environ.* in review	1-30 m
East Asia	Test sites for accuracy assessment	University of Wisconsin-Madison	Mertes C M, Schneider A, Sulla-Menashe D, Tatem A, Tan B 2014 Detecting change in urban areas at continental scales with MODIS data *Remote Sens. Environ.* in review	250-500 m

Acronyms: MODIS, Moderate Resolution Imaging Spectroradiometer, BRDF, bidirectional reflectance distribution function, NASA, National Aeronautics and Space Administration.

Table A3. Population data sources used to map population density, 2000-2010, for each country.

Country or region	Official name	Statistical agency	Link	Years of data available[a]	Level of data
Cambodia	Kingdom of Cambodia	National Institute of Statistics, Cambodia	http://www.nis.gov.kh	1998, 2008	province
China	People's Republic of China	National Bureau of Statistics, China	http://www.stats.gov.cn	2000, 2005, 2010	county, municipality
		China Data Center, University of Michigan	http://chinadatacenter.org	2000, 2010	county
Hong Kong	Hong Kong Special Administrative Region, China	Census and Statistics Department, Hong Kong SAR, China	http://www.censtatd.gov.hk	2001, 2011	district
North Korea	Democratic People's Republic of Korea	Central Bureau of Statistics, DPR Korea	http://www.geohive.com/cntry/northkorea.aspx	2005, 2008	province
Indonesia	Republic of Indonesia	Biro Pusat Statistik, Indonesia	http://www.bps.go.id	2000, 2005, 2010	province
Japan	Japan	Statistics Bureau, Management and Coordination Agency, Japan	http://www.stat.go.jp	2000, 2005, 2010	district
Laos	Lao People's Democratic Republic	Lao Department of Statistics	http://www.nsc.gov.la	1995, 2005, 2009, 2011	province
Malaysia	Malaysia	Department of Statistics, Malaysia	http://www.statistics.gov.my	2000, 2005, 2010	district
Mongolia	Mongolia	National Statistical Office, Mongolia	http://www.nso.mn	2000, 2010	aimag, soum
Myanmar	Republic of the Union of Myanmar	Department of Population, Myanmar	https://www.mnped.gov.mm	1983, 2002, 2004	district
Philippines	Republic of the Philippines	National Statistics Office, Philippines	http://www.census.gov.ph	2000, 2007, 2010	province, municipality
South Korea	Republic of Korea	National Statistical Office, Republic of Korea	http://kostat.go.kr	2000, 2005, 2010	city, district
Singapore	Republic of Singapore	Statistics Singapore	http://www.singstat.gov.sg	2000, 2010	region, district
Taiwan	Republic of China, Taiwan	Department of Household Registration Affairs, Taiwan	http://www.stat.gov.tw	2000, 2006, 2010	county
Thailand	Kingdom of Thailand	National Statistical Office, Thailand	http://www.nso.go.th	2000, 2010	changwat
Vietnam	Socialist Republic of Vietnam	General Statistical Office, Vietnam	http://www.gso.gov.vn	1999, 2009, 2011	province

[a] Maps of population density were produced for c 2000 and c 2010 using all available census data. Where data were not available, population data were adjusted forward or backward using inter-censal UN population growth rates (Tatem *et al* 2007, Linard *et al* 2013).

Table A4. Changes in urban land and urban population for agglomerations >100,000 in East-Southeast Asia.[a,b,c,d]

	Area within administrative boundary (km^2)	Urban land 2000 (km^2)	Urban land 2010 (km^2)	Urban population 2000 (persons)	Urban population 2010 (persons)	Average annual rate of change, urban land (%)	Average annual rate of change, urban population (%)	Ratio of urban land increase to urban population change (m^2/persons)
China	9,453,309.3	98,819.4	126,661.1	453,257,034	598,918,893	2.5	2.8	191:1
Japan	372,468.1	19,270.5	20,094.5	76,080,201	87,527,422	0.4	1.4	72:1
Indonesia	1,890,972.7	12,635.5	13,921.9	83,535,095	118,351,117	1.0	3.5	37:1
Thailand	514,093.0	4,616.1	5,365.6	15,451,438	19,947,409	1.5	2.6	167:1
Malaysia	329,424.2	4,644.3	5,364.4	11,566,137	17,074,669	1.5	4.0	131:1
Vietnam	328,385.3	4,200.9	5,098.2	22,854,276	33,863,070	2.0	4.0	82:1
South Korea	100,229.2	2,835.9	3,232.4	24,958,293	28,271,528	1.3	1.3	120:1
Philippines	295,987.7	2,332.9	2,907.9	19,397,798	26,882,521	2.2	3.3	77:1
Taiwan	36,223.7	1,782.9	2,043.3	13,801,713	14,801,705	1.4	0.7	260:1
Myanmar	670,746.8	1,838.4	2,030.1	8,452,657	11,235,349	1.0	2.9	69:1
North Korea	122,755.1	852.6	906.6	4,189,762	4,693,317	0.6	1.1	107:1
Mongolia	1,566,250.3	683.1	764.4	840,233	1,209,552	1.1	3.7	220:1
Singapore	755.4	337.3	403.5	2,539,073	3,412,239	1.8	3.0	76:1

Table A4. (Continued.)

	Area within administrative boundary (km^2)	Urban land 2000 (km^2)	Urban land 2010 (km^2)	Urban population 2000 (persons)	Urban population 2010 (persons)	Average annual rate of change, urban land (%)	Average annual rate of change, urban population (%)	Ratio of urban land increase to urban population change (m^2/persons)
Cambodia	181,354.0	218.3	290.9	1,195,233	1,806,264	2.9	4.2	119:1
Laos	229,878.0	162.0	222.6	296,091	629,370	3.2	7.8	182:1
Brunei	528.5	144.4	180.3	155,880	230,304	2.0	4.0	481:1
Timor-Leste	369.4	28.4	28.4	115,901	180.737	0.0	4.5	0:1
Total	**16,092,832.9**	**155,230.1**	**189,307.1**	**738,415,036**	**968,624,426**	**2.0**	**2.8**	**148:1**

[a] Urban extent maps produced at 250m resolution (Mertes *et al* 2014). In these maps, pixels containing at least 50% constructed surfaces are considered urban.

[b] Population data were estimated from the WorldPop population distribution maps (Linard *et al* 2013) for built-up areas within the urban expansion map.

[c] Administrative boundary data provided by GADM (2012).

[d] Agglomerations were defined by the administrative units corresponding to the contiguous built-up land area of cities over 100,000.

Table A5. List of independent cities comprising the 30 large agglomerations assessed in this research.

Rank[a]	Agglomeration[b]	Country	Cities, towns >100,000 included in agglomeration[c]				
1	**Pearl River Delta**	**China**	Conghua	Guangzhou	Luoyang	Shunde	Zhuhai
			Daling	Heshan	Nanhai	Sihui	
			Dongguan	Huiyang	Pingshan	Xinhui	
			Foshan	Huizhou	Qingyuan	Zengcheng	
			Gaoming	Jiangmen	Sanshui	Zhaoqing	
			Gaoyao	Kaiping	Shenzhen	Zhongshan	
2	**Tokyo**	**Japan**	Abiko	Hachioji	Kashiwa	Misato	Tachikawa
			Ageo	Hadano	Kasukabe	Mitaka	Takasaki
			Akishima	Higashikurume	Kawagoe	Musashino	Tama
			Asaka	Higashimurayama	Kawaguchi	Nagareyama	Toda
			Ashikaga	Hino	Kawasaki	Narashino	Tokorozawa
			Atsugi	Hiratsuka	Kiryu	Niiza	Tokyo
			Chiba	Hoya	Kisarazu	Noda	Tsuchiura
			Chigasaki	Ichihara	Kodaira	Odawara	Urawa
			Chofu	Ichikawa	Koganei	Ome	Urayasu
			Ebina	Iruma	Kokubunji	Omiya	Utsunomiya
			Fuchu	Isehara	Koshigaya	Ota	Yachiyo
			Fujimi	Isesaki	Kumagaya	Sagamihara	Yamato
			Fujisawa	Iwatsuki	Machida	Sakura	Yokohama
			Fukaya	Kamagaya	Maebashi	Sayama	Yokosuka
			Funabashi	Kamakura	Matsudo	Soka	Zama
3	**Shanghai**	**China**	Kunshan	Shanghai	Suzhou	Taicang	Wujiang
4	**Beijing**	**China**	Beijing	Sanhe			
5	**Bangkok**	**Thailand**	Bangkok	Nakhon Pathom	Pak Kret	Samut Prakan	
			Khlong Luang	Nonthaburi	Phra Pradaeng	Thanya Buri	
6	**Osaka**	**Japan**	Akashi	Ibaraki	Kawanishi	Neyagawa	Takatsuki
			Amagasaki	Ikeda	Kishiwada	Nishinomiya	Tondabayashi
			Daito	Itami	Kobe	Osaka	Toyonaka
			Habikino	Izumi	Kyoto	Sakai	Uji
			Higashiosaka	Kadoma	Matsubara	Sanda	Yao
			Himeji	Kakogawa	Mino	Suita	
			Hirakata	Kawachinagano	Moriguchi	Takarazuka	

Table A5. (Continued.)

Rank[a]	Agglomeration[b]	Country	Cities, towns > 100,000 included in agglomeration[c]				
7	**Nagoya**	**Japan**	Anjo	Ise	Kuwana	Okazaki	Toyota
			Gifu	Kakamigahara	Matsusaka	Seto	Tsu
			Handa	Kariya	Nagoya	Suzuka	Yokkaichi
			Ichinomiya	Kasugai	Nishio	Tajimi	
			Inazawa	Komaki	Ogaki	Tokai	
8	**Kuala Lumpur**	**Malaysia**	Ampang	Kuala Lumpur	Selayang Baru	Shah Alam	Ulu Kelang
			Klang	Petaling Jaya	Seremban	Subang Jaya	
9	**Tianjin**	**China**	Tianjin				
10	**Jakarta**	**Indonesia**	Bekasi	Cimanggis	Depok	Sawangan	
			Bogor	Ciomas	Jakarta	Serang	
			Ciawi	Ciputat	Pondok Aren	Serpong	
			Cibinong	Citeureup	Pondokgede	Tangerang	
11	**Hangzhou**	**China**	Hangzhou	Keqiao	Shaoxing	Xiaoshan	Yuhang
12	**Manila**	**Philippines**	Antipolo	Calamba	Makati	Muntinglupa	San Jose del Monte
			Bacoor	Caloocan	Malabon	Navotas	San Juan del Monte
			Baliuag	Cavite	Malolos	Paranaque	Santa Rosa
			Binan	Dasmarinas	Mandaluyong	Pasay	Tagig
			Binangonan	Imus	Marikina	Pasig	Taytay
			Cainta	Las Pinas	Meycauayan	Quezon City	Valenzuela
13	**Shantou**	**China**	Anbu	Chaoyang	Denghai	Jieyang	Puning
			Caitang	Chaozhou	Fengxi	Paotai	Shantou
14	**Seoul**	**South Korea**	Ansan	Koyang	Osan	Shihung	Uiwang
			Anyang	Kunpo	Puch'on	Songnam	
			Hanam	Kuri	P'yongt'aek	Suwon	
			Inch'on	Kwangmyong	Seoul	Uijongbu	
15	**Chengdu**	**Chengdu**	Chengdu	Chongzhou	Guanghan		
16	**Shenyang**	**China**	Fushun	Shenyang			
17	**Wuhan**	**China**	Wuhan				
18	**Hanoi**	**Vietnam**	Ha Dong	Hanoi			
19	**Singapore**	**Singapore-Malaysia**	Singapore	Johor Bahru			
20	**Ho Chi Minh City**	**Vietnam**	Bien Hoa	Ho Chi Minh City	Thu Daut Mot		
21	**XI'an**	**China**	Xi'an	Xianyang			
22	**Surabaya**	**Indonesia**	Gresik	Sidoarjo	Taman		
			Pasuruan	Surabaya	Waru		
23	**Chongqing**	**China**	Chongqing				
24	**Taipei**	**Taiwan, PRC**	Chungho	Hsintien	Pingchen	Tanshui	Yingko
			Chungli	Luchou	Sanchung	Taoyuan	Yungho
			Hsichih	Panchiao	Shulin	Tucheng	
			Hsinchuang	Pate	Taipei	Yangmei	
25	**Bandung**	**Indonesia**	Bandung	Cimahi	Ciparay	Margahayu	Padalarang
26	**Yangon**	**Myanmar**	Yangon City				
27	**Hong Kong**	**China**	Jiulong	Sheung Shui	Tseun Wan		
			Kwai Chung	Tai Po	Tuen Mun		
			Ma On Shan	Tin Shui Wai	Xianggang		
			Sha Tin	Tseung Kwan O	Xianggangzi		
28	**Phnom Penh**	**Cambodia**	Phnom Penh				
29	**Pyongyang**	**North Korea**	Pyongyang				
30	**Vientiane**	**Laos**	Vientiane				

[a] Rank was determined according to the 2010 agglomeration population estimated from the WorldPop population density maps produced in this work.

[b] Agglomerations were defined by the administrative units (GADM 2012) corresponding to the contiguous built-up land area of cities over 100,000.

[c] Cities within each agglomeration were compiled from all available city lists (table A1) and verified through local maps and urban planning documents.

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