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Building up or spreading out? Typologies of urban growth across 478 cities of 1 million+

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Supplementary material for this article is available online

Abstract

Urban form in both two- (2D) and three-dimensions (3D) has significant impacts on local and global environments. Here we developed the largest global dataset characterizing 2D and 3D urban growth for 478 cities with populations of one million or larger. Using remote sensing data from the SeaWinds scatterometer for 2001 and 2009, and the Global Human Settlement Layer for 2000 and 2014, we applied a cluster analysis and found five urban growth typologies: *stabilized, outward, mature upward, budding outward, upward and outward*. *Budding outward* is the dominant typology worldwide, per the largest total area. Cities characterized by *upward and outward* growth are few in number and concentrated primarily in China and South Korea, where there has been a large increase in high-rises during the study period. With the exception of East Asia, cities within a geographic region exhibit remarkably similar patterns of urban growth. Our results show that every city exhibits multiple urban growth typologies concurrently. Thus, while it is possible to describe a city by its dominant urban growth typology, a more accurate and comprehensive characterization would include some combination of the five typologies. The implications of the results for urban sustainability are multi-fold. First, the results suggest that there is considerable opportunity to shape future patterns of urbanization, given that most of the new urban growth is nascent and low magnitude outward expansion. Second, the clear geographic patterns and wide variations in the physical form of urban growth, within country and city, suggest that markets, national and subnational policies, including the absence of, can shape how cities grow. Third, the presence of different typologies within each city suggests the need for differentiated strategies for different parts of a single city. Finally, the new urban forms revealed in this analysis provide a first glimpse into the carbon lock-in of recently constructed energy-demanding infrastructure of urban settlements.

1. Introduction

Urban form is the two- and three-dimensional geometrical characteristics of the built-up environment (Batty and Longley 1994, Seto *et al* 2014, Wentz *et al* 2018). The two-dimensional notion refers to the layout and spatial arrangement of land use, including buildings, green space, and street design; it is what one sees from zenith, or above the urban environment, such as the footprint of settlements. In its three-dimensional meaning, urban form refers to the spatial totality of built elements and space in both the horizontal and vertical domains. Three-dimensional urban form includes the shape, size, geometry, verticality and volume of the built-up environment (Stokes and Seto 2019).

In the Fifth Assessment Report of the IPCC, urban form was identified as a major driver of urban greenhouse gas emissions (Seto *et al* 2014). At the global scale, changes in CO_2 levels can influence climate and lead to irreversible impacts such as sea level rise (Solomon *et al* 2009). Many studies have shown that urban texture, the geometrical structure formed by the spatial distribution of urban elements such as building, roads and green areas, can alter local climates (Oke 1982, Grimmond and Oke 1999, Zhou *et al* 2017). For example, a single high-rise can create significant downdraught. Multiple high-rises in close proximity create urban canyons which can affect the urban heat island effect (Oke 1981) and generate high wind speeds (Blocken *et al* 2008), both of which can affect human comfort and safety. Furthermore, urban form can influence travel behavior (Camagni *et al* 2002), which can affect ambient air quality (e.g. CO_2, SO_X, NO_X) of a region (Crane 2000, Hankey and Marshall 2017). Thus, urban form has significant impacts on both local and global environments.

Urban form is also correlated with energy demand, in terms of both embodied energy in construction material as well as operational energy (Steemers 2003, Ratti *et al* 2005). In high-rises, mechanical transportation requires elevator shafts and strong wind-load resisting system (Foraboschi *et al* 2014). Buildings with heights above 200 m (~50 stories) require more than one core support for structural stability (Batty 2018). Thus, a city with short and small buildings versus a city comprised of tall and large buildings will have different energy demands in terms of energetic operational and maintenance costs, dependency on artificial lightning, and heating and cooling (Roaf *et al* 2005). Although new sustainable designs for tall buildings focus more and more on reducing primary energy consumption, but their widespread application is still limited (Oldfield *et al* 2009). During one of the fastest urbanizing periods in the world, from 1975 to 2010, the number of buildings worldwide with heights greater than 200 m increased 38 times, from 28 to 1040 (Brass *et al* 2013). As the world's urban population continues to increase, the growth of infrastructure and building stock will require significant resources. As one example, the UN recently estimated that the demand for raw materials, including sand, gravel, iron ore, coal and wood, to build and operate cities will increase from 40 billion tons per year in 2010 to 90 billion tons per year in 2050 (IRP 2018). The study also shows that modern high-rises with managed densities urban form reduces the amount of construction material required in terms of urban infrastructure such as roads, sewerage, power, heating and telecoms compared to traditional continuous urban forms of high densities.

The study of urban form and its relationship with sustainability has a long history, with different disciplines emphasizing different aspects of urban form (Burton *et al* 2013). Because urban form is related to many aspects of sustainability, from the health sciences (Frank and Engelke 2001) and human well-being (Bloom *et al* 2008), to ecosystem health and environmental conditions, numerous typologies have been developed in order to understand the key aspects of the structure of the built environment that are related to sustainability outcomes of interest (Camagni *et al* 2002, Jabareen 2006). Despite the myriad studies, there is no consensus on the most critical aspect of urban form relative to sustainability. Efforts to describe the built-up environment and develop typologies of urban form range from qualitative approaches with traditions based in architecture and town planning (Alexander *et al* 1977, Kostof 1993) to quantitative approaches based on modern geographical analysis (Schneider and Woodcock 2008, Wentz *et al* 2018). Urban density, commonly defined as a ratio of either urban population to land area, or built-up land or housing units to land area, has emerged as one of the most important urban form typologies related to sustainability (Newman and Kenworthy 1989), with more than twenty different density measures used in research (Boyko and Cooper 2011). However, no single measure of urban density has been agreed upon for sustainability research. Thus, it comes as no surprise that new urban typologies related to sustainability continue to be developed, including those to characterize trajectories and dynamics of urban land expansion (Zhang and Seto 2013), urban mitigation and vulnerability to climate change (Solecki *et al* 2015), and urban energy use (Creutzig *et al* 2015).

Despite the plethora of new urban typologies, most of them have either focused on or utilized information on outward, 2D growth (Wentz *et al* 2014, Andrade-Núñez and Aide 2018, Zhu *et al* 2019). Likewise, most remote sensing algorithms developed to map urban land expansion have focused on outward urban growth and not volumetric growth or growth in vertical structure (Reba and Seto 2019). Remote sensing data that have been used to capture 3D form have come primarily from active remote sensing instruments such as Light Detection and Ranging (LiDAR), Synthetic Aperture Radar (SAR), and laser altimeters. These data have been used to study, among other things, building heights, volume, footprints and building density. SAR have been proven successful to characterize volumetric urban expansion (Henderson and Xia 1997, Gamba *et al* 2002, Dell'Acqua and Gamba 2006, Esch *et al* 2013). Other SAR data, such as the German terraSAR-X and Italian COSMO-Skymed with X-band resolution up to 1 m are used to map buildings and other human-made structures (Rossi and Gernhardt 2013, Zhu and Bamler 2010). However, most of these studies have been limited in geographic scope to individual city or neighborhood case studies, such as downtown Houston USA (Yu *et al* 2010), urban districts in Qingdao, China (Zhang 2015), Nairobi, Kenya (Henderson *et al* 2016), and mega-cities in East Asia (Zhang *et al* 2018). Another source of data to measure urban structure come from scatterometers. For example, the SeaWinds scatterometer onboard the QuikSCAT satellite launched in 1999, was designed to measure the speed and direction of winds that cause ocean waves but also have been used to characterize building volumes and other human-made structures (Hardin *et al* 1997, Nghiem *et al* 2009, Frolking *et al* 2013, Nguyen *et al* 2018, Mathews *et al* 2019).

Our goal in this paper is to characterize urban form in two- and three-dimensions and develop a large global dataset of urban volumetric growth. We aim to answer the following questions: (1) What are the key trends in upward and outward urban growth across regions and countries? (2) What are the primary typologies of urban growth patterns? (3) How do typologies vary by city and geography? (4) How are typologies associated with population densities? First, we examine urban growth trends for countries and regions. Second, we move to pixel-level analysis to evaluate how urban growth patterns cluster. Finally, we examine the variations of these clusters across cities and geographies.

2. Dataset and methodology

We combined the methods and insights of two peer-reviewed studies (Frolking *et al* 2013, Balk *et al* 2018) and one working paper (Mahendra and Seto 2019) to develop a new approach that allowed us to compare urban growth across cities worldwide. In Frolking *et al* (2013), two remotely sensed datasets, the backscatter from QuikSCAT SeaWinds scatterometer and night-time light data from NOAA's Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) were used to characterize 2- and 3D urban growth. Here, we modified their methodology and used built-up area from the Global Human Settlement Layer (GHSL) dataset instead of night-time light data. The GHSL built-up layer at 38 m spatial resolution classifies the landscape into built and non-built areas (https://ghsl.jrc.ec.europa.eu/data.php). Derived from Landsat data, GHSL estimates built-up area irrespective of administrative city boundaries. We chose to use GHSL instead of DMSP/OLS after an initial analysis comparing the two datasets which showed that the GHSL data can capture more variability in horizontal urban growth than DMSP/OLS. The results for Tokyo, London and New York illustrate the increased variability captured by GHSL (figure S1 is available online at stacks.iop.org/ERL/14/124077/mmedia). We hypothesized that the night-time light data do not perform as well as the GHSL, due to saturation and blooming.

To quantify upward growth, i.e. volumetric growth, we used the power-return-ratio (PR) generated from QuikSCAT by converting the microwave backscatter data from dB to $10^{\sigma^0_{\mathrm{dB}}/10}$, as described in Frolking *et al* (2013). We further calculated the difference in PR for the years 2001 and 2009. We computed outward growth by differencing total built area from 2000 to 2014 GHSL built-up layers. In order to standardize the differences in spatial resolution between the two datasets, we aggregated GHSL data from its native 38 m resolution to a 0.05° grid. While doing so, we calculated percentages of urban pixels in the 0.05° grid. We used raster package in R statistical programming language (v3.5.1) to conduct this analysis (R Core Team 2018, Hijmans 2018).

2.1. Selection of cities

We chose to analyze cities with a population of more than one million because the sensitivity and coarse spatial resolution of SeaWinds data may limit its ability to detect built structures in smaller cities (Nghiem *et al* 2009). To identify these cities, we used the Populated Places dataset (v 4.1.0) from Natural Earth which is derived from the Landscan dataset and maintained by the Oak Ridge National Laboratory (http://naturalearthdata.com/downloads/10m-cultural-vectors/10m-populated-places/). From this dataset, we identified 499 cities of over one million population.

2.2. Defining urban

For each city, we used a 11 × 11 grid comprised of 121 pixels with 0.05° resolution (~5.566 km), using, as the centroids, the latitude and longitude of the city center from the Natural Earth dataset. Thus, each pixel represents ~30.98 km^2 at the equator. Applying this grid as a cookie cutter, we extracted urban pixels for each city based on three criteria: (1) each pixel should include more than 20% urban cover in 2014 based on GHSL, (2) each pixel should be connected to the largest patch comprising the central pixel of the city and, (3) each pixel should include non-zero positive change in PR ratio. After applying all three criteria, our sample size was reduced to 478 cities (figure 1) totaling 13 754 urban pixels (~426 409 km^2). With the exception of Asia, we labeled each city using the United Nations (UN) defined world macro regions. For cities in Asia, we treated China, India and the Middle East as separate regions and kept the rest of Asia intact. Furthermore, we calculated average outward and average upward urban growth using all the urban pixels in each city (table S1).

2.3. Typologies of urban growth

To create typologies of urban growth based on intra-urban horizontal and vertical growth, we performed a cluster analysis on 13 754 urban pixels using *k*-means clustering algorithm in R (R Core Team 2018). Our clustering analysis is based on the statistical distribution of individual pixel values in a four-dimensional space comprised of the initial and change values of GHSL and PR. We used four input variables in our cluster analysis: GHSL_{2000} and PR_{2001} (to capture the initial state), and Δ GHSL $_{(2014–2000)}$ and Δ PR $_{(2009–2001)}$ (to capture change). The clustering algorithm partitions the data into *k* number of clusters and labels each pixel iteratively such that the distance between the pixel value and the mean of the assigned cluster is minimized (Hartigan and Wong 1979). The algorithm proceeds until further

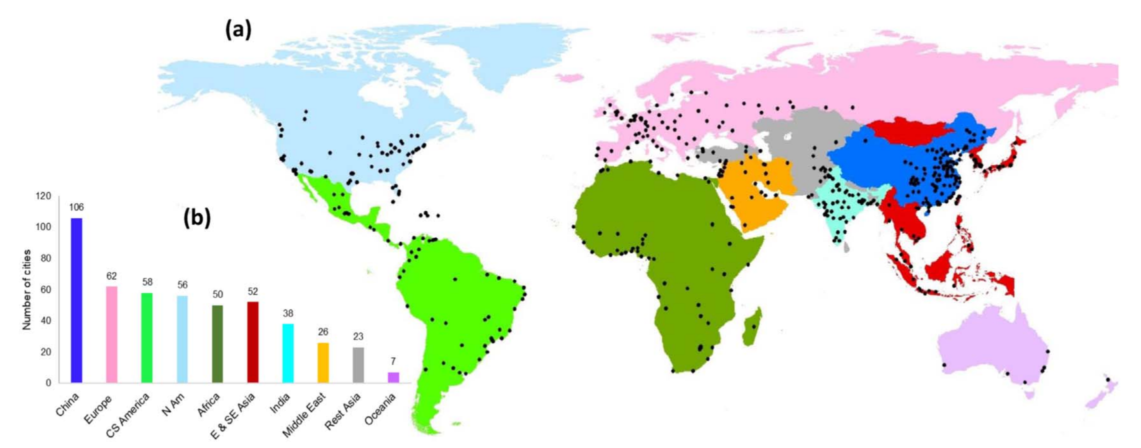


Figure 1. Geographical distribution of (a) cities and (b) the number of cities in each region. Numbers on the bars represent the number of cities in each selected region. The regional color-coding in the map corresponds to the bars and is consistent throughout the paper.

reassignment does not alter the total within-cluster sum of squares (WSS). The optimum number of clusters were decided based on WSS. We computed WSS for each k ($k = \{1,\ldots,15\}$), generated a scree plot (figure S2) and identified the optimum number of clusters based on the scree plot, by identifying k at which the slope of the curve starts to level off, as five. Finally, we qualitatively interpreted the statistical distributions of each of the clusters in the four dimensions to identify urban growth typologies using box plots (figure S3). In doing so, we categorized the initial outward and upward extent as very small, small, medium, large, very large and the change as very low, low, moderate, high and very high. Lastly, we calculated population densities for 2000 and 2015 of different urban growth typologies using GHSL population dataset (https://ghsl.jrc.ec.europa.eu/ghs_pop.php).

3. Results and discussion

3.1. Distinct urban growth patterns across geographies

We found distinct variations in upward and outward urban growth patterns across different geographies (figure 2). Cities where average urban growth is more upward than outward are concentrated in the East and Southeast Asia (E and SE Asia) and the Middle East. In contrast, more outward than upward urban growth is largely concentrated in cities in India and Africa. Chinese cities show both upward and outward growth. With a few exceptions, cities in the west (North and CS America) have undergone less outward and upward expansion than the rest of the world.

Various reasons are attributed to different patterns of growth across regions. In E and SE Asia, more upward than outward expansion is observed in Japan, Vietnam, South Korea, Taiwan, Hong Kong and Singapore. In Hong Kong and Singapore, horizontal growth is limited by geographic boundaries—both are island states—resulting in more upward growth (Al-Kodmany 2012). In both cases, high land prices prompt developers to build taller buildings (Ng 2005). Moreover, urban population growth drives the need to increase land supply, and the availability of affordable land in peripheral areas of cities typically drive outward growth. However, as populations in countries such as Japan and South Korea have been declining, they have not seen as much outward growth as the Asian and African cities (UN, DESA 2018). In China, we found both upward and outward urban expansion in cities such as Shanghai, Suzhou, Wuxi (figure 2(a)). Urbanization in China is distinctive compared to other rapidly urbanizing countries primarily due to significant role of Chinese government in land acquisition, construction and investment (World Bank 2015). For instance, the Chinese government created metropolitan governance for select cities like Beijing, Shanghai and Chongqing in order to allocate more functional responsibilities to the urban scale (Kamal-Chaoui *et al* 2009). The authorities in China have also directed urban construction to some areas with declining population trends (World Bank and DRC 2014).

In stark contrast to China and Japan, Indian cities have experienced relatively low levels of upward growth. Some argue that this is attributed to institutional factors such as restricted floor area ratios (FAR), which is the ratio of total floor area of a building relative to the total area of the building plot, and safety concerns if FAR limits are relaxed (Sridhar 2007, Brueckner and Sridhar 2012). Relatedly, in Africa, the combination of fewer capital investments in buildings and infrastructures (Lall *et al* 2017) and few policies on economic development, land use and urban planning are drivers of low-rise, outward urban growth (Kumar and Barrett 2008).

There is considerable variation in the average upward and outward growth among cities within a single region. There is more variability in average upward growth in China, E and SE Asia and

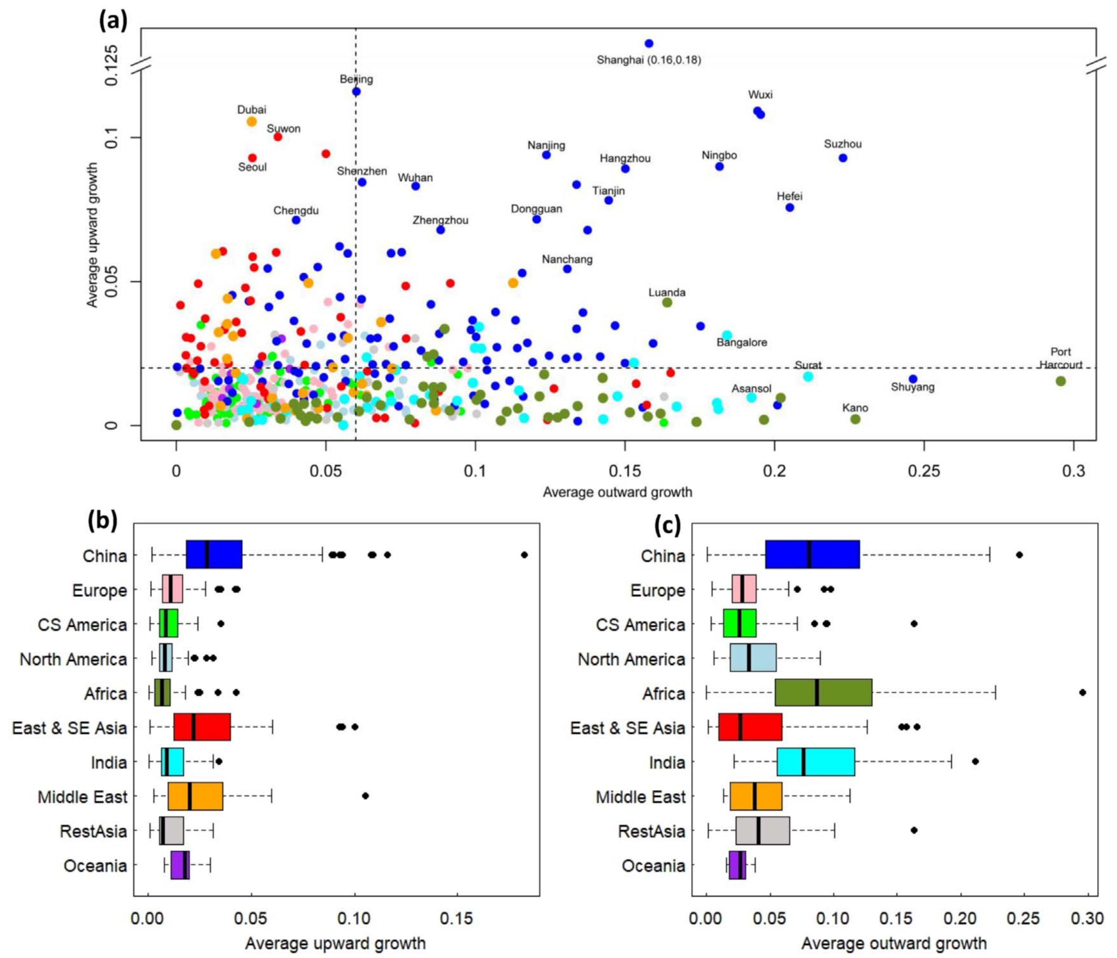


Figure 2. Three-dimensional urban growth in 478 cities: (a) average upward growth (change in mean backscatter power ratio for 2001–2009), and outward growth (change in percentage of urban cover for 2000–2014) by cities, (b) average upward and (c) average outward growth by region (Box plots show median, 1st and 3rd quartiles and outliers). The regional color-coding in the scatterplot corresponds to the box plots. Also, see table S1 for the list of 478 cities and their average urban growth.

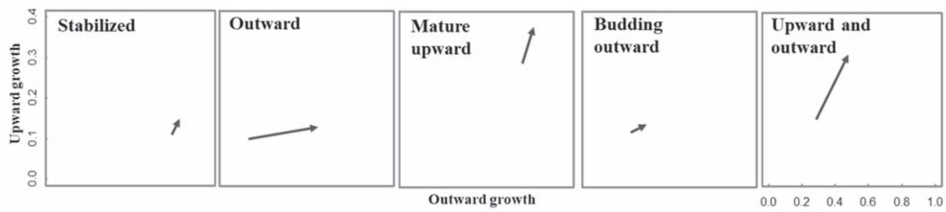
Middle East compared to other regions (figure 2(b)). There is higher variability of average outward growth (figure 2(c)) in China, Africa, and India than elsewhere. These three regions are the ones where urban population has been growing the fastest and have very large number of cities (UN, DESA 2018). The extent of land use planning and regulations also varies significantly across African, Indian and Chinese cities (Angel *et al* 2011). In regions such as Europe (e.g. Rotterdam, Amsterdam) and Central and South (CS) America (e.g. Bogota), there are few outlier cities where outward expansion is high. Most cities in these regions show similar and lower average upward and outward expansion. In North American cities, few outlier cities (e.g. New York, Last Vegas) show upward expansion whereas most of the cities show outward expansion. Cities in Oceania show both minimal upward and outward urban growth.

3.2. Five urban growth typologies

The intra-urban cluster analysis yielded five urban growth typologies (figure 3). Based on the characteristics of the clusters in four dimensions identified using boxplots (figure S3), we term them as *stabilized* (cluster 1), *outward* (cluster 2), *mature upward* (cluster 3), *budding outward* (cluster 4) and *upward and outward* (cluster 5). Urban pixels in each of these typologies are: 4379 (*stabilized*), 1531 (*outward*), 707 (*mature upward*), 6303 (*budding outward*), 834 (*upward and outward*).

Stabilized urban growth is characterized by urban pixels with very large initial urban cover and medium initial backscatter power ratio. However, there is negligible outward growth and very low upward growth. This urban growth typology is primarily in North and CS America and Europe. For example, in Los Angeles and Lima, more than 50% of the urban growth is *Stabilized* (figure 4).

Outward urban growth can be described by urban pixels with very small initial urban cover in both outward and upward dimensions. Change in urban cover in horizontal dimension is very high with low change in vertical dimension. Urban pixels in this typology has high magnitude in outward dimension. For example, Port Harcourt (Nigeria) and Surat (India) have more than 90% of *Outward* urban growth (figure 4).



Urban growth typology	*Stabilized*	*Outward*	*Mature upward*	*Budding outward*	*Upward and outward*
Initial Horizontal extent (GHS 2000)	Very large	Very small	Very large	Small	Medium
Initial Vertical extent (PR 2001)	Medium	Very small	Very large	Small	Medium
Change in horizontal extent	Very low	Very high	Very low	Moderate	Moderate
Change in Vertical extent	Low	Low	Moderate	Very low	Very high

Figure 3. Urban growth typologies, mean vector for each urban growth trajectory. Arrow vector represents change in urban extent (both in outward and upward dimension) for respective urban growth typology. The *x*-axis shows outward growth of urban built-up area based on the percentage urban cover in GHSL between 2000 and 2014, and the *y*-axis shows upward growth based on structural backscatter power ratio (PR), between 2001 and 2009. Arrow represent an urban pixel analyzed in 11 × 11 grid in a city; the tail represents the year 2001 for PR and 2000 for GHSL, and the head represents 2009 for PR and 2014 for GHSL. Also see figure S3 in supplementary information for statistical distribution of urban typologies.

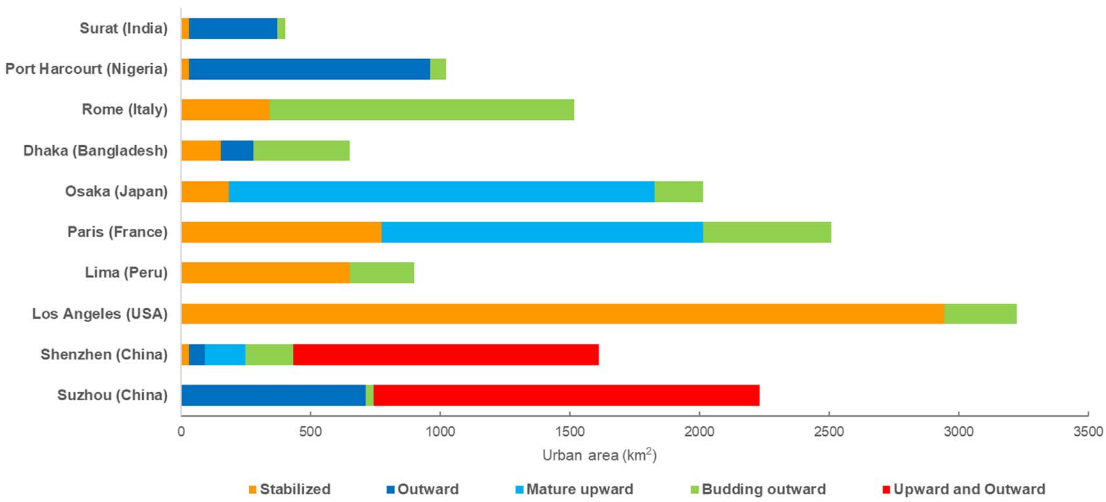


Figure 4. Distribution of urban growth typologies in ten cities. Cities are chosen to provide two examples of cities with one of the dominant five typologies. For example, *upward and outward* urban growth typology is dominant in Shenzhen and Suzhou cities.

Small initial urban extent in both dimensions and moderate outward and very low upward expansion is described as *budding outward*. This typology represents urban areas with nascent and slow pace of urbanization. *Budding outward* urban growth typology is observed in nearly all the cities accompanied by other typologies (figure 4), representing emerging development and new areas of growth.

We identified upward growth components in two typologies, *mature upward* and *upward and outward*. *Mature upward* urban growth is characterized by urban pixels with high initial urban extent and verticality but negligible outward growth and some upward growth within the study period. Only 6.2% (30 out of 478) cities show this typology as one their urban growth typologies, e.g. Osaka (Japan) and Paris (France) in figure 4. *Upward and outward* urban growth can be inferred to urban pixels with medium initial urban cover in both outward and upward dimensions but high change in upward and outward urban extents. Given the simultaneity of upward and outward changes we label this cluster as *upward and outward.* This typology is typical of big cities in China (86% of total *upward and outward* urban growth cluster falls in China) and few cities located in South Korea and United Arab Emirates. In South Korea, *upward and outward* growth is mainly centered in Seoul. This is not surprising since Seoul comprised half of the

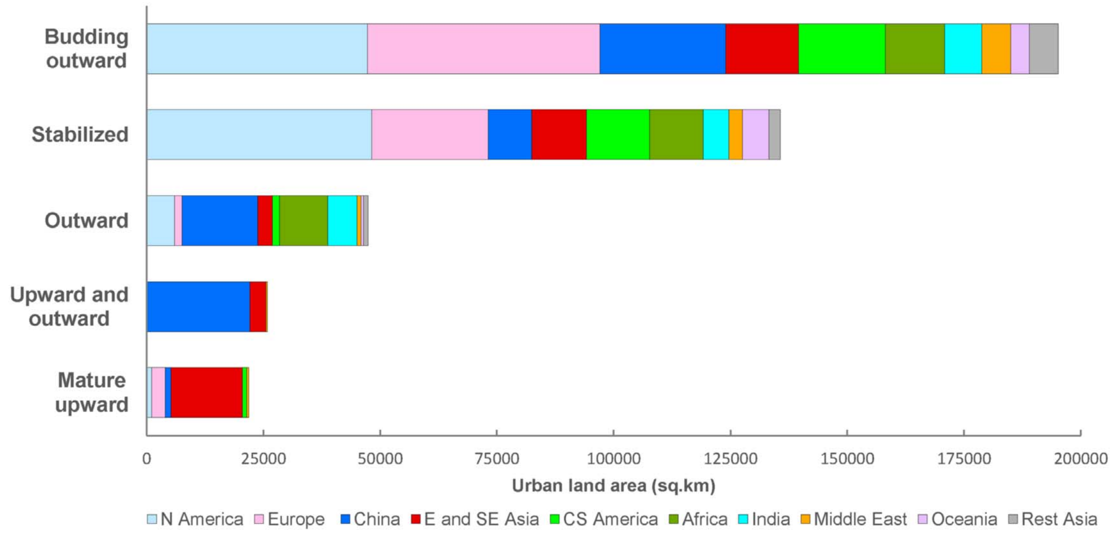


Figure 5. Distribution of urban land area across five typologies and geographic regions. Here, urban land area on *x*-axis is calculated by multiplying the number of urban pixels falling in each geographical region with area of one pixel, approximately 30.98 km^2 at the equator.

South Korea's urban land and 60% of the total urban population in 2010 (World Bank 2015).

3.3. Every city is comprised of multiple growth typologies

Our results show that cities are an amalgamation of the five urban growth typologies (figure S4). Out of 478 cities, 82% of the cities have two or three types of urban growth typologies with majority of the cities showing *budding outward*, *outward*, and *stabilized* urban growth. Six cities—Guangzhou, Incheon, Riyadh, Seoul, Shenzhen, and Singapore—exhibit all five urban growth typologies. Around 10% of the cities (46 out of 478) show only one urban growth typology, but most of these cities have fewer than five pixels (e.g. Jinhua (China), Yerevan (Armenia)). Figure S4 in supplementary information shows 3D urban growth for all the 478 cities.

Our results suggest that worldwide *budding outward* is the most common type of urban growth in terms of land area (figure 5), accounting for 46% (~ 195 266 km^2) of the total urban land assessed in this study. Thus, around half of the global urban area assessed is slow paced with low magnitude of outward urban growth, suggesting a large window of opportunity to shape future urban growth. We can make this growth sustainable by planning infrastructure growth in urban areas to be greener, connected, resource efficient and resilient (Burton *et al* 2013, Dempsey *et al* 2011).

Budding outward urban growth is followed by *stabilized* (36%) and *outward* (11%). More *budding outward* than *stabilized* urban growth signifies that more land area is being converted to new urban land as compared to densification of the existing urban areas. Furthermore, *outward* typology is one-third compared to *budding outward*, which signifies that horizontal expansion with high magnitude is concentrated in limited regions. Variations in land area covered by *outward* urban growth typology point that rapid outward urban growth in the study period is strenuous in China and Africa.

Upward urban growth accounts for only 11% of the urban land area for the study cities under *upward and outward* (6%) and *mature upward* (5%) typologies. China accounts for around 5% of the *upward and outward* growth, with the remaining 1% occurs in South Korea (E and SE Asia) and UAE (Middle East). About 3.6% of *mature upward* growth is located in E and SE Asia regions (Japan, Taiwan, South Korea and Singapore), with the remaining 1.4% distributed across mega-cities around the world. We did not find either of these upward typologies in Africa or India.

We found marked differences in the amount of urban growth across sub-regions of Africa, from 11 772 km^2 in South Africa, to 2292 km^2 in East Africa (figure S5). However, despite this large range in the magnitude of growth, there is not much variation in the patterns of growth. *Budding outward*, *outward* and *stabilized* urban growth typologies are present in all the sub-regions of Africa with relatively more outward growth in West Africa compared to other cities. The distribution of urban growth typologies varies by city, but overall patterns of urban growth are not that different. Thus, despite being a big continent with different histories, we examine Africa as a single region.

3.4. Urban growth typologies vary by geography

With the exception of East Asia, cities within a geographic region show similar urban growth typologies (figure 6). Urban growth typologies in North America (e.g. Baltimore, Cleveland) are chiefly *budding outward* or *stabilized*, while in Europe (e.g. Stuttgart, Turin) and CS America (e.g. Brasilia, Santiago) are dominantly characterized as *budding*

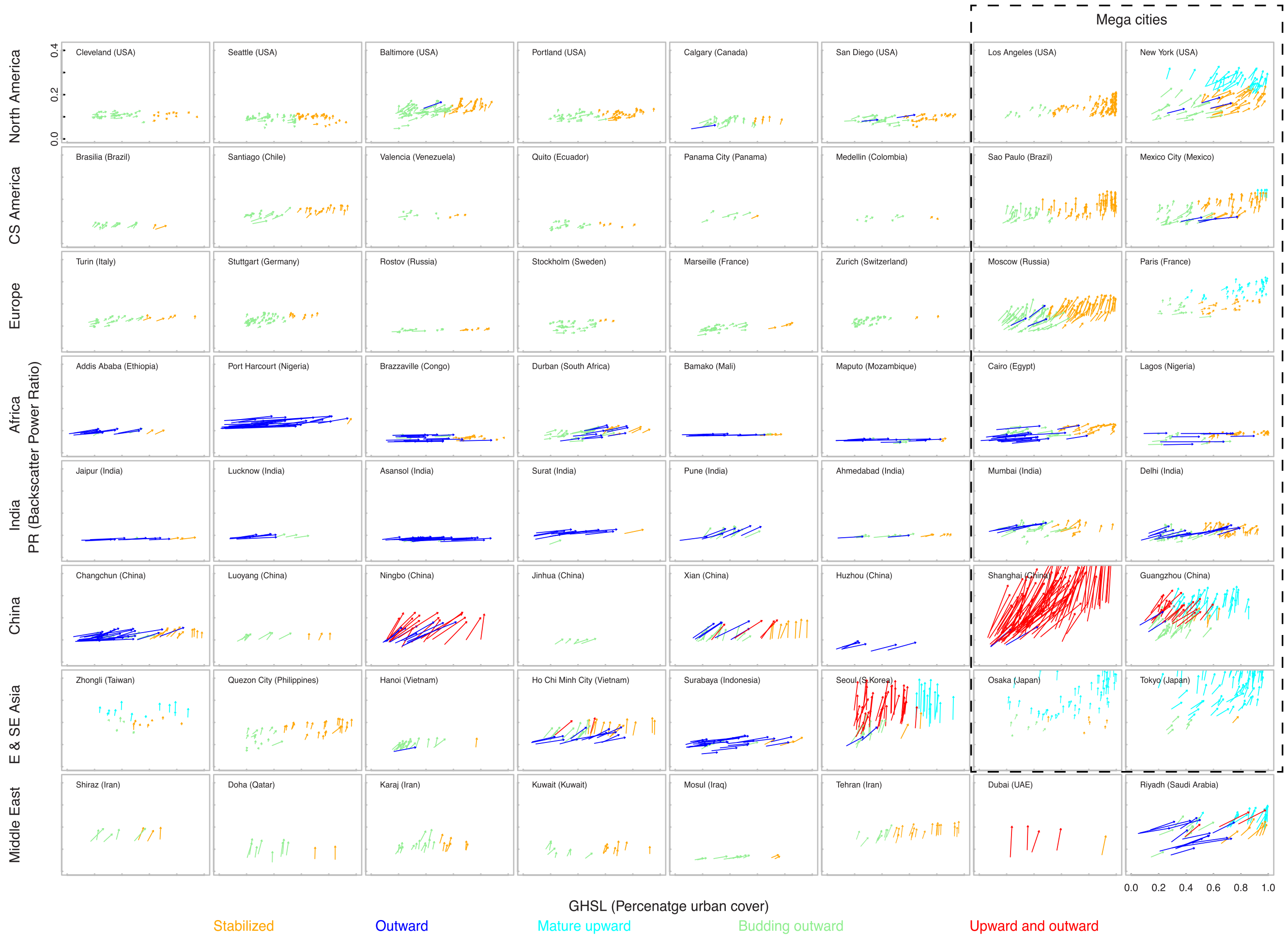
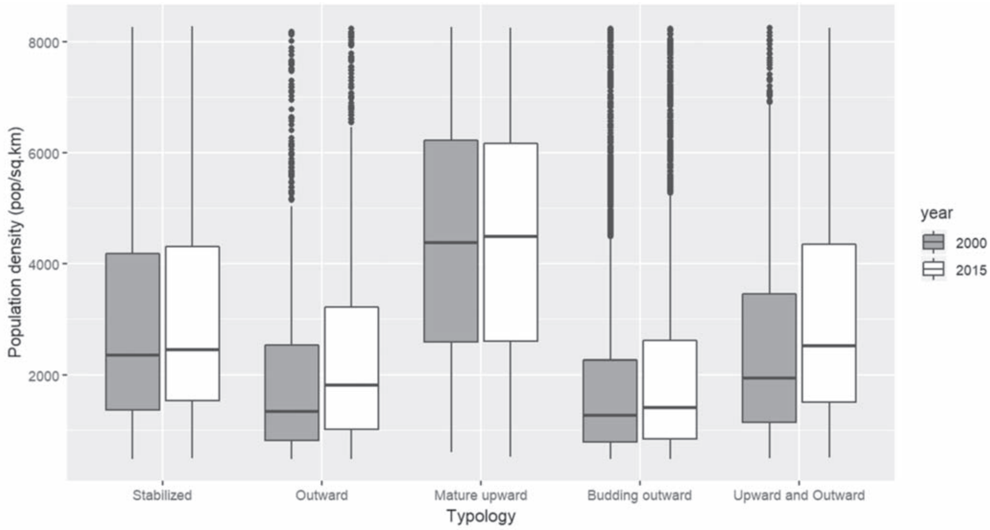


Figure 6. Regional variations in upward and outward urban growth. Sample of cities are chosen to show the regional trend and include two mega-cities per region except Middle East. There is no mega city in Middle east in 2011 (UN DESA 2012). The *x*-axis shows outward growth of urban built-up area based on GHSL between 2000 and 2014, and *y*-axis shows upward growth based on backscatter power ratio (PR), between 2001 and 2009. Arrows represent the pixels analyzed in a 11 × 11 grid around each city's center; the tail represents the year 2001 for PR and 2000 for GHSL, and the head represents 2009 for PR and 2014 for GHSL. Arrow color corresponds to the five clusters identified in this study. Number of pixels distributed across different urban growth typologies for all the cities is shown in S4.



No. of pixels	4379	1531	707	6303	834
Mean pop density (2000)	4615	1973	6567	1789	3899
Mean pop density (2015)	5448	2988	7274	2166	5395

Figure 7. Boxplots of population densities for 2000 and 2015 in the five urban growth typologies. Box area shows 25%–75% of the observations of the respective typology.

outward. *Budding outward* growth is expected for North American cities as they are characterized by low-density, single-family sub-urbanization, but surprising for European cities which have long been conceived as 'compact' (Ewing 1997, Brueckner 2000). Similar to North America, slow paced urban expansion or *budding outward* growth is becoming a characteristic of European urbanization (Hoffmann-Martinot and Sellers 2005, Huang *et al* 2007, Guastella *et al* 2019). The spatial patterns of urban Europe have been changing for at least the past twenty-five years. In 1993, the renowned urban scholar, Sir Peter Hall, presciently hypothesized that seven major forces were reshaping the spatial structure of cities in Europe. Among these factors, he noted that transformation of eastern Europe, in-migration and demographic shifts, and globalization and the rise of the informational economy together were creating new commercial and residential nodes and fueling an 'American scale of deconcentration'(Hall 1993). Other scholars have corroborated Hall's observations through empirical analysis and have found a 'New Model' of European urbanization comprised of isolated points of growth—similar to budding outward growth—and have attributed these patterns in part to advances in transport technology (Gernon and Peck 2007).

East Asia is characterized by considerable heterogeneities in urban growth typologies, with various combinations of growth trajectories in different countries. *Mature upward* is concentrated in Japan (e.g. Osaka, Tokyo) and Taiwan (e.g. Zhongli) comprising 90% of the global *mature upward* growth. Few cities in China (e.g. Shanghai, Ningbo) and South Korea (e.g. Seoul) have *upward and outward* as the dominant growth typology. Land use regulations in Seoul have been well developed since the 1970s, with strong planning institutions, which generally support *upward growth*. This is not the case with Indonesian cities where resources and enforcement of plans are lower and rural to urban migration is the primary driver for increase in the urban land (Samad *et al* 2016). Across much of the cities in Indonesia like Surabaya, *outward* is one of the dominant urban growth typologies. These heterogeneities in urban form point to differences in physical, political and institutional controls at the national level and within a region (Yokohari *et al* 2000, Huang *et al* 2007).

Furthermore, China show significant variations in urban growth typologies within and between cities. Inter-city variations in China reveal five distinct traits: dominant *upward and outward* urban growth (e.g. Beijing, Shanghai, Wuxi), dominant *outward* growth (e.g. Changchun, Qingdao, Linyi), mixed growth (e.g. Xian, Tianjin, Shenzhen), and low urban growth (e.g. Lanzhou, Shantou, Jinan). These different patterns of urban growth in Chinese cities are attributed to drivers such as rural to urban migration and foreign direct investment in the real estate sector, especially in cities providing incentives through special economic zones and in the more developed coastal cities (Ma 2004, Schneider and Mertes 2014). At the same time, local governments also began converting agricultural land to urban use to generate revenues (Yeh *et al* 2011), which led to the outward growth of many small cities.

Disconnected urban landscapes with only changes in the upward dimension is representative of urban growth in Middle East (e.g. Tehran, Doha, Dubai). Urban areas in this region show considerable change in volumetric growth. In fact, the total number of high-rises show an increase of 18 times, from three in 2000 to fifty-four in 2010 (Brass *et al* 2013). Some scholars have argued that this upward growth is attributed to various reasons including, technological advancement, economic stability, and a desire to build higher to signify wealth (Batty 2018).

Urban growth in mega-cities, cities with population >10 million, show more diverse urban growth typologies and in general, more urban land area compared to other cities in their respective regions (figure 6). For example, in Europe *budding outward* and *stabilized* are the common urban growth types in most of the cities and average urban land area is 1240 km^2. In Paris and Moscow, we also found *mature upward* and *outward* urban growth patterns. In Moscow, the urban land area is more than double (3190 km^2) that of the average European city. We found primarily *mature upward* growth in mega-cities of developed countries and *outward* growth in mega-cities of developing countries. For example, New York City and Paris show *mature upward* growth while cities in developing countries such as Delhi and Lagos show more *outward* growth.

3.5. Mature upward typology shows highest population density

Our analysis of population densities across different urban growth typologies illustrate three findings (figure 7). First, as expected, different urban growth typologies exhibit markedly different population densities, with higher intensity of urbanization (i.e. *mature upward*) corresponding with higher population densities. Similarly, lower population densities are associated with *budding outward* and *outward* typologies. The *budding outward* typology, which has the largest number of pixels in the study, show the lowest population densities both in 2000 (1789 persons per km^2) and 2015 (2166 persons per km^2). Second, higher population densities are related to upward growth typologies. Many studies have shown that higher population densities are a necessary condition for reducing transport energy use, urban carbon emission emissions and to transition urban sustainability (Seto *et al* 2014, Creutzig *et al* 2015, Stokes and Seto 2019). Our results show high population densities of 6567 persons per km^2 in 2000 and 7274 persons per km^2 in 2015 are in urban areas with *mature upward* growth typology. It suggests that *mature upward* is more likely to be correlated with lower transport energy use than other typologies. However, further empirical analysis is needed for a more conclusive assessment. Third, given that the most commonly occurring typology is *budding outward*, which also has the lowest population densities compared to other typologies, it suggests that transitioning these urban areas towards *upward and outward* or other urban forms with higher population densities will be important for urban sustainability.

3.6. Implications for urban sustainability

The results have multiple implications for urban sustainability. First, the results showing that most of the new urban land area worldwide is *budding outward*, suggests that there is considerable opportunity to shape future patterns of urbanization. However, this window of opportunity will shrink or close as basic infrastructure such as roads and power lines are constructed. Once established, urban form is easily entrenched and difficult to alter. Therefore, there is an urgent need to develop strategies for sustainable urban growth that are based on scientific evidence and good design that fosters equity, culture and society, while protecting the environment. The future eco-sustainable infrastructure should aim to combine modern technological innovations which emphasize on energy efficient structures and resource saving by using minimum land for human use. Our study shows that this is critical not just for a few cities, but many cities across regions worldwide.

Second, the clear geographic patterns and wide variations in the physical form of urban growth, between regions, and within a single country and city, suggests that markets, national and subnational policies, including the absence of, can shape how cities grow. While this study did not explicitly examine the drivers underlying these urban growth patterns, the geographic differences in urban growth patterns suggests that the forces that drive the physical expansion of urban areas vary by country. Other studies of drivers of urban growth have shown that national policies on land use and transport, variations in international capital flows, and country-level GDP explain differences in country-level rates of urban expansion (Seto *et al* 2011). The regional heterogeneities in urban form that we observed underscore the differences in policies and institutional controls across countries that have been found by other studies (Yokohari *et al* 2000, Huang *et al* 2007).

Third, approximately 90% of the cities in our study exhibit multiple typologies of urban growth, thus illustrating that different areas within a city undergo different types of urban growth. For example, a detailed analysis of urban growth in Bangalore has found significantly different styles of urban development in the city core versus the urban periphery (Reilly *et al* 2009). Our analysis corroborates this finding and suggests the need for differentiated urban growth strategies for different parts of a city.

Fourth, high population densities are associated with *mature upward* growth whereas low population densities with *budding outward*. Studies have consistently found higher urban densities to be correlated with lower energy use. In one of the most globally comprehensive studies of 274 samples representing cities of all sizes and regions worldwide, Creutzig *et al* (2015) found that for less affluent cities (<10 000 USD per capita), high population densities of 4600 persons per km^2 or greater showed the lowest energy use (~20 GJ per capita). As our study demonstrates that only 5% of the urban area is associated with *mature upward* while ~46% is *budding outward*, very limited urban area is under lower energy use. In order to achieve urban sustainability goal for our cities and communities (SDG 11), we need to steer urban growth to upward development in order to reduce energy use from transport and other sectors.

Finally, the new urban forms revealed in this analysis provide a first glimpse into the carbon lock-in of recently constructed energy-demanding infrastructure of urban settlements. Carbon lock-in refers to the persistence of carbon-intensive technologies shaped by mutually reinforcing institutional, behavioral and infrastructural systems (Seto *et al* 2016). The long life of urban infrastructures and urban form create initial conditions in behavior that are reinforced by institutions and can lock societies into carbon-intensive emissions pathways that are difficult to change. For example, low-density patterns of urban development may create and lock-in auto-dependence, which in turn reinforces the need to maintain and further develop auto-infrastructures. This further creates institutional lock-in in favor of auto-oriented development and creates obstacles, be it personal or institutional, to develop alternative solutions such as mass transit that go against these mutually reinforcing lock-in effects. This emphasizes the importance of initial conditions and early decisions about how urban areas develop. Our results show that for most of the world's cities with populations greater than 1 million, urban-related energy demand pathways are still nascent and plastic.

4. Conclusion

Recently, an expert panel for the journal *Nature Sustainability* called for more geographically diverse and greater global coverage of studies of urban areas (Acuto *et al* 2018). This paper fills these knowledge gaps by developing the largest dataset of 2D and 3D volumetric growth for 478 cities. Timely and accurate information on how urban built-up environments are changing is increasingly important as humankind becomes more of an urban species. This study reveals previously undocumented recent and rapid changes in urban volumetric structure worldwide. These observations reflect pronounced shifts in the form and structure of cities. Our study shows cities are worldwide rapidly increasing their built-up infrastructure, with tremendous opportunity to shape emerging urban forms towards more sustainable outcomes. Sustainable growth is contingent on harmony between development and environment. Therefore, our planning of future urban growth should be based on efficient use of available resources with more and more emphasis on green infrastructure thereby saving the environment.

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Data availability statement

The data that support the findings of this study are openly available. Here are the links to GHSL (https://ghsl.jrc.ec.europa.eu/ghs_bu2019.php), SeaWinds (https://scp.byu.edu/SCPproducts.html). Additionally, city level information generated (478 cities) in this study are available in the supplementary data.

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