CHAPTER 3

Understanding and Measuring Urban Expansion

THE CLASSIFICATION OF SATELLITE IMAGERY

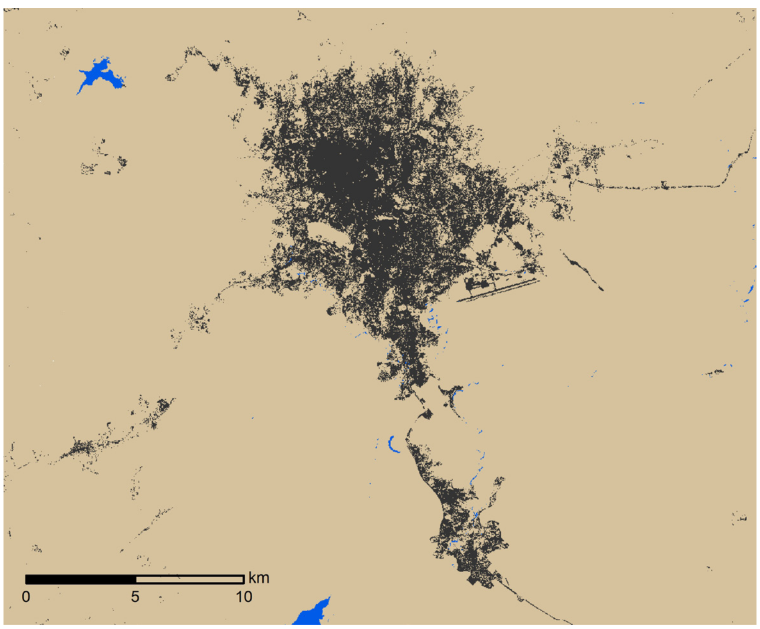
The maps of the urban extent of cities in the global sample were created using Landsat imagery that has been available since the early 1970s with improved quality over time. For the Atlas, we used cloud-free images from Landsat 5 (1984), Landsat 6 (1993), Landsat 7 (1999) and Landsat 8 (2013) satellites. The images are available every 16 days in scenes of 185-by-185 kilometers each with a typical pixel size of 30-by-30 meters. These images have several spectral bands that can be used to identify impervious surfaces roughly corresponding to built-up areas, as well as water surfaces. This makes it possible to classify them by human-assisted algorithms into three classes with a high degree of accuracy: built-up, open space, and water. Potere and his colleagues tested an earlier classification of Landsat imagery of a subset of cities in the global sample by our research team by comparing it to Google Earth imagery in thousands of randomly selected locations. They concluded that

> [t]he user's accuracy for the urban class was quite high, indicating that a portion of the Landsat-based site that is labeled "urban" will also appear as urbanized in the high-resolution

> imagery 91% of the time. The producer's accuracy for urban areas is slightly lower, indicating that urbanized areas within our sample were correctly identified 89.3% of the time. For this assessment, both the user's and producer's accuracies were important because we wanted to be certain that the … map collection was neither missing urban land (urban omission errors) nor mislabeling nonurban areas as urban land (urban commission errors). (Potere et al., 2008, 6546)

The classification of the study area of Addis Ababa, Ethiopia, in 2014 into these three classes—built-up, open space (not built-up), and water, is shown in figure 3.1. In this figure, built-up pixels are identified in both large and small clusters or patches. Most built-up pixels are contiguous and clearly associated with the main urban cluster of the city, but some are found along inter-city roads and some in scattered villages throughout the study area. A geographic information system (GIS) allows us to count the built-up pixels within the study area and calculate the total built-up area within the study area.

FIGURE 3.1:
30-by-30 meter pixels in Landsat satellite imagery for the study area of Addis Ababa, Ethiopia, in 1986, classified into built-up (black), open space (light brown), and water (blue) areas.



MAPS AND METRICS OF THE URBAN EXTENT OF CITIES

We differentiated the built-up pixels classified in the Landsat imagery for all cities in the global sample into three types—urban, suburban, and rural—depending on the share of built-up pixels within the Walking Distance Circle—defined as a circle with a one-square-kilometer area and a 584-meter radius, roughly a ten-minute walk—around each one of them:

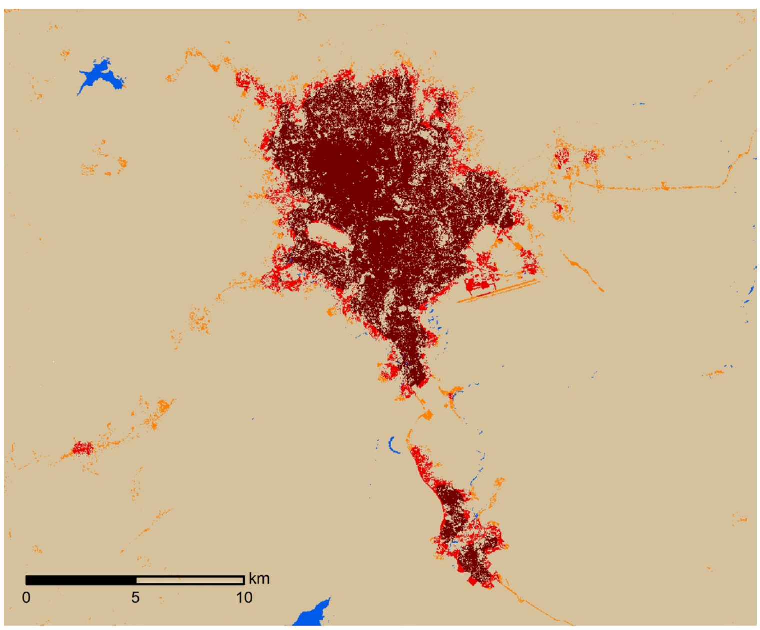
> *Urban* pixels are the majority of built-up pixels (50% or more) in their Walking Distance Circle;

Suburban pixels are 25–50% built-up pixels in their Walking Distance Circle; and

Rural pixels are less than 25% built-up pixels in their Walking Distance Circle.

The cutoff percentages for this three-fold division are somewhat arbitrary. They were chosen to correspond with the researchers' perceptions of what constitutes urban, rural, and suburban areas in a large number of real-world cities. It should be noted that in the 2012 version of the *Atlas*, the cutoff between suburban and rural pixels was 10%, rather than 25%. This cutoff point led to the identification of large rural areas on the fringe of cities as suburban. This cutoff point was therefore corrected to 25%. The map of the study area of 1986 Addis Ababa, Ethiopia, identifying urban, suburban, and rural pixels is shown in figure 3.2. Again, using GIS software, we calculated the shares of the urban, suburban, and rural built-up areas from this map.

FIGURE 3.2:
The built-up area within the study area of Addis Ababa, Ethiopia, in 1986 differentiated into urban (dark red), suburban (red) and rural (ochre) pixels.



Clearly, a city contains not only built-up areas but open spaces in and around them as well. Both city and country now interpenetrate and fragment each other on a vast scale. As Gottman and Harper note, "Breaking out of the old bounds, walls, boulevards, or administrative limits which set it apart, the city has massively invaded the open country, though parts of the countryside may have kept their rural appearance" (1990, 101). It is therefore particularly difficult to determine which open spaces belong to a contemporary city and which do not, or alternatively, which open spaces are disturbed by the city, and which are not. Landscape ecology studies maintain that settlements developed near a forest or prairie affect vegetation and wildlife along their edges, often in a belt up to 100 meters wide (Brand and George, 2001; Chen, Franklin, and Spies, 1992; Winter, Johnson, and Faaborg, 2000). This insight was used to distinguish urbanized open spaces from rural open spaces and to identify three distinct types of open spaces that together make up all the open space in a given study area:

Fringe open space consists of all open space pixels within 100 meters of urban or suburban pixels;

Captured open space consists of all open space clusters that are fully surrounded by urban and suburban built-up pixels and the fringe open space pixels around them, and that are less than 200 hectares in area; and

Rural open space consists of all open spaces that are not fringe or captured open spaces.

Fringe open space and captured open space, taken together, make up the urbanized open space in a given study area. In other words, urbanized open space and rural open space make up the entire open space within a given study area. Unfortunately, we cannot differentiate urbanized open space into public and private open spaces using satellite imagery. Using GIS software, we can, however, calculate the areas of the different types of open space within the study area.

The urban and suburban built-up area, together with the urbanized open space in and around them, make up *urban clusters*. There can be several urban clusters within a given study area, not all of them associated with a particular city. The urban clusters within the study area of Addis Ababa, Ethiopia, in 1986, with the open space within the study area differentiated into fringe open space, captured open space, and rural open space are shown in figure 3.3.

The largest urban cluster in a given study area is associated with the main city in the study area. Its city hall is identified and located to ensure that it is within this urban cluster. If there are more urban clusters close by, we need to determine whether they belong to this main cluster or form independent settlements that are not part of this cluster. Again, there is no rigorous procedure to determine this simply by examining satellite imagery. Local residents often know whether two separate clusters form one or two distinct cities. In the absence of local knowledge, we relied on the geographical proximity of nearby clusters to determine whether to include them in the main cluster using an inclusion rule. The inclusion rule operates by drawing a *buffer*—a zone with a border that is equidistant from the edge of the cluster—around each urban cluster, with the area of the buffer equal to one-quarter of the area of the cluster. The inclusion rule unites all clusters whose buffers intersect one another. The largest urban cluster in a given study area of a given city, together with the clusters added to it by the inclusion rule, is defined as the *urban extent* of the city. Urban clusters outside the urban extent are defined as *ex-urban* areas. The urban extent of 1986 Addis Ababa, Ethiopia, together with the ex-urban areas within its study area, is shown in figure 3.4.

FIGURE 3.3:
The urban clusters in the study area of Addis Ababa, Ethiopia in 1986, with open space within the study area differentiated into fringe open space (light green), captured open space (bright green), rural open space (dark green).

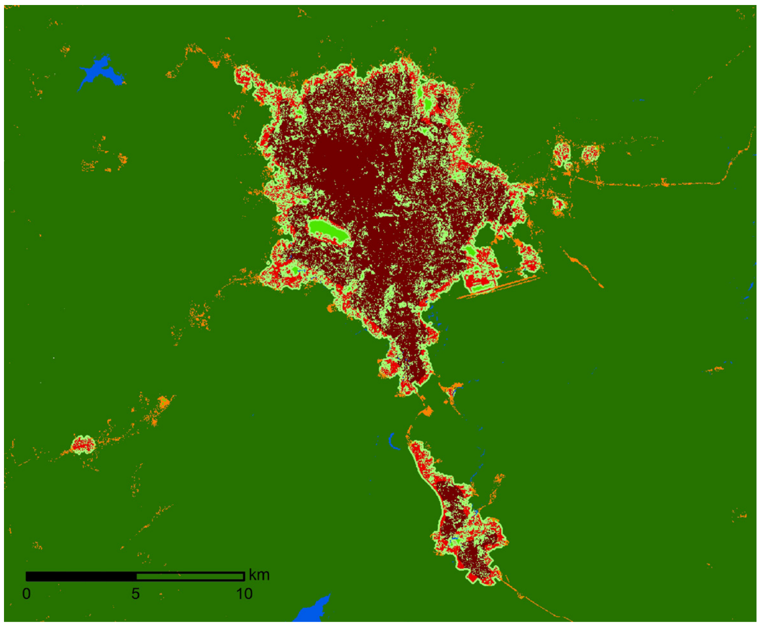
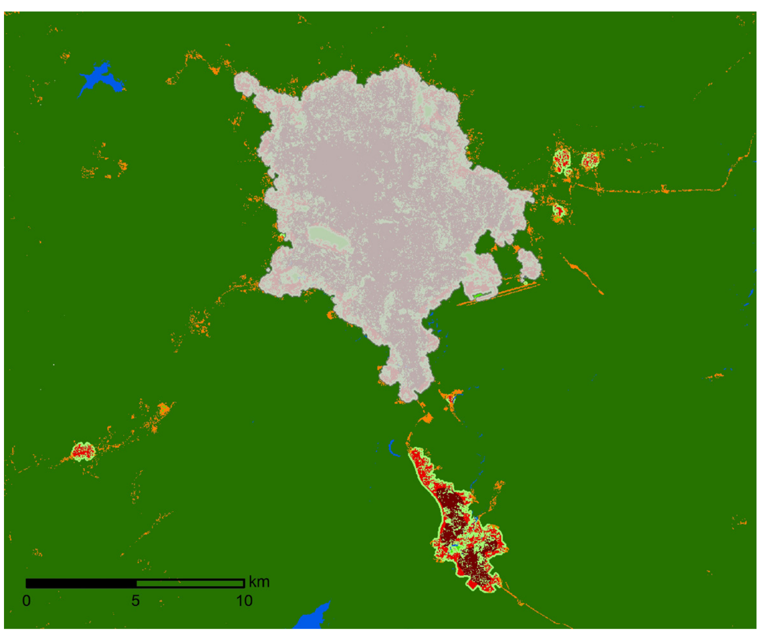
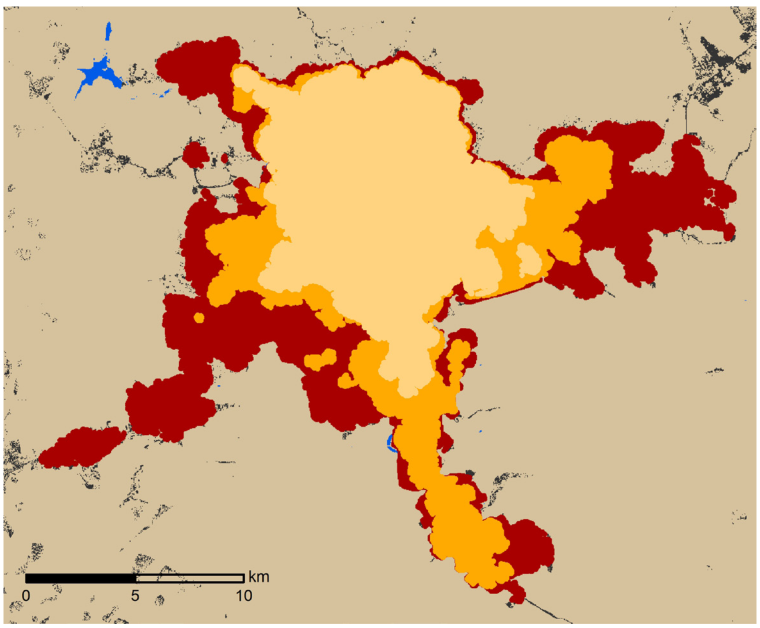


FIGURE 3.4:
The urban extent (grey) of Addis Ababa, Ethiopia in 1986 and the ex-urban areas within its study area.



We used the same procedure to generate maps for the urban extent of all the cities in the sample for three time periods: circa 1990, circa 2000, and circa 2014. This allowed us to identify new areas of expansion between 1990 and 2014 and to calculate the urban extent in each period as well as the annual rates of expansion between these dates. The expansion of the urban extent of Addis Ababa is shown in figure 3.5.

FIGURE 3.5:
The expansion of the urban extent of Addis Ababa, Ethiopia: The area developed before 1986 (ochre), the area developed between 1986 and 2000 (orange), the area developed between 2000 and 2010 (brown).



Finally, creating maps of the urban extent of cities in two or more time periods allowed us to investigate the composition of the added area in greater detail. Indeed, we can determine what share of the built-up area added between two time periods was added by filling in any urbanized open space within the earlier urban extent, what share was added by extending that extent outwards in a contiguous manner, what share was added by leapfrogging over rural open space into new areas in a noncontiguous manner, and what share was added by incorporating ex-urban and rural settlements that were already built-up in the earlier period into the new urban extent. We can define four types of newly built-up areas that together constitute all the built-up area added to the earlier urban extent between two time periods:

Infill consists of all built-up pixels added in the new period that occupy urbanized open space within the urban extent of the earlier period;

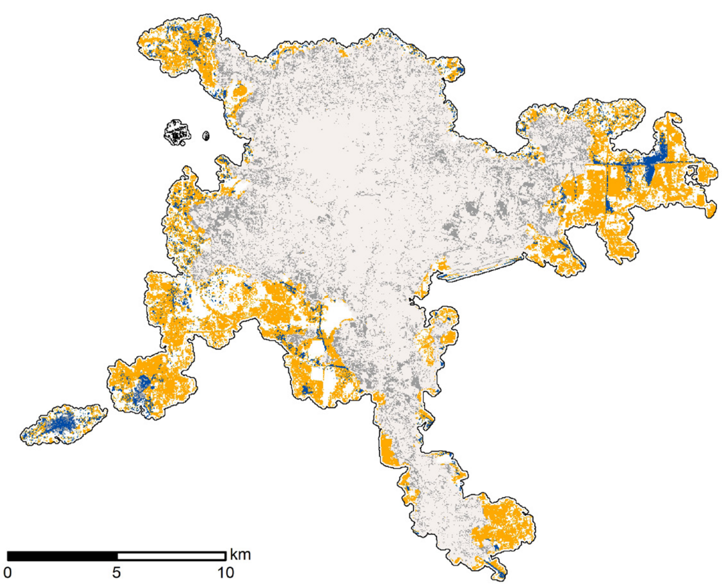
Extension consists of all built-up pixels added in the new period that constitute contiguous urban clusters that are attached to the urban extent of the earlier period;

Leapfrog consists of all built-up pixels added in the new period that constitute new contiguous urban clusters that are not attached to the urban extent of the earlier period or to new extension clusters; and

Inclusion consists of all urban, rural, or suburban built-up pixels that were outside the urban extent in the earlier period and are now within the urban extent of the new period.

We can map the infill, extension, leapfrog, and inclusion areas for all cities in the global sample during two time periods: ~1990 to ~2000; and ~2000 to ~2014. We can then calculate the composition of the added area during these periods. The map showing the composition of the area added between 2000 and 2010 in Addis Ababa, Ethiopia, is shown in figure 3.6.

FIGURE 3.6:
The composition of the added built-up area in Addis Ababa, Ethiopia, between 2000 and 2014, showing the share of infill (grey), extension (orange), leapfrog (black), and inclusion (blue).



DENSITY, FRAGMENTATION, AND COMPACTNESS METRICS

The maps and their associated metrics described in the previous section allow us to measure a number of important spatial attributes of cities in a consistent manner, making possible comparison among cities as well as comparisons over time. Three of these attributes are mapped and measured: density, fragmentation, and compactness. Density measures the intensity of use of the urban extent or the built-up area of a city by its population. Fragmentation measures the degree to which the built-up area saturates the city's urban extent or, conversely, the extent to which the built-up area within it is fragmented by urbanized open space. Compactness measures the extent to which the overall geographic shape of urban extent approximates a circle, the shape that minimizes the average distance from any point within it to its center or, alternatively, the shape that minimizes the average distance between all points within it.

The density of the population of a city varies greatly *across* its urban extent. It has been found to decline systematically with distance from the city center. It is typically higher in low-income neighborhoods than in higher-income areas and it approaches zero in industrial, commercial, or civic districts that contain no residences, or in empty open spaces. Density is typically defined as a ratio of the number of people per unit of area. In this Atlas, we use hectares to measure area; a hectare constitutes one-hundredth of a square kilometer or approximately 2.5 acres. Our interest in the study of urban expansion suggests that an appropriate measure of density is the average density of the entire urban extent of the city because it is this measure that translates a city's population into the overall area it occupies. For example, a city of one million people with an average density of 100 persons per hectare will occupy 10,000 hectares. In other words, if we could estimate a city's future population and its future density, we could derive a measure of the total area it will occupy. That said, we may also be interested in measuring the density of the built-up area within the city's urban extent because this measure is independent from the degree to which a city may be fragmented. We therefore calculated two density metrics for each city in the sample in each time period:

> *Urban extent density* is the ratio of the total population of the city and its urban extent, measured in persons per hectare.
>
> *Built-up area density* is the ratio of the total population of the city and its built-up area, measured in persons per hectare.

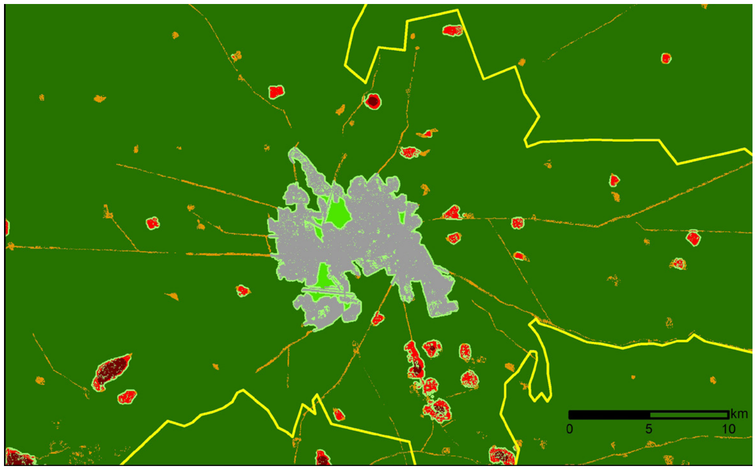
Urban extent density is always lower than built-up area density. Also, because the urban extent of the city contains its urbanized open space, urban extent density is not independent from the city's level of fragmentation while built-up area density is. Two cities with the same population and the same built-up area will have the same built-up area density. If one city is more fragmented—its built-up area occupies only 40% of its urban extent—and the other city's built-up area occupies 80% of its urban extent, then the urban extent density in the former will be half that of the latter.

The determination of the density of a given city's urban extent requires a correct estimate of the population of the city at the date of that urban extent. It also requires that the population be associated with all that extent and only with that extent, rather than with a different area that is smaller or larger than that extent. Typically, when a city's population is associated with its name, it is difficult to know whether it refers only to the central city that bears that name, to the central city and its suburbs and outlying municipalities, or to a large region that contains that city as well as its rural hinterland.

In general, the only way that we can obtain correct population estimates is to associate a population with an enumeration zone in the manner that national censuses typically do. A population census is indeed a map of enumeration zones, each with a well-defined boundary, with a population associated with each zone. Such maps provide the best possible population estimates. That said, in some countries it is possible to obtain digital maps of enumeration zones and their associated populations at the level of city blocks, while in others it is only possible to obtain maps at the county or provincial level. We have sought to obtain the most detailed maps of enumeration zones for the cities in the global sample, using a number of valuable sources, including but not limited to: The Center for International Earth Science Information Network (CIESIN) at Columbia University, www.citypopulation.de (Brinkhoff, 2016), the Chinese Academy of Sciences, and various national census bureaus.

The method for obtaining the population of an urban extent of a given city at a particular date required identifying the set of enumeration zones and their populations that fully contained that urban extent at that date, or interpolating or extrapolating the populations of these enumeration zones to estimate their populations at that date. The population analysis apportioned the populations of individual enumeration zones evenly to all built-up pixels within them. Within a zone, only a fraction of the built-up pixels may actually be within the urban extent boundary; in other words, an enumeration zone that intersects the urban extent, especially at the periphery, may contain a number of built -up pixels that are inside the urban extent as well as a number of pixels that are outside the urban extent. For each zone that intersected the urban extent, we calculated the share of its built-up pixels that were inside the urban extent boundary and we multiplied that share by the total population of the zone. Summing this result over all zones that intersected the urban extent, we obtained the new urban extent population. We attempted to address a source of bias in the population apportionment by developing a procedure for identifying and removing built up pixels associated with rural roads. In large zones on the periphery with many roads, apportioning population evenly to all built up pixels would underestimate the true population associated with the urban extent within that zone. Other sources of bias could not be adequately addressed, namely, the procedure assumes that the population densities of rural built-up pixels and urban extent pixels (urban and suburban built-up pixels) within an enumeration zone are identical. The identification of rural roads, rural settlements, and urban extent pixels in the study area of Marrakesh, Morocco in 2002 is shown in figure 3.7.

FIGURE 3.7:
The identification of urban extent pixels (grey), and rural built up pixels (orange)—including rural settlement and rural road pixels—in the study area of Marrakesh, Morocco in 2002, used to allocate the population of the enumeration zone (yellow) to the urban extent.



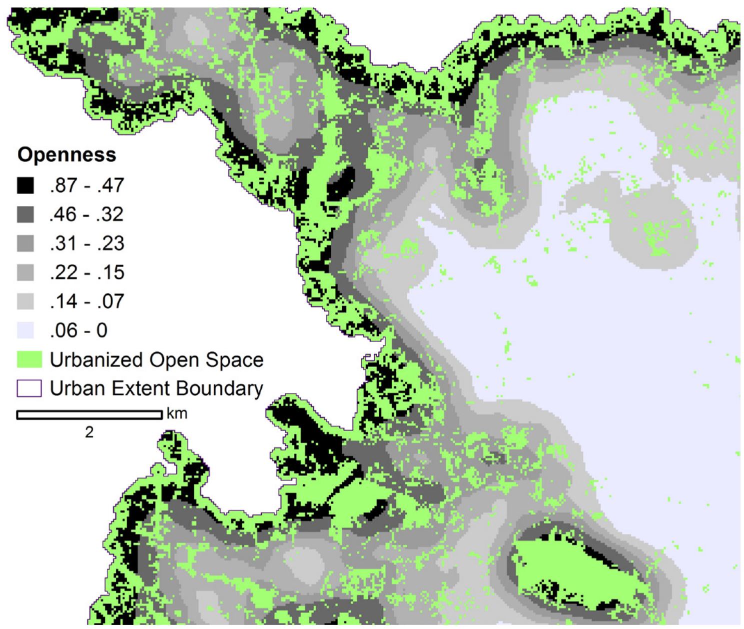
Obtaining accurate population estimates for the urban extents of cities in the global sample allowed us to compare densities in different time periods to assess whether they are increasing or decreasing over time, either in individual cities, in cities of different types, or in the universe of cities as a whole. It also allowed us to construct statistical models that explain variation in densities among cities in the sample or in the universe as a whole.

As noted earlier, the Atlas also provides information on the fragmentation of the urban extents of cities: the degree to which their built-up areas are fragmented by open space or, conversely, the degree to which their built-up areas fragment the open space in and around them. Fragmentation matters for a number of reasons. The more fragmented the built-up area, the lower its urban extent density, the greater the distance between locations in the city, and the more open space is disturbed by the city. Conversely, the more fragmented the city, the closer its built-up areas are to open space, possibly an important amenity. The landscape ecology literature provides numerous methods and metrics for measuring fragmentation (see McGarigal and Marks, 1994). The Atlas provides two measures of urban fragmentation, highly correlated with each other, that are particularly relevant in the study of cities:

> *Saturation* is the ratio of the built-up area within the urban extent of the city and its urban extent.
>
> The *openness index* is the average share of open space pixels within the Walking Distance Circle (a circle with an area of 1km^2 and a radius of 564 meters) of every built-up pixel within the urban extent.

Both indices have values ranging from 0 to 1. Saturation is at a maximum when the urban extent contains no open space at all and at a minimum when it contains only open space. Conversely, the openness index is at a maximum when the urban extent contains only open space and at a minimum when it contains no open space at all. Clearly, urban built-up pixels have lower openness values than suburban built-up pixels or rural built-up pixels. A map showing the variation in openness values across the urban extent of Addis Ababa in 2014 is shown in figure 3.8. The openness index for Addis Ababa for that year was 0.24.

FIGURE 3.8:
The openness values of built-up pixels within the urban extent of Addis Ababa, Ethiopia, in 2014, range from high values (dark colors) on the urban periphery to low values (light colors) in the city center. The openness index for the city as a whole, 0.24, is the average of these values.

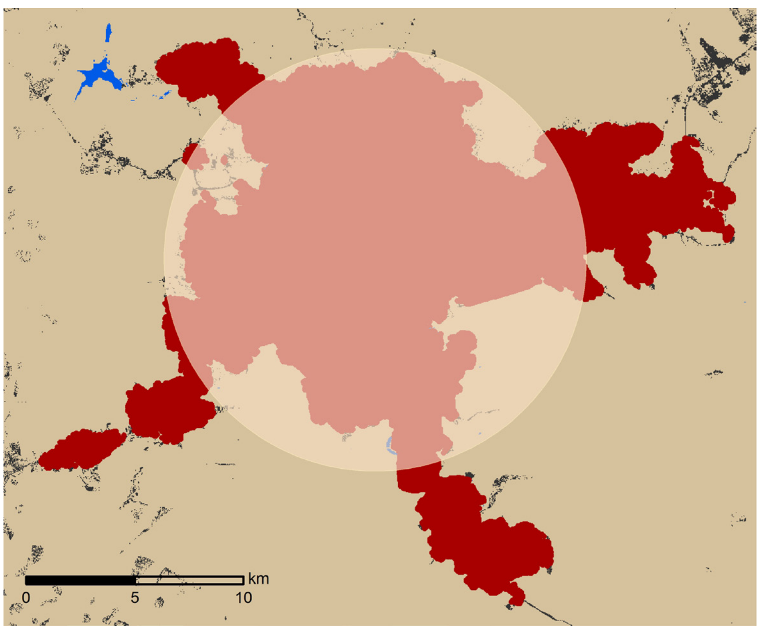


Finally, the Atlas provides information on the compactness of the urban extents of cities. Compactness, in the sense used here, is the two-dimensional shape compactness of the urban extent in geographic space, to be distinguished from other measures of the compactness of cities that are associated with density or with its three-dimensional compactness. The perfect circle is considered to be the most compact of all two-dimensional shapes in a number of respects (Angel et al., 2010). An urban extent of a city is considered to be more compact the closer it is to being a perfect circle. Again, many metrics have been proposed for measuring shape compactness, but most are irrelevant for measuring the compactness of cities where the main concern is one of maximizing access, either access to jobs in the Central Business District (CBD) in monocentric cities or access from all locations to all others in more decentralized cities. In this Atlas, we produced metrics of two compactness attributes of cities that are highly correlated with each other. Both rely on comparing the shape of the urban extent to the shape of the *equal area circle*, a circle with the area of the urban extent, centered at city hall.

> The *proximity index* is the ratio of the average beeline distance of all points in the equal area circle to city hall and the average beeline distance of all points in the urban extent to city hall.
>
> The *cohesion index* is the ratio of the average beeline distance of all points to all other points in the equal area circle and the average beeline distance of all points to all other points in the urban extent.

Both indices vary between 0 and 1, with higher values corresponding to urban extents that are closer in shape to the circle. The urban extent of 2014 Addis Ababa, Ethiopia, and its equal area circle are shown in figure 3.9 below. Its proximity index was 0.84 and its cohesion index was 0.82 that year.

FIGURE 3.9:
The urban extent of Addis Ababa, Ethiopia, in 2010 and its associated equal area circle.



In the following pages, we provide maps of the urban extents of the 200 cities in the sample and tables and charts of the metrics associated with them.