The Persistent Decline in Urban Densities: Global and Historical Evidence of 'Sprawl'

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Abstract

Using satellite imagery, census data and historical maps, we report on density variation among cities the world over. We find significant differences in the average population density in the built-up areas of a global sample of 120 cities: In 2000, average density was 28±5 persons per hectare in cities in land-rich developed countries, 70±8 in cities in other developed countries, and 135±11 in cities in developing countries. We also find that built-up area densities in this sample declined significantly, at an average annual rate of 2.0±0.4 percent, between 1990 and 2000. We report on the five-fold decline in average tract density in 20 U.S. cities between 1910 and 2000, at an average long-term rate of 1.9 percent per annum, on the slowing down of the rate of decline in recent decades, and on the decline in several other density metrics during this period. Using historical maps and historical demographic data for 1800-2000, we also report on the threefold decline in average urbanized area densities in a global sample of 30 cities during the twentieth century, following an increase in average density in the nineteenth century. On average, densities in this historical sample have been in decline since their peak circa 1890±16, at an average long-term annual rate of 1.0-1.5 percent. All or most of the significant factors accounting for density variations and density decline are identified in multiple regression models and the implications of the findings for urban containment and compact city strategies in different regions are examined. At current rates of density decline in the cities of developing countries, for example, when their urban populations double in the next 30 years, as now expected, their built-up areas will likely *triple*. Minimum preparations for this massive expansion are clearly in order.

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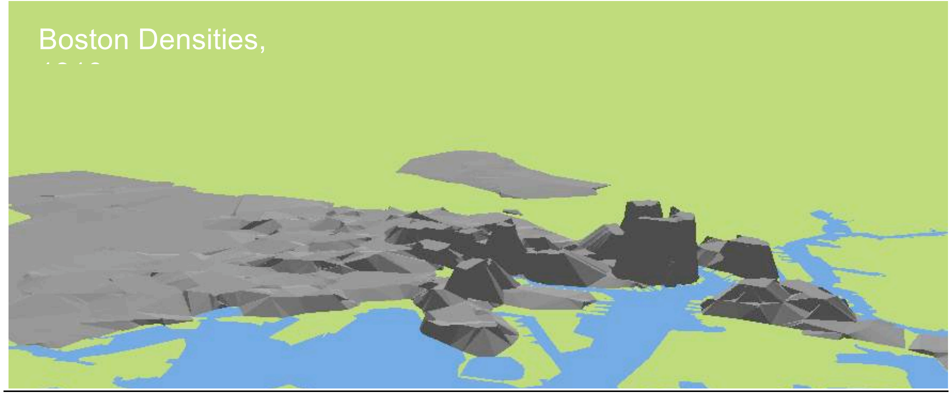
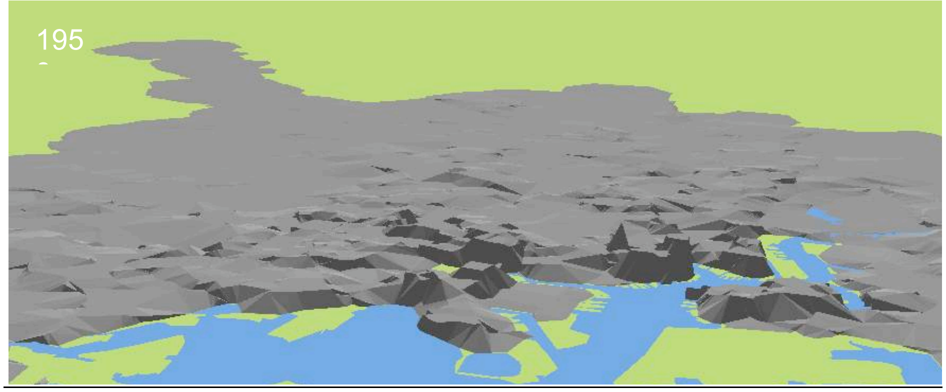
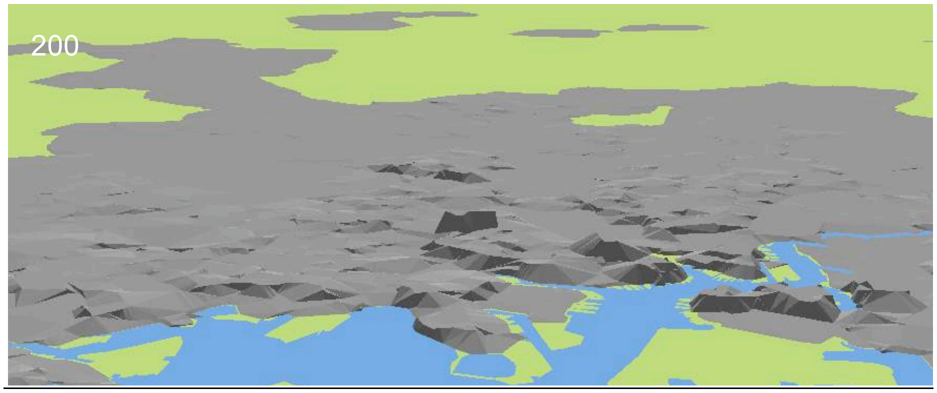
Global and Historical Evidence of 'Sprawl'







I. INTRODUCTION

Containing *sprawl*: The need for evidence

There are many of us who believe that it is in the public interest to contain urban sprawl and make cities the world over more compact. Politicians, activists, scholars and planners now readily assert that left to their own devices, cities and metropolitan areas across the globe appropriate too much of the countryside. Surely, except for an insignificant minority, no one believes anymore that we can or should prevent people from coming to cities in search of better lives. That belief has now largely been discarded and replaced by an assertion that the amount of land that cities occupy is too large for the number of people who inhabit and use that land. In other words, our urban containment and compact city advocates now assert that the *density* at which urban land is occupied is too low and needs to be increased.

The questions that we must now answer so as to give credence to this assertion are, first and foremost, empirical ones: How do urban population densities vary from city to city? Are they too low in some cities, optimal in some cities, and too high in others, or are they too low everywhere? With or without our interventions, when cities grow in population, do their land areas expand at the same rate as their populations, at a faster rate, or at a slower rate? Do these rates differ among different cities and at different times? What are the factors that determine urban population densities and cause them to change? And, finally, are densities subject to effective policy intervention or is trying to control them likely to be as futile as trying to prevent people from coming to cities? The answers to these questions form the core of this essay.

It is worth noting that the idea for this study originated with the following question: Could it be that urban containment and compact city strategies are now appropriate in some developed countries but inappropriate in many, if not most, developing countries?

There is no question that many villagers, especially in developing countries, are still flocking to cities and we need to make ample room for cities to grow and expand in order to accommodate them. In contrast, there is also little doubt that, in most developed countries, urbanization ─ the movement of the population into cities and towns ─ has almost reached a plateau. Urban expansion now often takes place in the near absence of strong population pressure. In most, if not in all, developed countries loud voices have been heard for some time now calling for strong measures to contain the further expansion of cities and to prevent them for spreading into the countryside, now perceived to be more vulnerable than ever before. Calls for urban containment are typically accompanied by demands for the adoption of policies and plans to make cities more compact, to rebuild them at higher densities, and to encourage new higher-density development on the urban fringe based on *new urbanism* principles (see, for example, Congress for New Urbanism, 1999). London's Green belt (1935), Seoul's green belt (1971), Portland's Urban Growth Boundary (1973) and Mexico City's *Bando Dos* (2000) are well-known examples of urban containment strategies. The *Alta de Lisboa* project in north Lisbon is a typical recent example of high-density new urbanism development on the metropolitan fringe.

The justifications for urban containment and densification policies are ample and need not be repeated here. The anti-sprawl literature, from the popular to the academic, is vast and varied and we assume that the reader cannot help but be familiar with several of its representative examples. The conviction that these policies are the right strategies for our troubled times, that they are, in fact, strategies to ensure our very survival on the planet, is now widespread. Rigorous evidence that containment and compact city strategies indeed work and that their societal benefits exceed their negative side effects is rather meager, but that is almost beside the point: Political support for these measures is substantial and growing.

The urban containment and compact city rhetoric is also spreading to cities in developing countries where its value may be more questionable. Could it be that urban containment policies are inappropriate for developing countries at the present time? Could it be that densities in developing-country cities, on the whole, are high enough? How different are they from densities in developed countries? Can authorities in developing-country cities ensure compliance with zoning and land use regulations designed to contain urban expansion? Would it not be more realistic to make room for expansion at the projected densities rather than trying to contain expansion and failing in the attempt? If so, how much land would be needed to accommodate the coming expansion given realistic projections of urban population growth and urban densities? Answers to these questions also demand a rigorous empirical investigation and they too form the core of this essay.

Five measurable attributes of urban expansion or *sprawl*

This essay is a part of a larger global study of urban expansion or 'sprawl'.[1] Most of the literature on urban expansion, especially of late, focuses on 'sprawl' in developed countries and particularly in the United States, usually with an eye to its disturbing aspects. Our survey of this literature in search of ways to measure sprawl revealed an interesting dissonance. On the one hand, there is an almost universal consensus, with a few minor exceptions, on what are the key manifestations of sprawl: endless cities, low densities, fuzzy boundaries between city and countryside, a polycentric urban structure, large expanses of single-use zones, ribbons and commercial strips, scattered development, leapfrogging development, and the excessive fragmentation of open space among others. On the other hand, there is the oft-repeated lament that sprawl, as an overarching characteristic common to all these manifestations, is ill defined and therefore difficult to measure in a convincing and systematic way.

Our study of urban sprawl and the literature associated with it has convinced us that its key attributes simply cannot be measured with one single metric. In fact, we have identified five measurable attributes of sprawl, each focused on the change over time of one or another of its essential characteristics. This paper focuses on one of them — density—and, more particularly, on the decline in density over time, as one of these five attributes of urban expansion or 'sprawl'.

We begin by making a few basic distinctions. Following Galster et al (2001), we define and measure sprawl both as a *pattern* of urban land use—that is, a spatial configuration of a metropolitan area at a point in time—and as a *process*, namely as the change in the spatial structure of cities over time. Sprawl as a pattern or a process is to be distinguished from the *causes* that bring about such a pattern, or from the *consequences* of such patterns. In this paper, we examine sprawl both as a pattern and as a process, with a special emphasis on the latter. We then seek to explain the variation in spatial patterns

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[1] The terms 'urban expansion' and 'sprawl' will be used interchangeably throughout this paper without necessarily attributing positive or negative attributes to these phenomena.

and their change over time using multiple regression models with the causes of sprawl as independent variables. In our conclusion we point at some of the key consequences of sprawl. In general, we seek to make clear distinctions between pattern, process, causes and consequences and to avoid definitions that fuse them together uncritically, such as the following definition offered by the Sierra Club:

> What is suburban sprawl? Suburban sprawl is irresponsible, poorly planned development that destroys green space, increases traffic and air pollution, crowds schools and drives up taxes. (Sierra Club 2000, 2)

We take sprawl to be a *relative* rather than an absolute characterization of an urban landscape. We have no interest in creating a black-and-white distinction between a sprawling city and a compact city. We are only interested in relative measures that can be used to compare a single city at two points in time to determine whether it is more sprawling or less sprawling now than before; or to compare two cities to determine which one is more sprawling. In historical terms, the sprawl of yesteryear, the endless suburbs built in the 1940s in Los Angeles for example, may not longer be considered “true” sprawl in comparison with the newer large-lot mansions now springing up in the rural areas of New Jersey, on the outer fringes of the New York metropolitan area (see figure 1.1). In fact, Los Angeles, as we shall see later, is now one of the densest and most compact of American cities.

In this study, we focus on the *process* of urban expansion or sprawl, rather than on their static characteristics. After a review of the literature and a thorough examination of a wide range of metrics for measuring this process in a rigorous, policy-sensitive manner, we have identified five discrete attributes of this process that can now be measured and analyzed systematically and that together provide a relatively comprehensive[2] characterization of this process. They are:

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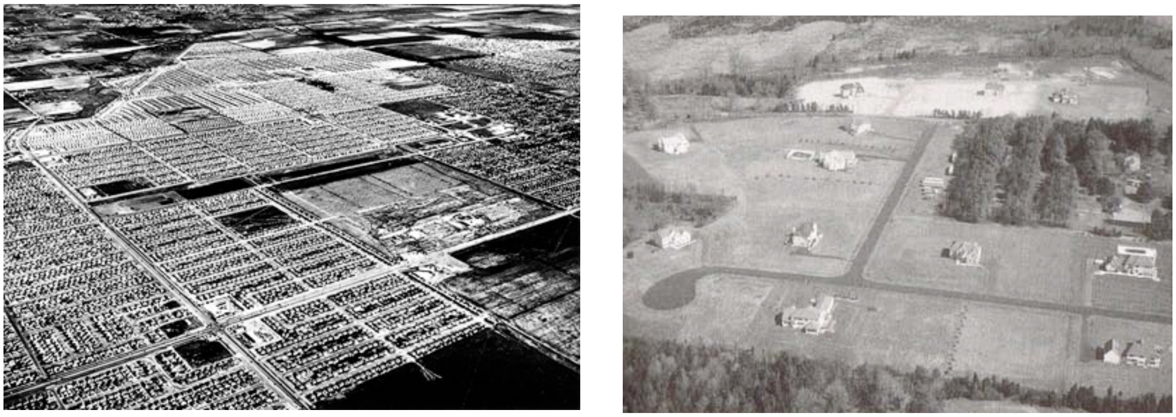
[2] These attributes do not include some aspects of sprawl often mentioned in the literature that are more difficult to measure systematically in a global study of cities, such as the decentralization of employment (Glaeser and Kahn, 2003); polycentric development (Anas, Arnott and Small, 1998 and Clausen and Hall, 1973); “unplanned, uncontrolled, and uncoordinated single use development” (Nelson et al, 1995, 1); or the absence of public open spaces (Schneider, 1970 and Ewing, 1994).

Figure 1.1: The 1940s Lakewood suburb of Los Angeles and the present-day Franklin Township of New Jersey[3]



1. *Expansion*, or the formation of 'endless' cities: typically measured by the increase over time of the total built-up area (or impervious surface) of cities, sometimes including the open spaces captured by the built-up area or the open spaces on the urban fringe affected by urban development. Sinclair (1967), Brueckner and Fansler (1983), Lowry (1988), and Hasse and Lathrop (2001), for example, define and measure sprawl as the quantity of land converted to urban use.

2. *Decongestion*, or the decline of urban densities: typically measured as the decline over time of the ratio of the total urban population and the total built-up area it occupies. Brueckner and Fansler (1983), Brueckner (2000), Civco, Hurd, Arnold and Prisloe (2000), Ewing et al (2002), Fulton et al (2001), and El Nasser and Overberg (2001), for example, define and measure sprawl as low density or density decline.

3. *Suburbanization*, or the decentralization of metropolitan areas: typically measured by the decline in both parameters of the density curve—its intercept and its gradient, the first corresponding to maximum densities at the urban center and the second to the rate of decline in density as distance from the city center increases. Self (1961), Gottman and Harper (1967), Jackson (1972), Kasarda and Redfearn (1975), and Hall (1997) for example, define and measure sprawl as the increasing share of the urban population living in suburbs.

4. *Fragmentation*, or scattered development: typically measured by the relative amount and the spatial structure of the open spaces that are fragmented by the non-contiguous and non-compact expansion of cities into the surrounding countryside. Clawson (1962), Peiser (1989), Carruthers and Ulfarsson (2001), Heim (2001) Weitz and Moore (1998), and Burchfield *et al* (2007), for example, define and measure sprawl as non-contiguous development.

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[3] Sources: Waldie, D. J., undated and Burchell et al, 2005, 127 (photograph by Anton Nelessen).

5. *Dispersion*, or the reduced interconnected of the urban footprint: typically measured by compactness metrics (Angel, Parent and Civco, 2009) or by some of the accessibility metrics found in the literature and reviewed by Ewing who claims that “[u]ltimately what distinguished sprawl from alternative development patterns is poor accessibility of related land uses to one another” (Ewing, 1994, 2).

This paper focuses primarily on decongestion, namely on the decline of average urban densities, and to a minor extent on the suburbanization and decentralization of metropolitan areas and the gradual reduction of the differences in density between city and suburb. A second paper will focus the formation of ‘endless’ cities, and, more particularly, on estimating and projecting the total land in urban use in all countries based on an evaluation of recent global land cover data and on explaining variations in urban land cover among countries. A third paper will focus on describing and explaining the variations in fragmentation and its recent decline in a global sample of 120 cities.

Why should we be concerned with measuring the attributes of urban expansion or sprawl? From a scientific perspective, any phenomenon that humans observe and come to believe is of some importance to their lives merits precise measurement. To quote Lord Kelvin (McHale, 145):

> When you measure what you are speaking about and express it in numbers, you know something about it, but if you cannot express it in numbers your knowledge about it is of a meager and unsatisfactory kind.

From a strict *public policy* perspective this is certainly a worthwhile pursuit, and the author shares the conviction that, if we, as a public, want to deal effectively with urban expansion— whether to forbid it, constrain it, guide it, actively prepare for it, or leave it be—it is clearly imperative that we define it rigorously and measure it systematically. As Brueckner (2000, 161) warns:

> The stakes in this policy debate are substantial…. [A]n attack on urban sprawl will ultimately lead to denser cities containing smaller dwellings. If the criticisms of urban sprawl are correct, then the loss from lower housing consumption would be offset by other gains such as improved access to open space and lower traffic congestion. But if the attack on urban sprawl is misguided, with few benefits arising from restricted city sizes, people would be packed into denser cities for no good reason, leading to a reduction in the American standard of living…. If only mild measures are needed to restrict urban growth, but draconian measures are used instead, consumers are likely to end up worse off.

Being able to *measure* urban expansion in a convincing manner would make it possible, at the very least,

1. To focus the policy debate by reducing complex maps containing large amount of information to a single metric or a small set of complementary metrics;
2. To explain the variations in levels of sprawl and the causes and consequences of urban sprawl in a rigorous fashion, using quantitative statistical modeling;
3. To set numerical targets for the management of urban expansion, to assess whether the targets are being attained, and to determine which policies are effective in attaining them;
4. To generate regional and global norms that would facilitate comparisons between metropolitan regions; and
5. To measure the amount of land in urban use, to project future needs, and to ensure the adequate supply of public goods—e.g. infrastructure, open space, and common facilities—for urban expansion.

The rigorous and systematic measurement of urban expansion or sprawl using satellite imagery—a methodology that has recently become available and increasingly affordable—should also enable us to answer a number of important policy questions that are often raised in the literature:

1. To what extent is sprawl ubiquitous and universal rather than the result of particular land use policies in particular countries?
2. Are urban densities declining, stabilizing, or increasing over time?
3. Are vacant spaces left in the urban expansion process gradually being filled in, or is the presence of vacant land in the city footprint a more-or-less permanent feature of the urban landscape?
4. Should developing-country cities pursue similar urban expansion policies to those now being advocated in developed countries? and
5. Is sprawl likely to be reversed if transportation costs increase markedly and transportation externalities—like congestion and pollution—are internalized?

The reader should keep in mind, however, that from a purely *political* perspective, it is not so clear that the rigorous definition and measurement of sprawl is an unmitigated good:

> [T]he term "sprawl" has never had a coherent or precise definition. This has been one of the reasons it has been such a powerful polemical tool…. Because of the lack of precise agreement about what sprawl is, individuals have been free to rally around certain broad but quite abstract concepts as a way to explain what is wrong with developments they see around them without necessarily agreeing on any specific diagnosis of the problems or any concrete set of prescriptions. It has allowed people with radically different assumptions to find common cause. (Bruegmann, 115)

It should not come as a surprise, therefore, that the literature on urban sprawl is, for the most part, highly politicized, and that every researcher is automatically suspect of harboring biases that prevent him or her from presenting an objective view of the phenomenon at hand. But that need not mean that we should abstain from trying to define and measure sprawl precisely, from making our proposed measurements transparent, or from advancing our common understanding of what specific measures mean, what they bring to light, and what they hide. This paper attempts to do just that by focusing on density and density change, the most-oft mentioned characteristics of sprawl both in the academic and in the popular literature.

Because of the public nature of the sprawl debate, we have restricted ourselves to measures of urban extent and expansion that correspond to the common intuitive understanding of the phenomenon. As Horn and his colleagues (Horn, Hampton and Vandenbeg, 106) observe, "[t]he *de facto* arbiter of what measure is best is intuition: which one most 'fully encompasses our intuitive notion' (Niemi et al, 1159), or which one best results in a 'correspondence between visual and quantitative expression'" (Manninen, 75-76). This assertion necessarily means that the common understanding of what constitutes sprawl needs to be taken seriously and cannot be simply dismissed. Measures of sprawl that may be very meaningful and insightful to analysts may turn out not to be particularly useful in policy discussions or in presentations to the general public. Our informal survey of the vast sprawl literature makes it quite clear that density and its decline over time are the attributes of sprawl most-often alluded to, and it is to density that we now turn our attention.

The evolving motivations for measuring urban densities

What is the rationale for measuring urban population densities and, more specifically, in measuring them in a particular way?

The study of urban population densities has now undergone three major transformations since its inception in the late nineteenth century: from concerns with excessively high densities in central cities, to concerns with the radical density shifts accompanying suburbanization, to concerns with the low densities resulting from excessive sprawl. These transformations were necessitated by tectonic shifts in the concerns of politicians, reformers, scholars, and planners with the problems besetting cities in different historical periods and, more recently, in different regions. We contend here that, in large measure, while density metrics did co-exist side by side, each transformation brought into focus a different metric for measuring and explaining density.

Throughout history and until the end of the 18th century, all the cities in the world—even the largest ones—were walking cities. Their physical size was generally limited to an area small enough for people to move from one place to another on foot. Goods were moved by pack animals or carted and a small minority could travel on horseback or by carriage, but, by and large, the great majority walked. The city of Ur in ancient Babylon, for example, is believed to have had a population of half a million people living at a density of 500 persons per hectare (Clark, 1977, 315, quoting Woolley, 1954). The center of the city could be easily reached by foot from its furthest point in less than half an hour. Paris in 1800 had a similar density, 500 persons per hectare, and its built-up area of 11 km^2 was roughly circular, with its edge some two kilometers away from the city center (see figure 6.3). Urban population densities, on the whole, were high by modern standards, and politicians, reformers, scholars, and planners occasionally voiced their concerns with excessive density and overcrowded conditions in particular neighborhoods. These concerns became much more acute with the advent of the industrial city, when the life expectancy of people who migrated to cities declined relative their life expectancy in the countryside.

During the period of rapid urbanization and the formation of industrial cities—starting in the late seventeenth century and lasting until the early decades of the twentieth century—many cities expanded well beyond their walking range. There is also some evidence that their central densities increased in the early phases of industrialization, sometimes quite rapidly, as large numbers of people migrated in from rural areas or from abroad. As noted by Clark, one of the early students of urban population density:

> The advent of the nineteenth century industrial city compelled people to live at far greater densities than had ever been known before, with consequent effects upon their health and well being. (Clark, 1977, 340)

Politicians, reformers, scholars, and planners became seriously concerned with living conditions in the newly overcrowded neighborhoods at the centers of cities:

> At the recent annual meeting of the Children Aid Society, special attention was called by the reports to the overcrowding in tenement-houses, as the prolific source of juvenile crime. The truth is that in no city of the civilized world does this terrible evil and cause of disease and crime exist in nearly the same degree as in New York. (New York Times, 3 December 1876)

The measurement of density during this phase focused on the measurement of *maximum densities* in individual, small neighborhoods:

> The Tenth Ward has a population at the rate of 185,513 to the square mile[4]; the

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[4] 708 persons per hectare.

> Seventeenth 170,006[5], and so on with others equally overcrowded. Portions of particular wards are even in worse condition (New York Times, 3 December 1876).

Reformers sought to reduce these densities through decongestion policies made possible by the development of new transportation technologies from the early nineteenth century onwards, technologies that reduced the cost of movement in cities and made it possible for large numbers of people to commute over greater distances. These initially included the ferryboat, the horse-drawn omnibus, the horse car on rails (see figure 1.2), and the bicycle, and some time later various forms of motorized transport: the trolley, the streetcar, the cable car, the commuter train, and the subway, and then the private automobile and the bus.

Figure 1.2: The last horse cars on rails in New York City, 1917[6]

> The 'rise of the suburbs' it is, which furnishes the solid basis of a hope that the evils of city life, so far as they result from overcrowding, may be in large part removed. (Weber, 1899, 475)
>
> The Lower East Side…contained 398,000 people in 1910, 303,000 in 1920, 182,000 in 1930, and 147,000 in 1940. To reformers who had long pressed for the depopulation of the slums, this leveling out of neighborhoods was a welcome and much celebrated relief. (Jackson, 1985, 185)

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[5] 657 persons per hectare.

[6] Source: http://www.cable-car-guy.com/images/ny_last_horsecar_001.jpg.

During the middle decades of the twentieth century—the decades when the use of private automobiles for commuting to work became ubiquitous and reached new peaks—politicians, reformers, scholars, and urban planners became concerned that the declines in central city populations have gone too far, creating dangerous imbalances between core cities and suburbs. For many, the problems of central cities—high taxes, bad schools, racial tensions, crime and congestion—were to blame for accelerating suburbanization, and had to be confronted so as to slow it down:

> These problems lead affluent central city residents to migrate to the suburbs, which leads to a further deterioration of the quality of life and the fiscal situation of central areas, which induces further out-migration. (Mieszkowski and Mills, 1993, 137)

The measurement of density during this phase focused on the spatial structure of cities, often characterized by a *density curve* showing density declining at a constant rate as distance from the city center increased (Clark, 1951). Studies showed that the downward slope of this curve tended to become flatter over time[7]:

> [V]irtually all cities in the developed world and most others elsewhere decentralized during the last century or more—the density gradient has declined over time. (Anas, Arnott and Small, 1998, 1436)

In recent decades, the decongestion of the high-density neighborhoods in central cities, the declining importance of the urban core and the emergence of polycentric cities have decreased the importance of both maximum densities and the density curve as a reliable and useful description of urban spatial structure. In the second half of the twentieth century, politicians, reformers, scholars, and planners became concerned with excessive 'sprawl', worried that cities were becoming too dispersed and were invading too much of their surrounding countryside, damaging farmland, forests, wetlands, wildlife, and watersheds. Of late, additional concerns with air pollution, global warming, and limited oil supplies sparked new interest in urban densities that would be high enough to sustain public transport.

The measurement of density to address these new concerns focused on *average density*, as a metric for tracking the total land area taken up by the city population and for monitoring the rate of land consumption relative to the rate of population growth.

> An analysis of the density trends in every metropolitan area in the United States between 1982 and 1997 reveals: Most metropolitan areas in the United States are adding urbanized land at a much faster rate than they are adding population. (Fulton et al, 2001, 1)

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[7] Or, in mathematical terms, that the gradient $\square$ of the density curve $d(r) = d(0) \cdot e^{-\square \cdot r}$, where r is the distance from the city center and d(r) is the density at that distance, tended to become smaller over time. See, for example, Mills and Tan, 1980.

It is important to note here that the total land area taken up by cities—the denominator in the calculation of average density—now needed to be measured in at least three different ways to address different concerns:

1. The *built-up area* of the city corresponding to the total amount of impervious surface there, including rooftops, roads, and all paved surfaces;

2. The *urbanized area* of the city corresponding to the built-up area and the captured open space within it; and

3. The *city footprint* of the city, which includes the built-up area and the *affected* open space in and around it.

The first measure, the built-up area, is the area of impervious surface. It can now be detected and measured unambiguously by remote sensing and used in a consistent manner to compare urban areas over time and space. It also addresses concerns with excessive paving that may result in flooding and soil erosion. The second measure—which includes parks, land to be kept free of construction (e.g. steep slopes and floodplains), and vacant lots—addresses the concerns with leapfrogging development and the non-contiguous nature of urban expansion. It is also a realistic estimate of the amount of land needed for planned urban expansion, given the short lifespan of vacant lots in non-contiguous urban expansion. The third measure focuses on the land that is fragmented, affected, and in some sense taken away from adjacent non-urban land uses by urban development. Landscape ecology studies, for example, note that development at the edge of a forest or a prairie affects vegetation and wildlife along their edges, often in a belt some 100 meters in width.[8] In our own density metrics, to be elaborated upon later, we included all open space within 100 meters of urban and suburban built-up areas to be part of the city footprint of cities. All three area measures are used as denominators for calculating density and its change over time in the global sample of 120 cities that forms one of the three key databases of this paper.

In conclusion, it is important to note here that not all of the concerns with density in developed countries were shared by developing-country politicians, reformers, scholars and planners in different time periods. Cities in developing countries have undergone similar—though not identical—transformations, but possibly with a time lag. While rural-urban migration in developed countries has by now largely ebbed, many developing countries are still urbanizing rapidly. Average population densities in developing-country cities are still much higher, as we shall see below. Suburbanization is on the rise, but at an early stage, and it is taking place at higher densities than those in developed countries. To be sure, maximum population densities in some districts of central cities are still

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[8] Studies in forest ecology identify different edge widths depending on the species being studied. Brand and George (2001) give an average edge width of 115 meters for the four bird species studied. Chen, Franklin and Spies (1992) discuss edge-widths of up to 137 meters, and one of the references in their paper lists edge-widths of 300-600 meters. Winter, Johnson and Faaborg (2000) give edge widths of 30-50 meters. We have chosen a 100-meter edge width as an average of the different edge widths discussed in the literature.

extremely high. The density of Chamra Bazaar—the central area of Dharavi, Mumbai's largest slum—was estimated to be as high as 3,300 persons per hectare, several times the average density in Mumbai as a whole. There are still serious concerns with high central-city densities and the need for deconcentration, and there is some data to show that cities in developing countries are now undergoing substantial deconcentration.[9]

Developing countries are still in the midst of rapid urbanization. The population of their cities is now scheduled to double between 2000 and 2030, from 1.98 billion to 3.95 billion (U.N. Population Division, 2008. File 3: Urban Population at Mid-Year by Major Area, Region and Country, 1950-2050 [thousands]). If these projections are to be taken seriously, reformers must now seek to make sure that there are adequate lands with minimal urban infrastructure for accommodating the projected urban population growth. The measurement of density to address this concern also focuses on average density and its change over time, as a metric for projecting the amount of land needed to accommodate projected urban population growth. The total amount of urbanized land in each country in 2000 and its projection into the future, given projected declines in average densities, will be the subject of a separate paper.

In this essay, we shall focus mainly—but certainly not exclusively—on the different metrics associated with average density, given the common interest in this metric in both developed and developing countries, albeit for different reasons. The measurement of average density, in different cities and in different time periods, is the key to understanding how much land is in urban use and why it varies across space and time. It is also the key to making realistic projections of how much land will be needed to accommodate the expected urban population growth, especially in the developing countries.

II. DENSITY METRICS

The unit of investigation in this essay is the metropolitan area, typically a core city surrounded by suburbs and secondary cities that form a relatively contiguous whole. We report on our study of densities of metropolitan areas in all world regions and over time, in some cases over a decade and in some others over as much as two centuries. While the focus is on metropolitan areas, the terms 'city', 'town', 'urban area,' 'metropolitan area' and 'metropolis' are used interchangeably.

Cities occupy land and city people use that land. Land in urban use includes all land in residential, commercial, industrial, and office use; land used for transport, parks, and public facilities; protected land, and vacant land. In the year 2000, land in urban use constituted less than one percent of the total land area of the planet (Potere et al, 2009). Land in urban use is to be distinguished from land in non-urban use that includes all cultivated lands, pasture lands, forests, farms and villages, inter-city roads, and nature areas. The exact cutoff point that distinguishes metropolitan areas, cities, and towns from villages large and small varies from country to country, yet each country defines a specific share of its total population as urban. According to the United Nations, some 3

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[9] For data on Mumbai, see for example Mills and Tan, 1980, tables 2, 4 and 8, 315-8.

billion people, slightly over half the total world population of the world, lived in cities in the year 2000. The authors and their colleagues estimated (Angel et al, 2005, table II-1, 18) that approximately three-quarters of this population lived in cities that had populations of 100,000 or more.

We now have fairly detailed projections of the population inhabiting cities, countries, regions, and the world as a whole (see, for example, U.N. Population division, 2008). We do not have very good information about how much land an average urban dweller is likely to require in the future. We can start by asking how much land urban dwellers have occupied in the more recent past and in the more distant past. This knowledge should help make our projections more realistic. Surely, the average amount of land per person and the average density—defined as the average number of persons per unit of land—are interchangeable terms. One is the reciprocal of the other. From a scientific perspective we are therefore interested in the following two questions: How do urban population densities vary from place to place and why? And how do urban population densities vary from time to time and why?

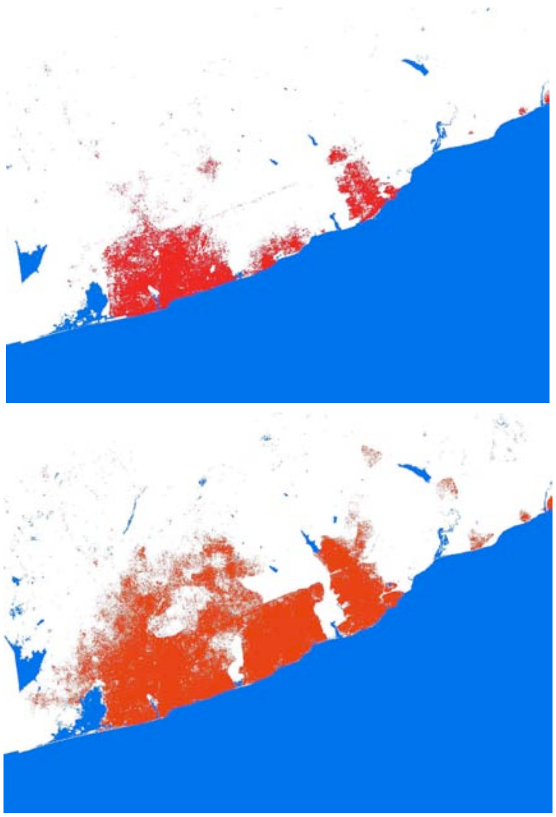
The main focus of this paper is on the examination of empirical evidence regarding the average population density of land in urban use in individual metropolitan areas across space and time. We explore average built-up area densities, urbanized area densities, and city footprint densities (to be defined below) in 2000 and the change in these average population densities from 1990 to 2000 in a global stratified sample of 120 cities that had populations in excess of 100,000 in 2000. We explore the change in several additional density parameters—average tract density, maximum tract density, the tract density gradient, and the tract density curve intercept (to be defined below)—in 20 U.S. cities between 1910 and 2000 and in 65 U.S. cities between 1950 and 2000. And we explore the change in average urbanized area densities in a global set of 30 cities between 1800 and 2000. All in all, as the title of this paper suggests, and as we shall see later, we find all these density parameters to be in significant decline everywhere for periods extending to a century or more.

Average density is the simplest quantitative measure of the relationship between the people who reside in a metropolitan area and the land they occupy and use. In the foregoing discussion, we will use the term ‘density’, ‘average density’, and ‘average population density’ interchangeably too. In general, when a lot of people occupy a given land area, density is said to be high, and when only a few people occupy that area, density is said to be low. Low densities or declining densities are therefore the simplest quantitative indicators of urban ‘sprawl’.

In quantitative terms, when the number of people occupying a fixed land area doubles, its density doubles. When the land area occupied by a fixed number of people doubles, its density is halved. Density is thus a ratio: population divided by area. It is typically measured in people per hectare, denoted p/ha, and this is the measure we shall employ here. A hectare is equal to 10,000m^2, one-hundredth of a km^2, or ~2.5 acres (2.471 to be exact). There are ~259 hectares in a square mile.

If the population of a city grows faster than its area, its density increases. It becomes less ‘sprawled’. If the area of the city grows faster than its population, its density declines. It becomes more ‘sprawled’. Between 1985 and 2000, for example, the population of Accra increased from 1.48 to 2.66 million, an 80 percent increase. Its built-up area increased from 8,000 to 32,000 hectares, a 300 percent increase. During this period, the average density in Accra declined from 77 persons per hectare to 58 persons per hectare. Accra became more ‘sprawled’ (see figure 2.1).

Figure 2.1: The expansion of the built-up area of Accra, Ghana (shown in red), 1985-2000



Conversely, between 1991 and 2000, to take another example, the population of Johannesburg increased from 3.52 to 4.70 million, a 33 percent increase. Its built-up area increased from 87,200 to 99,300 hectares, a 14 percent increase. During this period, the average density in Johannesburg increased from 39 persons per hectare to 48 persons per hectare. Johannesburg became more ‘compact’ as apartheid ended and blacks could occupy the inner low-density neighborhoods of the city that were forbidden to them before.

In the past, researchers have found it difficult to compare average urban population densities because of the different ways that urban areas were defined and measured in different places. This has changed in recent years with the advent of satellite imagery.

There are at least five ways to define and measure the land area of the metropolis for the purpose of studying density, four of which are used in this study:

1. The administrative area;
2. The area of 'urban' census tracts;
3. The built-up area;
4. The urbanized area; and
5. The city footprint.

There is no escape from using one administrative area or another to measure densities because population data is only collected for administrative areas with well-defined boundaries. But the overall administrative area of a city or a metropolis is not a particularly good denominator for measuring urban density. First, it can change by fiat through the incorporation of new areas into its city limits, thus causing density to change overnight. Second, it can be much larger than the built-up area of the city. To take one example: In the year 2000, the administrative area of the Municipality of Beijing was 16,800 km^2, some 11 times larger than its built-up area in that year. Wolman et al (2005) devote an entire article to the question of what land area should be considered in measuring sprawl in the United States, and note that using the administrative area will usually under-estimate density, thereby overestimating sprawl. They propose a novel way to measure area—the Extended Urban Area—that unfortunately requires commuting and other data that is readily available in the U.S. but not available elsewhere. In this study, we did not use the administrative areas of cities for calculating average density. We did use the four other measures of area in defining and calculating average density. We discuss them briefly below:

Built-up area density

The built-up area of the city—the 'built city' (Parr, 2007, 382)—is the easiest to visualize, to identify, and to classify by remote sensing. Affordable satellite imagery has made it possible to map and measure the actual built-up areas of cities for the purpose of calculating density (Fulton et al, 2001; Burchfield et al, 2005). In the study of the global sample of 120 cities reported here, we classified satellite images into built-up areas and non-built-up areas using *Landsat* imagery with 30m^2 pixels. For each city, we calculated the total built-up area within the smallest set of administrative districts containing the main contiguous built-up areas of the city. For most cities in the sample, these districts were fairly large, typically the size of counties. The *Average Built-up Area Density* was then calculated as the ratio of the total population in this set of districts and the total area of the built-up pixels within these districts.

We classified the built-up areas of cities into three types: (1) The *urban* built-up area, defined as the set of built-up pixels that have a majority of built-up pixels in a circle of 1-

km^2 area around them; (2) the *suburban* area, defined as the set of built-up pixels that have more than 10 percent built-up pixels in a circle of 1-km^2 area around them; and (3) the *rural* built-up area, defined as the set of built-up pixels that have less than 10 percent built-up pixels in a circle of 1-km^2 area around them. While rural built-up areas were considered not to disturb nearby open space, both urban and suburban built-up areas were taken into account in calculating the city footprint, as we shall see below.

The urban, rural and suburban built-up areas of Bandung in July of 1991 are shown in figure 2.2 below. At that time, the total built-up area of Bandung within the set of administrative districts circumscribing it amounted to 10,900 hectares. In that year, Bandung had a population of 3.0 million within these administrative districts. Its average built-up area density was therefore 274 persons per hectare.

Urbanized area density

While the built-up area is the least controversial denominator for measuring density, it tends to under-estimate land in urban use because it does not include the *urbanized open space*—the open space captured inside the built-up area. These open spaces may be permanent, e.g. in parks, or temporary, e.g. in vacant lands. The authors have constructed a metric for measuring urbanized open space by trial and error and settled on a metric that appears to capture the interior open spaces in a city in a consistent fashion. Urbanized open space is defined as the set of open space pixels that have a majority of built-up pixels in a circle of 1-km^2 area around them. Figure 2.2 shows the urbanized open space (in yellow) in Bandung in 1991. Urbanized open space added 2,950 hectares or 27 percent, to the built-up area of Bandung that year. Its average urbanized area density was therefore 215 persons per hectare, some 21 percent lower than its average built-up area density.

City footprint density

Studies in landscape ecology suggest that urban and suburban built-up areas within 100 meters of a natural habitat disturb both plant and wildlife in that habitat and can thus be said to affect that open space. The *city footprint* was defined as the sum of the urban and suburban areas, the affected open space fringe within a 100-meter buffer of their built-up areas, and the internal open spaces captured by both. Figure 2.3 shows the city footprint of Bandung in 1991. The city footprint added 10,800 hectares, or 100 percent, to the built-up area of Bandung that year. Its average city footprint density was therefore 135 persons per hectare, 37 percent lower than its average urbanized area density, and half its average built-up area density.

Figure 2.2: The built-up area and urbanized area of Bandung, 1991

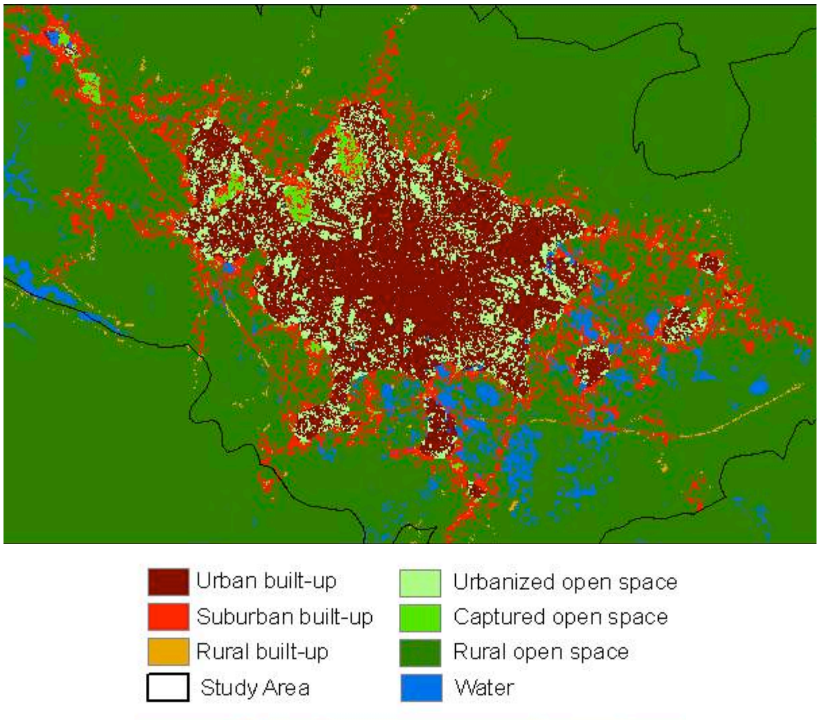
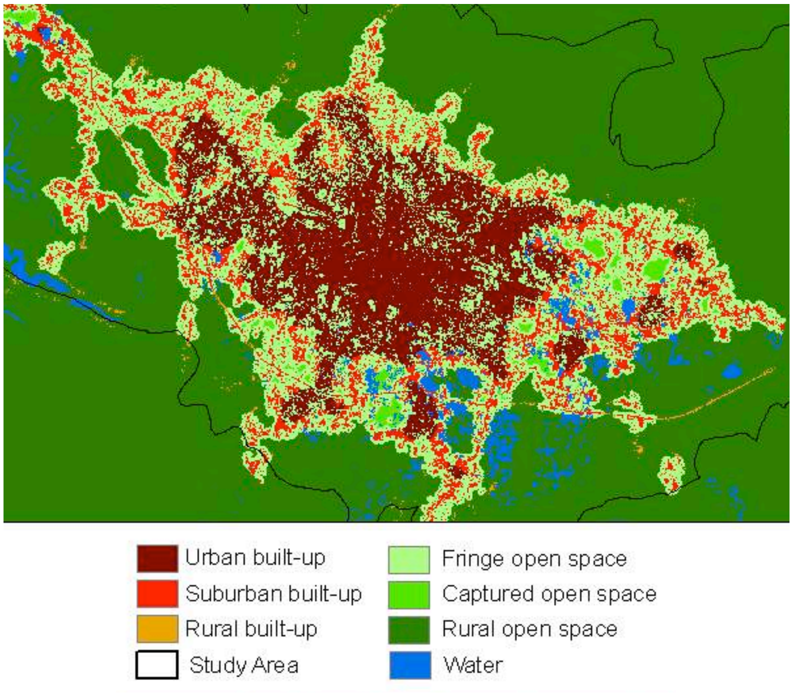


Figure 2.3: The built-up area the city footprint of Bandung, 1991



Even though the adoption of the 100–meter buffer for defining the city footprint may appear arbitrary from the perspective of providing us with a realistic outline of the city area, it is not quite arbitrary. In fact, as we shall see below, city footprint density is quite similar to urban tract density, when urban tracts are defined in the same way that the U.S. census defines them: contiguous tracts with density in excess of 1,000 persons per square mile (3.86 persons per hectare).

For most of the 120 cities in the global sample and the 30 cities in the global historical sample we were not able to obtain information at the census tract level. This information was available, however, for 20 U.S. cities for the period 1910-2000 and for 65 U.S. cities for the period 1950-2000. In these cities we were therefore able to study the change in three additional 'urban' tract density metrics over time. These three metrics are defined below. We first examine average urban tract density and maximum tract density and their relationships with the three density measures defined earlier.

Average 'urban' tract density

For U.S. cities, and for the few other cities in the global sample where population and area data were available at a more disaggregated spatial scale, we defined the urban land area of the metropolis as *the collection of 'urban' census tracts* within the set of administrative districts circumscribing the metropolitan area. In general, we use the term census tract loosely to mean a small geographical district within the administrative area of the city for which population data is available. The U.S. Census Bureau, for example, defines a census tract as follows:

> Census tracts are small, relatively permanent statistical subdivisions of a county…. Census tracts generally have between 1,500 and 8,000 people, with an optimum size of 4,000 people…. The spatial size of census tracts varies widely depending on the density of settlement. Census tract boundaries are delineated with the intention of being maintained over many decades…. However, physical changes in street patterns caused by highway construction, new developments, and so forth, may require occasional boundary revisions. In addition, census tracts occasionally are split due to population growth or combined as a result of substantial population decline. (U.S. Census, 2000)

Census tracts were defined as 'urban' when their densities exceeded a certain threshold. We used the U.S. Census threshold of 1,000 persons per square mile (3.86 persons per hectare) to include or exclude a tract from the urban area. The area thus defined by the U.S. Census is the area used by El Nasser and Overberg (2001), for example, in their measurement of U.S. sprawl. *Average Urban Tract Density* was thus calculated as the ratio of the total population in 'urban' tracts divided by their total area.

Maximum tract density

Maximum density in a single tract, most probably a tract with a very small area because tracts are designed to contain populations of similar size, is likely to be an outlier. We therefore defined maximum tract density as the ratio of the total population and the total area of the *densest one percent* of tracts. For purposes of comparison we also defined Maximum Built-up Area Density in a similar way. We looked at the one percent of tracts with the highest built-up area density. We then calculated the total population and the total built-up area in these tracts. The ratio of their total population and their total built-up area was defined as the Maximum Built-up Area Density in the city. Maximum Urbanized Area Density and Maximum City footprint Density we computed in a similar way.

Urban tracts necessary contain open space, be it the permanent open space of parks, playgrounds and conservation areas, or vacant land yet to be developed. It is also to be expected that the tracts further out from the city center are likely to contain a greater share of open space than those nearer the center, and that those in the center itself will be fully built and contain little or no open space. All in all, therefore, we should expect average tract density to be much lower than built-up area density, somewhat lower than urbanized area density, and most similar to city footprint density. On the other hand, because tracts with maximum densities tend to be fully built, we should expect all maximum densities to be similar to each other. This is, in fact, born by evidence from the year 2000 in the 10 U.S. cities that formed part of the global sample of 120 cities. Table 2.1 below shows the data for the four average density metrics and the four maximum density metrics for these 10 cities. Table 2.2 shows the results of fitting regression lines through the origin to data on average densities and maximum densities.

Table 2.1: Data for the four average density metrics and the four maximum density metrics in 10 U.S. cities, 2000

City	Average Density				Maximum Density			
	Tract	City Footprint	Urbanized Area	Built-up Area	Tract	City Footprint	Urbanized Area	Built-up Area
Los Angeles	25	28	31	38	250	250	250	248
Chicago	17	17	20	24	211	234	235	245
Modesto	16	17	21	27	50	50	50	57
Philadelphia	15	16	20	28	173	173	173	176
Houston	13	14	17	23	85	85	94	102
Pittsburgh	13	14	22	30	101	100	100	132
Springfield	12	12	15	22	52	52	52	55
Minneapolis	12	13	16	23	88	90	90	94
Tacoma	11	12	14	19	43	43	43	48
Cincinnati	10	11	17	24	66	68	68	76

Table 2.2: A comparison of tract densities with built-up area densities, urbanized area densities and city footprint densities in 10 U.S. cities, 2000

Dependent Variable	Independent Variable	Regression Coefficient when Constant=0	Standard Error	t-Statistic
Average Built-Up Area Density	Average Tract Density	1.73	0.09	19.56
Average Urbanized Area Density	Average Tract Density	1.32	0.04	29.72
Average City footprint Density	Average Tract Density	1.09	0.01	97.74
Maximum Built-Up Area Density	Maximum Tract Density	1.06	0.02	45.25
Maximum Urbanized Area Density	Maximum Tract Density	1.04	0.02	60.06
Maximum City footprint Density	Maximum Tract Density	1.03	0.01	73.39

A glance at these two tables reveals a systematic relationship between average densities. Average city footprint densities turn out to be quite similar to average tract densities. Average urbanized area densities are one-third higher than average tract densities and average built-up area densities are two-thirds higher. Maximum densities, regardless of how they are calculated, are quite similar because they typically capture densities in fully built urban tracts. Surely, we should not rush to generalize rules of thumb regarding the relationships between the different density metrics because it is quite clear, as we shall see later, that some of these relationships do change over time. What is abundantly clear, however, is that average tract densities tend to be considerably lower than built-up area densities. This is to be expected because urban tracts as the U.S. Census defines them and as we have defined them here include a considerable amount of open space captured within the built-up area of cities.

We can now introduce two more density metrics that will be used in our analysis of census tract data of U.S. cities between 1910 and 2000 and between 1950 and 2000:

The tract density gradient

Clark (1951) postulated and showed that urban population densities decline at a constant rate as distance from the centre increases. This would imply that density will decline exponentially as distance increases. This decline with distance has been amply documented for many cities. For cities for which tract data are available, following Clark, we graphed the average ring density[10] on the Y-axis against the distance of the center of that ring from the Central Business District (CBD) on the X-axis, and fit a negative

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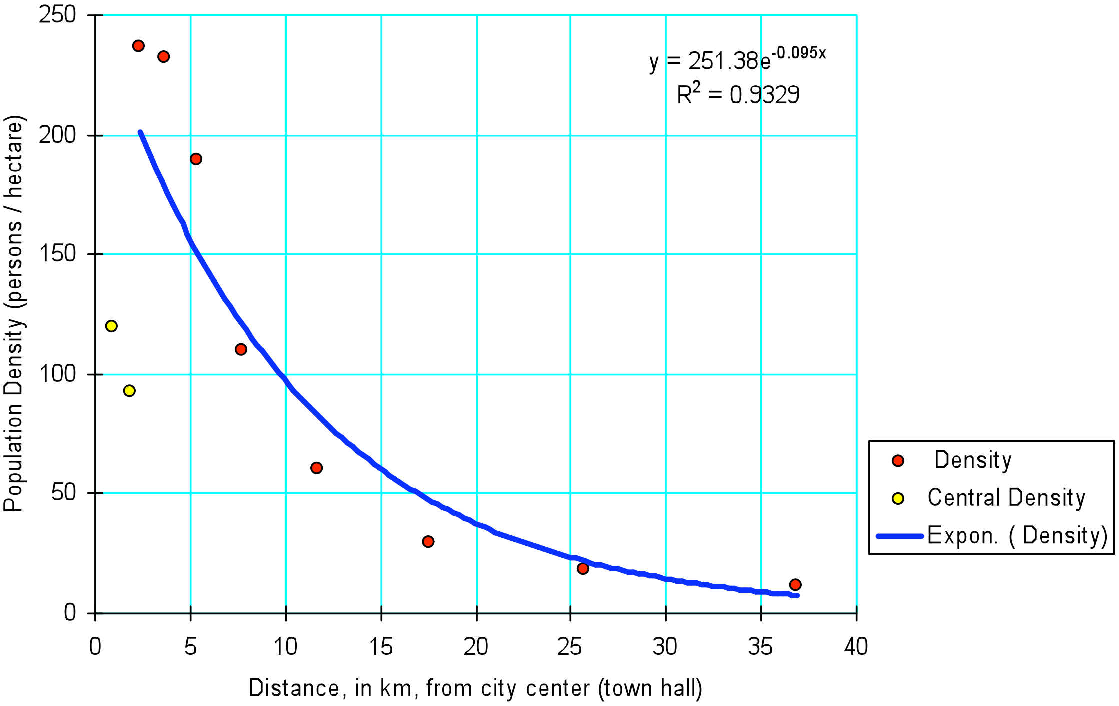
[10] We divided the city into ten rings with the width of each ring varying in proportion to the logarithm of the average distance of that ring from the city center.

exponential curve to the data. The slope of this curve is the tract density gradient. The average ring density (in red) and the density curve (in blue) for Paris in 2000 are shown in figure 2.4 below. Central ring densities, shown in yellow, are lower because of the proliferation of public, office and commercial buildings in the city center and were not included in estimating the density curve. For Paris that year, the gradient of the density curve was -0.095. It indicates that density declined by 9.5 percent, on average, as distance from the center of Paris increased by one kilometer.

Figure 2.4: The density curve and its function for Paris, 2000 (blue)



The density curve intercept

The intersection of the density curve as defined above with the Y-axis is the tract density curve intercept. For Paris in 2000 it was 251. It would indicate that the predicted maximum density at the center of Paris in 2000 was 251 persons per hectare, but that would be an unreliable estimate because the exponential density curve fails to account for the relative absence of residences at the centers of cities (as shown in figure 2.4 by the central ring densities in yellow).

To conclude this section, tables 2.3 and 2.4 below show the values for the tract density metrics introduced in this section[11] for nine cities in the global sample of 120 cities for

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[11] We also provide data for the median tract density in this group of cities. Median tract densities were found to be quite similar to average tract densities and will not be discussed further in this paper. The calculation of the density curve gradient and intercept for this table was somewhat different than that applied for the construction of the curve for Paris shown in figure 2.4. Here we simply plotted the density of each census tract on the Y-axis and the

which tract-level density data were available. Table 2.3 shows, for example, that the density gradient for Johannesburg is almost 0 indicating that there is virtually no different in density between the center of the metropolitan area and its periphery, largely due to sparse white suburbs in the center and the denser black townships on the urban periphery. Table 2.4 shows the correlations among these different metrics. Average tract density is found to be highly correlated with median tract density, maximum tract density, and the density curve intercept.

Table 2.3: A comparison of tract density metrics for 9 cities in the global sample, 2000

City	No. of	Tract Density			Density Curve		
		Average	Median	Maximum	Gradient	Intercept	R^2
Bandung	238	72	105	519	0.178	311	0.447
Tokyo	141	70	69	722	0.039	176	0.178
Paris	368	40	30	324	0.087	144	0.555
Johannesburg	631	30	22	270	0.006	26	0.003
Los Angeles	2601	25	35	145	0.019	59	0.224
Milano	153	24	15	80	0.037	34	0.236
Kampala	138	23	41	271	0.184	144	0.487
Chicago	1774	17	26	138	0.037	69	0.456
Houston	609	13	16	60	0.022	23	0.126

Table 2.4: Correlations among tract density metrics for 9 cities in the global sample, 2000

Variable	Tract Density			Density Curve	
	Average	Median	Maximum	Gradient	Intercept
Average	1.00				
Median	0.89	1.00			
Maximum	0.93	0.79	1.00		
Den. Curve Gradient	0.39	0.62	0.35	1.00	
Den. Curve Intercept	0.85	0.94	0.76	0.78	1.00

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distance of the centroid of that tract on the X-axis and fit a negative exponential curve to the scatter of points. The resulting curves are typically flatter than those obtained by the ring method used in figure 2.4 and their R^2 values are considerably lower.

Each one of the density metrics defined in this section sheds light on one or another important aspect of urban spatial structure. In sections IV-VII we report on our findings regarding the actual values that these metrics attain in different cities at different times.

III. SOURCES OF DATA

Three different data sets were developed and used in this study:

1. The global sample of 120 cities, 1990-2000;
2. The set of 20 U.S. cities, 1910-2000 and of 65 U.S. cities, 1950-2000; and
3. The global sub-sample of 30 cities, 1800-2000.

The three data sources complemented each other. The study of density and density change in the global sample of cities 120 cities between 1990 and 2000 was initially motivated by the concern with urban growth management the world over and especially in developing countries. It focused on assembling a good global database on urban extent and the rate of urban expansion. More specifically, it was also motivated by the need to bring together the study of urban extent and expansion in both developed countries and developing countries under one umbrella, so that they can be effectively studied in a common comparative framework.

In an earlier publication of the initial results pertaining to this data set, *The Dynamics of Global Urban Expansion* (Angel et al, 2005), the authors and their colleagues reported on a global pattern of decline in average built-up area densities in an initial group of 90 cities in the global sample for which results were available. In the present study we report on the global decline in densities between 1990 and 2000 in the entire sample in more detail and in a more rigorous manner, using new information to explain the variations in density and density change among cities.

While the statistical results concerning the decline in density between 1990 and 2000 in cities the world over are extremely robust, as we shall see below, it is still possible to argue that this decline was only temporary, the result of specific conditions that existed in the 1990s. To explore this contention, we sought to examine density change over a longer time period. To this effect, we used a second data set: census tract data for 20 U.S. cities extending back to 1910 and for 65 U.S. cities dating back to 1950. Using this data set also made it possible to study change in other density metrics—the maximum tract density, the tract density gradient, and the tract density curve intercept—to see whether changes in these density metrics paralleled changes in average tract densities. If that were the case, it would suggest that the investigation of average densities in this and similar studies should give us good indications about the probable behavior of other density metrics for which information is more difficult to come by. As we shall see below, we found a pattern of long-term decline and similar patterns of change over time in all density metrics in U.S. cities during the twentieth century.

It would still be possible to argue that the decline in average tract density and other associated tract density metrics is a U.S. phenomenon—another instance of American exceptionalism. Sprawl, after all, is often considered to be a purely American phenomenon. In his excellent study, *Crabgrass Frontier: The Suburbanization of the United States*, Kenneth Jackson concludes that specific and unique factors have led to the creation of low-density suburbs in the U.S. that are different from other places and thus exceptional:

> [E]conomic factors, along with racial prejudice and a pervasive fondness for grass and solitude, made private and detached houses affordable and desirable to the middle class, and they produced a spread out environment of work, residence, and consumption that has thus far been more pronounced in the United States than elsewhere. (Jackson, 1985, 296)

To examine density change on a *global* scale over a longer period of time, we constructed a third data set of 30 cities, which was largely a sub-sample of the global sample of 120 cities. This sub-sample included cities from all world regions, and for this set of cities we calculated the average population densities of their urbanized areas for the period 1800-2000 using historical maps and historical demographic estimates. Again, as we shall see below, we found a regular pattern of density change with a long period of recent decline lasting, on average, over a century. In the following paragraphs we report on these three data sets in greater detail.

The global sample of 120 cities, 1990-2000

In an earlier study, we identified a total of 3,945 cities that had populations of 100,000 or more in the year 2000, and were home to a total of 2.12 billion people or three-quarters of the world's urban population at that time. The global sample of 120 cities is a stratified sample of cities from this universe. The sample selection is described in detail in Angel el al (2005, Chapter II). We selected cities from nine geographic regions, four population size classes and four per capita income classes. The list of cities appears in table 1 and their locations and regions appear in figure 3.3.

The reader should note that we sampled these categories by population, rather than by the number of cities. That is, we divided the total population in the universe into four city size categories, for example, and selected one-quarter of the cities in the sample from each size category. As a result, cities in the smallest size category—100,000 to 528,000—were under-represented. Of the total universe of cities, 3,131 cities, or 79 percent, were in this category. And although one-quarter of the sample (29 cities) was in this category, they only represented 0.9 percent of the cities in this category. In comparison, cities in the largest size category—4.18 million or more—were over-represented. 27 cities, or 48 percent, were included in the global sample.

For each city in the global sample, we obtained two medium-resolution *Landsat* satellite images, one as close as possible to 1990 and one as close as possible to 2000. These images were classified into built-up and non-built-up 30m^2 pixels, using a thematic extraction algorithm described in detail in Angel et al (2005, Chapter III). Potere, using 10,000 Google Earth validation sites, found that pixels identified as built-up in our sample were found to be built-up in Google Earth 91 percent of the time. Conversely, pixels identified as urban in Google Earth were identified as urban in our sample 89 percent of the time (Potere, 2008, 61). In the terms commonly used in satellite imagery analysis, our sample was thus found to have high producer and user accuracy. Its estimates of the built-up area of cities should thus be considered quite reliable.

For each city in the sample, we obtained population figures for two census periods for administrative districts encompassing the built-up areas of the cities in the sample, one circa 1990 and one circa 2000. We interpolated the population for the dates corresponding to the satellite images for each city assuming a constant rate of population growth between census periods. For most cities, we could only obtain population figures for relatively large administrative districts, sometimes containing a much larger area than the built-up area of the city. For each city we calculated the total population within the smallest set of administrative districts containing the main contiguous built-up areas of the city.

Using ArcGIS software, we calculated the built-up area, the urbanized area and the city footprint within the relevant administrative districts. In some cases, when districts were larger than those covered by the *Landsat* images, we had to estimate the built-up area outside the image using a distance decay function (see Angel at al, 2005, 53-54). Then, using the population figures for these districts, we calculated the average built-up area density, the average urbanized area density, and the average city footprint density for each city in the sample, and interpolated values for these metrics for 1990 and 2000.

Figure 3.1: The nine regions, the global sample of 120 cities (black dots) and the global sub-sample of 30 cities (red squares)

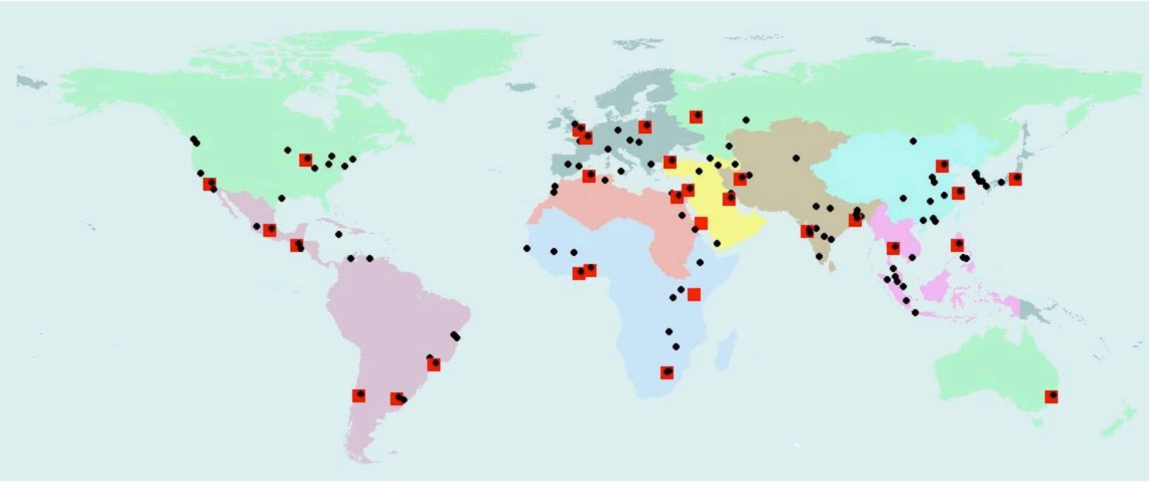


Table 3.1: The global sample of 120 cities, 1990-2000

City, Country	Population 2000	GNP/cap in PPP ($), 1995
East Asia & Pacific		
Shanghai, China	12,900,000	3,547
Beijing, China	10,800,000	3,547
Seoul, Korea	9,887,779	13,958
Hong Kong, China	6,927,000	3,547
Guangzhou, China	3,893,000	3,547
Pusan, Korea	3,830,000	13,958
Zhengzhou, China	2,070,000	3,547
Yulin, China	1,558,000	3,547
Yiyang, China	1,343,000	3,547
Leshan, China	1,137,000	3,547
Ulan Bator, Mongolia	738,000	1,491
Changzhi, China	593,500	3,547
Anqing, China	566,100	3,547
Ansan, Korea	549,900	13,958
Chinju, Korea	287,100	13,958
Chonan, Korea	114,600	13,958
Developed Countries		
Tokyo, Japan	26,400,000	23,828
Paris, France	9,624,000	23,225
London, England	8,219,226	22,652
Milano, Italy	4,251,000	22,875
Madrid, Spain	4,072,000	18,314
Warszawa, Poland	2,269,000	9,114
Vienna, Austria	2,070,000	25,694
Budapest, Hungary	1,825,000	11,301

City, Country	Population 2000	GNP/cap in PPP ($), 1995
Latin America & Caribbean (cont.)+D35		
Tijuana, Mexico	1,167,000	8,182
Kingston, Jamaica	912,500	3,370
Ribeirão Preto, Brazil	502,333	6,781
Valledupar, Colombia	274,300	5,618
Guarujá, Brazil	269,104	6,781
Ilhéus, Brazil	161,898	6,781
Jequié, Brazil	130,207	6,781
Northern Africa		
Cairo, Egypt	10,600,000	3,253
Alexandria, Egypt	4,113,000	3,253
Casablanca, Morocco	3,541,000	3,195
Algiers, Algeria	2,760,740	4,979
Marrakech, Morocco	736,500	3,195
Port Sudan, Sudan	384,100	1,512
Aswan, Egypt	219,017	3,253
Tébessa, Algeria	163,279	4,979
Land-Rich Developed Countries		
Los Angeles, U.S.A.	16,373,645	31,338
Moscow, Russia	9,321,000	6,644
Chicago, U.S.A.	9,157,540	31,338
Philadelphia, U.S.A.	6,188,463	31,338
Houston, U.S.A.	4,669,571	31,338
Sydney, Australia	3,664,000	24,013
Minneapolis, U.S.A.	2,968,806	31,338
Pittsburgh, U.S.A.	2,358,695	31,338

City, Country	Population 2000	GNP/cap in PPP ($), 1995
South & Central Asia (cont.)		
Vijayawada, India	1,237,000	2,220
Rajshahi, Bangladesh	1,016,000	1,427
Ahvaz, Iran	997,000	5,460
Shimkent, Kazakhstan	360,100	4,215
Jalna, India	244,523	2,220
Gorgan, Iran	188,710	5,460
Saidpur, Bangladesh	114,000	1,427
Southeast Asia		
Manila, Philippines	10,900,000	3,668
Bangkok, Thailand	7,281,000	5,846
Ho Chi Minh City, Vietnam	4,615,000	1,854
Singapore, Singapore	3,567,000	21,832
Bandung, Indonesia	3,409,000	2,807
Medan, Indonesia	1,879,000	2,807
Palembang, Inbdonesia	1,422,000	2,807
Kuala Lumpur, Mnalaysia	1,378,000	8,217
Cebu, Philippines	718,821	3,668
Ipoh, Malaysia	566,211	8,217
Bacolod, Philippines	429,076	3,668
Songkhla, Thailand	342,475	5,846
Sub-Saharan Africa		
Addis Ababa, Ethiopia	2,639,000	648
Johannesburg, South Africa	2,335,000	8,667
Accra, Ghana	1,976,000	1,804
Harare, Zimbabwe	1,752,000	2,372

Fukuoka, Japan	1,341,470	23,828	Cincinnati, U.S.A.	1,979,202	31,338	Ibadan, Nigeria	1,731,000	808
Thessaloniki, Greece	789,000	15,280	Tacoma, U.S.A.	596,415	31,338	Pretoria, South Africa	1,508,000	8,667
Palermo, Italy	684,300	22,875	Springfield, MA, U.S.A.	591,932	31,338	Kampala, Uganda	1,212,000	1,164
Sheffield, England	640,048	22,652	Astrakhan, Russia	486,100	6,644	Bamako, Mali	1,131,000	683
Leipzig, Germany	446,491	23,913	Modesto, U.S.A.	446,997	31,338	Ouagadougou, Burkina Faso	1,130,000	931
Akashi, Japan	293,117	23,828	St. Catharines, Canada	389,600	25,456	Ndola, Zambia	568,600	715
Le Mans, France	194,825	23,225	Victoria, Canada	317,506	25,456	Banjul, Gambia	399,386	1,542
Castellon de la Plana, Spain	144,500	18,314	Oktyabrsky, Russia	111,500	6,644	Kigali, Rwanda	351,400	1,019
Latin America & Caribbean			**South & Central Asia**			**Western Asia**		
Mexico City, Mexico	18,100,000	8,182	Mumbai, India	18,100,000	2,220	Istanbul, Turkey	9,451,000	5,731
Sao Paulo, Brazil	17,800,000	6,781	Kolkota, India	12,900,000	2,220	Tel Aviv, Israel	2,181,000	18,895
Buenos Aires, Argentina	12,600,000	11,131	Dhaka, Bangladesh	12,300,000	1,427	Baku, Azarbaijan	1,936,000	2,358
Santiago, Chile	5,538,000	8,412	Teheran, Iran	7,225,000	5,460	Sana'a, Yemen	1,653,300	760
Guadalajara, Mexico	3,908,000	8,182	Hyderabad, India	6,842,000	2,220	Yerevan, Armenia	1,406,765	2,222
Guatemala City, Guatemala	3,242,000	3,633	Pune, India	3,489,000	2,220	Kuwait City, Kuwait	1,190,000	14,471
Caracas, Venezuela	3,153,000	5,174	Kanpur, India	2,450,000	2,220	Malatya,Turkey	437,000	5,731
San Salvador, El Salvador	1,408,000	4,307	Jaipur, India	2,145,000	2,220	Zugdidi, Georgia	104,947	1,722
Montevideo, Uruguay	1,236,000	8,130	Coimbatore, India	1,292,000	2,220			

To explain the variation in density and density change in the global sample of cities with the use of multiple regression models, we used additional data from one primary source and from several secondary sources. The authors, together with several other colleagues, conducted a field survey in each one of the cities in the sample, using a local informant for each city. Informants had to fill in a survey questionnaire that requested information on the most recent census; on selected prices and wages; on the status of metropolitan area planning, zoning, land subdivision, and enforcement; on the housing and land markets; on characteristics of three typical dwelling units on the market; on characteristics of informal settlements; on a recently-occupied informal settlement visited; on characteristics of three dwelling units in the informal settlement visited; and on the availability and characteristics of housing finance. This survey was used as a primary data source for the cities in the global sample.

In addition, we collected data at the national level from a variety of secondary sources. Finally, we supplemented these data with data on *buildable land* in and around these cities. We first created a circle about the Central Business District of each city, with an area four times the size of its Urbanized Area. Using slope and water data, we then calculated the share of land in the circle that had a slope of less than 15°.

The set of 20 U.S. cities, 1910-2000, and 65 U.S. cities, 1950-2000

Historical population density data at the census tract level for U.S. cities and metropolitan areas is now readily available in digital maps (shapefiles) that can be analyzed using ArcGIS software. 20 U.S. cities were chosen for analysis for one principal reason: the availability of census tract digital maps (shapefiles) and population data extending as far back as possible, for some almost a full century. For seven of these cities—Baltimore, Boston, Chicago, Cleveland, New York, Pittsburgh, and St. Louis—tract density maps are available from 1910 onwards. Because of data loss, only three cities—Chicago, Cleveland, and Milwaukee—have tract density maps for 1920. For eleven additional cities—Buffalo, Cincinnati, Columbus, Detroit, Indianapolis, Los Angeles, Milwaukee, Nashville, St. Paul, Syracuse, and Washington—tract density maps are available from 1930 onwards, and for two of additional cities—Minneapolis and Philadelphia—tract density maps are available from 1940 onwards. For a more detailed study of the change in the rate of decline in average tract density over time, we also included 45 additional cities for which census tract data is available from 1950 onwards. These were cities and metropolitan areas that had populations in their urbanized area (all census tracts within their metropolitan areas with populations in excess of 1,000 persons per square mile) in excess of 50,000 in the year 2000, and that had non-zero populations in their urbanized areas from 1950 onwards.

We chose to focus on this data set for three reasons. First, it was the only readily available ArcGIS-compatible data set that included information on historical urban densities at the tract level, going back to 1910. That meant that we could study the change in density over a longer period of time than the single decade 1990-2000 for which we have data for a global sample of cities. Second, the availability of historical data on tract densities made it possible to study change over time of several density metrics over and above average tract density, and to determine the extent to which the change over time in various tract density metrics paralleled the change over time in average tract density. The density metrics to be compared to average tract density were maximum tract density, the tract density gradient, and the tract density curve intercept, all as defined earlier.

Third, the availability of density data for several decades made it possible to investigate both the average rate of density change over time and the second-order changes in that rate of change. Namely, it made it possible to investigate whether the rate of density change—whether positive or negative—was accelerating or slowing down over time. This in important because if we are interested in projecting urban densities into the future, we should not simply assume that densities will remain the same, nor that they will decline or increase at a constant rate.

The outer boundaries of the Urbanized Areas (UAs) of U.S. cities in 2000 were taken to be the outer boundaries of the cities studied. As noted earlier, the U.S. Census defines an

Urbanized Area as a set of contiguous census block groups or census tracts with a minimum density of 1,000 persons per square mile that together encompass a population of at least 50,000 people. The Urbanized Areas in the 2000 U.S. Census were used to delimit the 20 and 65 U.S. metropolitan areas used in this part of the study. Census tract shapefiles for 2000 were downloaded from the Environmental Systems Research Institute (ESRI). (http://arcdata.esri.com/data/tiger2000/tiger_download.cfm) Historical census tract shapefiles and historical population data for these census tracts were downloaded from the National Historic Geographic Information System (http://www.nhgis.org/). City Hall, identified in Goggle Earth, was taken to be the center of the city for purposes of calculating the parameters of its density curve.

Finally, there were 10 U.S. cities that were both in the global sample of 120 cities and in the set of U.S. cities. For these cities, we have tract density data, as well as densities pertaining to the built-up area, the urbanized area, and the city footprint for each tract for the year 2000. By comparing these densities in the previous section, we hinted at the relationships between the different metrics for measuring average densities when only one or another set of data is available. The comparisons between average tract densities and average built-up area densities, urbanized area densities, and city footprint densities for these 10 cities were given in tables 2.1 and 2.2 earlier. Also given there were the comparative values for maximum densities in these cities.

The global sub-sample of 30 cities, 1800-2000:

A global historical sub-sample of 30 cities was created to explore long-term changes in urban population density from the onset of the Industrial Revolution circa 1800 until the end of the twentieth century. This sample was created to determine whether the long-term decline in average density observed in the set of 20 U.S. cities was due to American exceptionalism, or was part of a global phenomenon. The selection of cities for historical analysis was guided by three factors: their inclusion in the global sample of 120 cities, their regional distribution, and the availability of maps depicting their urbanized area at 20-25 year intervals. Inclusion in the 120-city sample ensured that the sub-sample was indeed representative and that urbanized area maps for the period 1990-2000 were available. As high quality historic maps depicting the urbanized areas of cities were difficult to find, they needed to be spaced at intervals for which maps were realistically available. Twenty-five year intervals were deemed sufficient to analyze changes in population, income, and urbanized area over the 200-year period.

Three cities—Jeddah, Lagos, and Nairobi—do not belong to the 120-city sample but were included in the 30-city sub-sample to create an even global distribution. Strict adherence to the 200-year window disqualified a great number of cities, as many cities in the 120 sample did not exist in 1800. For a few cities in the sub-sample—Chicago, Nairobi, Sao Paulo, and Tel Aviv—our investigation began in the middle of the nineteenth century or the beginning of the twentieth century.

The assembly of maps for the study was greatly facilitated by the fact that many map collections were recently digitized and put on the Internet. Library and Internet research as well as correspondence with academics and planning professionals yielded all of the historical maps used in this study. Particularly helpful resources include the New York Public Library Map Room, The David Rumsey Online Map Collection, and the Map History/History of Cartography section of the WWW-Virtual Library. For maps to be included in the study they needed to depict the totality of the built-up area of the metropolitan agglomeration. At earlier dates, this was less of an issue as the spatial extent of cities was well defined and their shape relatively compact and therefore easily recognizable: a map of the city typically captured the entire metropolitan agglomeration for the agglomeration was relatively small and self-contained. Throughout the twentieth century, however, metropolitan areas grew many times in size and defining the boundaries of their agglomerations became significantly more difficult.

Road maps and administrative boundary maps, while plentiful in number, were not used if they failed to show built-up areas or urbanized areas. In addition to the built- up area/urbanized area requirement, maps needed to contain sufficient *reference points* that could be identified on Google Earth so that historic maps could be stretched so as to fit a geographically accurate representation of space such as Google Earth. This process, known as *georeferencing*, ensured that maps of different sizes and at different scales could be accurately compared to one another. Reference points included street intersections, bridges, and historic buildings such as churches, well-defined administrative boundaries, or geographic features such as a land protrusion into a body of water or a bend in a river. We were acutely aware that streets and rivers do change their course over time and considerable efforts were made to ensure that we had properly identified reference points on Google Earth.

Ultimately, all maps were converted to digital formats so that they could be manipulated with geographic information system (GIS) software, specifically with ArcGIS software. Paper maps in atlases, books, and encyclopedias, or loose maps, such as military maps, topographic maps, and government surveys, were converted via high-resolution scanners or digital photography. Images on the Internet are already in digital format and were downloaded or copied. In several instances, books, atlases, and maps found on the Internet were sought in their original form to obtain a higher resolution image.

Once all historic maps for a city were successfully georeferenced, we created files for the spatial extent of the urbanized area by tracing the urbanized area over the georeferenced map. This procedure required a certain level of interpretation but we are confident that our urbanized area files provide relatively accurate representations. Due to the great variety in map quality depicting the built-up area and urbanized area of cities, some estimates of the urbanized area of cities are probably more precise than others.

Arriving at an estimate of population density required population data in addition to built-up area data. A particular concern in the acquisition of population data was the degree to which the reported population matched the spatial extent of the urbanized area. Two publications, the United Nation's *World Urbanization Prospects* and Chandler and Fox's *4000 Years of Urban Growth* proved invaluable to our investigation of historical urban populations. Both works report population at the level of the urban agglomeration for

1950 – 2000 and 1800 – 1925 respectively. Despite its comprehensive coverage, many cities in the sub-sample were not reported in the Chandler study and additional research was needed to obtain the populations of several cities for the period 1800–1950.

The challenges inherent in historical urban population research mirrored those in the identification of urbanized area: at earlier dates the correspondence between population figures and the urbanized area was much clearer while at later dates it became more difficult to discern whether the reported population matches the extent of the urbanized area. A degree of discretion was thus needed to determine which population figures matched which urbanized areas. Population figures were culled from a variety of sources including historical studies on cities, and most notably, historical demography websites that compile population statistics reported in atlases, gazetteers, encyclopedias and geographic dictionaries over the last 200 years. Admittedly, there is still room for debate whether the reported population matches the actual population for the urbanized area of historical maps in each particular case. Nevertheless, we are confident that the potential for error is not so large that it could distort our reported overall trends in historical population densities.

Digitized maps of the urbanized area for each city for each date were created, and the area of each urbanized area file was calculated using ARCGIS software. The population associated with each map was interpolated from available historical population data, assuming a constant population growth rate in the intervening period. The calculation of average population density was then a simple matter of dividing population by area. Altogether, a total of 159 secondary sources were used to extract historical maps (see map references), and several sources were composite maps of the built-up area of a given city for several dates. Maps from all these sources were digitized. Together with 54 additional maps for periods circa 1990 and 2000 of the 27 cities in the global sample, a total of 261 maps were used to calculate average population densities and their change over time in the 30 cities in the sub-sample, an average of 8.7 maps per city approximately 19±1 years apart. A sample of the maps used to map and calculate the urbanized areas of Moscow, for example, is shown in figure 3.1.

Figure 3.1: Maps of Moscow in 1808, 1836, 1893 and 1914 showing its urbanized area

Table 3.2: The Global Sub-Sample of Cities, 1800- 2000

	City Population		
City, Country	1800	1900	2000
East Asia			
Beijing, China	1,100,000	1,100,000	9,782,000
Shanghai, China	90,000	619,000	13,243,000
Tokyo, Japan	685,000	1,497,000	34,450,000
Southeast Asia			
Bangkok, Thailand	45,000	267,000	6,332,000
Manila, Philippines	77,000	190,000	9,950,000
South and Central Asia			
Kolkata, India	162,000	1,085,000	13,058,000
Mumbai, India	140,000	780,000	16,086,000
Tehran, Iran	30,000	150,000	6,979,000
West Asia			
Istanbul, Turkey	570,000	900,000	8,744,000
Jeddah, Saudi Arabia	20,000	30,000	2,509,000
Kuwait City, Kuwait	10,000	20,000	1,549,000
Tel Aviv-Jaffa, Israel	5,000	45,762	2,752,000
Western Europe			
London, England	861,000	6,480,000	8,225,000
Paris, France	547,000	3,300,000	9,692,000
Eastern Europe			
Moscow, Russia	248,000	1,120,000	10,103,000
Warsaw, Poland	75,000	784,000	1,666,000
North Africa			
Algiers, Algeria	73,000	314,000	2,754,000
Cairo, Egypt	186,000	595,000	10,391,000
West Africa			
Accra, Ghana	10,000	17,386	1,674,000
Lagos, Nigeria	<5,000	40,000	8,422,000
East and South Africa			
Johannesburg, S. Africa	0	173,000	4,695,165
Nairobi, Kenya	0	5,000	2,233,000
North America			
Chicago, U.S.A.	0	1,698,575	8,333,000
Los Angeles, U.S.A	150	102,479	11,814,000
Central America			
Guatemala City, Guatemala	25,000	74,000	908,000
Mexico City, Mexico	128,000	368,000	18,066,000
South America			
Buenos Aires, Argentina	34,000	806,000	11,847,000
Santiago, Chile	21,000	290,000	5,326,000
Sao Paulo, Brazil	10,858	239,000	17,099,000
Australia/Oceania			
Sydney, Australia	2,000	478,000	4,078,000

IV. DENSITY DIFFERENCES IN THE GLOBAL SAMPLE OF 120 CITIES, 2000

The relationships between built-up area densities, urbanized area densities, and city footprint densities in the global sample

We have noted earlier that the measurement of average urban population density in a city with a known population yields different results depending on the denominator—the area considered to be 'the city' in question. We measured the density of the 120 cities in the global sample in three different ways, using three different area measures for each city: the built-up area, the urbanized area (containing the open space captured by the built-up area), and the city footprint (containing the open space within 100 meters of the urban and suburban built-up area of the city). Clearly, the built-up area is the smallest of the three and hence built-up area densities are expected to be higher than urbanized area densities and those, in turn, are expected to be higher than city footprint densities.

The first question we must ask ourselves is: Are there systematic relationships between these three measures of density in the global sample of cities? In this section, we begin to explore these relationships. We first note that all three-density metrics are highly correlated. The Pearson correlations between built-up area density and urbanized area density in both 1990 and 2000 were both above 0.995; and the correlations of both densities with city footprint density in both dates were all above 0.955.

Second, we note that the ratio between the mean urbanized area and the mean built-up area of cities in the sample was 1.22 in 1990 and 1.21 in 2000. On average, therefore, urbanized open space added some 21-22 percent to the area of cities over and above their built-up areas in 1990-2000. In other words, the built-up area of cities captured, on average, one-fifth of its area in open space. As a result, mean urbanized area density was 82 percent of built-up area density in 1990 and 83 percent in 2000 (see figure 4.1).

Third, we note that the ratio between the mean city footprint and the mean built-up area of cities in the sample was 2.01±0.06 in 1990 and 1.93±0.07 in 2000. Whether the difference between the two ratios is statistically significant is an issue that will be discussed later. For now, we should take note that, on average, city footprints that include the fragmented and affected open spaces in and around cities appear to *double* the area of cities. City footprint densities should therefore be expected to be *half* those of built-up area densities: mean city footprint densities were 51 percent and 53 percent of the mean built-up area density in 1990 and 2000 respectively. This relationship is shown graphically in figure 4.2.

Figure 4.1: The relationship between built-up area and urbanized area densities in the global sample of cities in 1990 and 2000
(developing countries in red and developed countries in yellow)

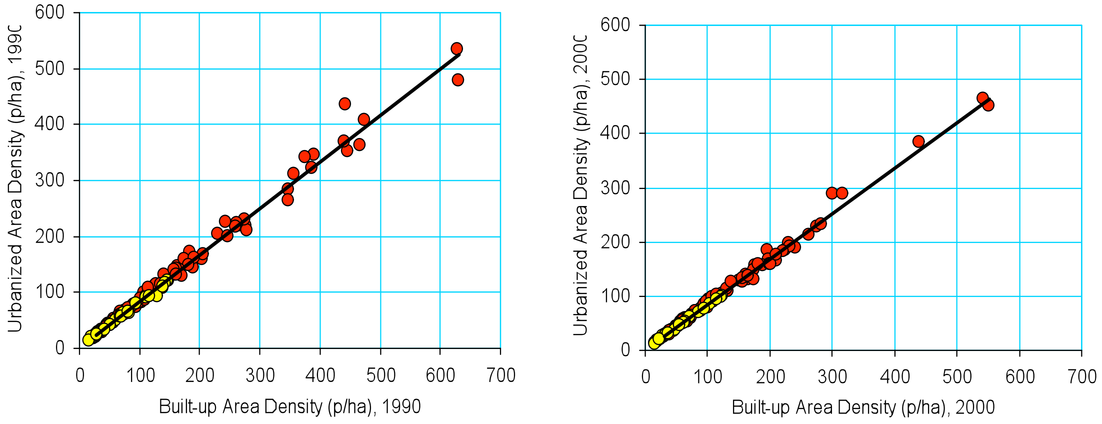
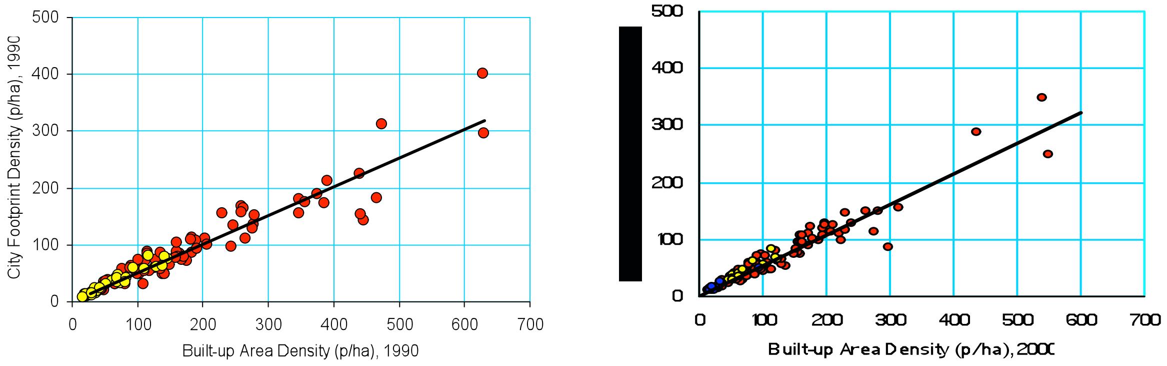


Figure 4.2: The relationship between built-up area and city footprint densities in the global sample of cities in 1990 and 2000 (developing countries in red and developed countries in yellow)



The remaining discussion in this section will focus on built-up area densities and their decline over time in the global sample of cities. At the end of the section we shall briefly return to the discussion of urbanized area densities and city footprint densities and their parallel declines in the global sample between 1990 and 2000.

Density differences among cities in regional sub-groups

As noted earlier, the 120 cities in the global sample were selected from nine geographic regions. We can divide these regions into two major groups—the developing countries and the developed countries. 88 cities in the global sample were located in developing countries and 32 in developed countries. We can further divide the *developed* countries into two groups—land-rich developed countries and other developed countries. Land-rich developed countries were defined as those countries that had more than 6,000m^2 per capita in arable land and permanent crops in the year 2000.[12] 16 cities in the global sample were located in land-rich developed countries—the U.S., Canada, Australia and the Russian Federation—and 16 in other developed countries. We conducted independent-samples t-tests to determine whether average built-up areas densities in the cities in these regional groupings were significantly different from each other in 2000.

Independent sample t-tests show that average built-up area densities in cities in developing countries and in cities in developed countries were significantly different: In 2000, for example, they averaged 135±11 persons per hectare in the former and 49±6 p/ha in the latter. In fact we can say with a 95 percent level of confidence that the average density in the universe of developing country cities in 2000 was 86±24 persons per hectare higher than that of cities in developed countries.

Similar independent sample t-tests also showed that densities in cities in the three regional groupings were significantly different from each other in both 1990 and 2000.

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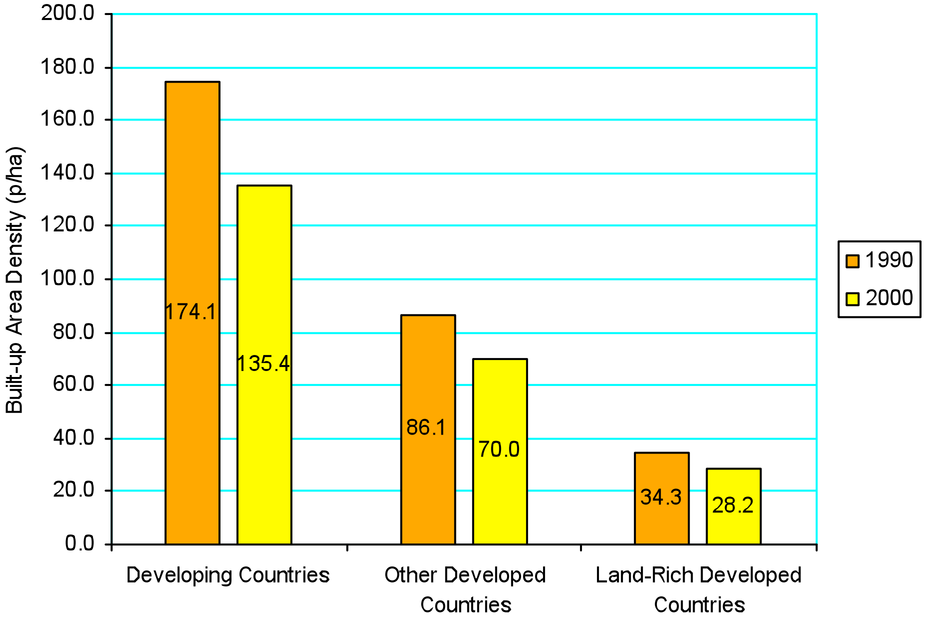
[12] The only land-rich *developing* country in the global sample was Argentina and we therefore refrained from dividing developing countries into land-rich developing countries and other developing countries.

The average built-up area density in cities in developing countries in 1990 was 174±14 persons per hectare, in other developed countries it was 86±9 p/ha, and in land-rich developed countries it was 34±7 p/ha. The average built-up area density in cities in developing countries in 2000 was 135±11 persons per hectare, in other developed countries it was 70±8 p/ha, and in land-rich developed countries it was 28±5 p/ha (see figure 4.3).

Figure 4.3: Density differences among cities in three regional sub-groups, 1990 and 2000



In general terms, we can therefore conclude that in both 1990 and 2000 average built-up area densities in developing countries were roughly double those in cities in other developed countries, and that densities in other developed countries were roughly double, in turn, those of land-rich developed countries.

Hypotheses that may explain density differences in the universe of cities

The significant differences in average built-up area densities among cities in the three regional subgroups already suggest two explanations of why densities vary from city to city in the global sample: income matters and the availability of plenty of land for urban expansion matters. In general, cities in countries with higher levels of development, measured, say, by GDP per capita, are found to have significantly lower densities; and cities in land-rich countries, measured, say, by the amount of arable land per person in the country, are found to have lower densities than cities in countries with lower amounts of arable land per capita. Both findings make intuitive sense. The higher the per capita income in the country, the more resources are available for building larger houses, for having wider roads, more expansive workplaces and shopping areas, larger gardens and parks, and more extensive public facilities. The more arable land in the country, the less likely is land to be hoarded, the cheaper it will be to extend cities into agricultural areas, and the less public and official resistance will likely be encountered in efforts to convert rural land to urban use.

To test and explain density differences among cities more rigorously, we posited a number of hypotheses regarding variations in density among cities and to test these hypotheses using a set of multiple regression models with average built-up area density in the city in 2000 as their dependent variable and a host of explanatory factors as independent variables.

The theory seeking to explain the average population density of urban areas and its change over time is not fully developed. Colin Clark observed in his classic paper on urban population densities (1951, 495) that there are

> two possibilities for development, if the population is increasing. Either transport costs are reduced, enabling the city to spread out; or they cannot be reduced, in which case density has to increase at all points.

A host of factors have been put forth in an effort to explain variations in density across space and time. These can be divided into five broad groups: Physical factors, demographic factors, economic factors, technological factors, and political factors.

The traditional urban economic model developed by Alonso, Muth, and Mills in the 1960s (Alonso, 1964; Muth, 1969; Mills, 1972) provides a good foundation for explaining the effects of most of these factors on the average density in the city. We will not describe the model in detail here: Suffices to say that it makes possible the formulation of several important hypotheses regarding the average population densities of cities. These hypotheses are presented here in their negative form, as null hypotheses to be rejected by statistical testing.

Hypothesis 1: *Geographic constraints on urban expansion that may increase transport costs do not increase average densities*. The variable used to test this hypothesis was **Buildable Land**, defined as the share of dry land with a slope less than 15 in a circle about the center of the city with an area equal to four times the urbanized area of the city in 2000.

Hypothesis 2: *Larger cities that may have higher aggregate demand for land that results in higher average land prices do not have higher average densities.* The variable used to test this hypothesis was the **City Population** in 2000.

Hypothesis 3: *Higher incomes that may increase the consumption of land by households and firms do not reduce average densities.* The variable used to test the income hypothesis was **Income** with a ten-year time lag, defined as the national per capita Gross Domestic Product (GDP) per capita in 1990.

Hypothesis 4: *Lower transport costs do not reduce average densities.* The variables used to test this hypothesis were: (1) **Car Ownership**, defined as the national car ownership rate in 1990, (2) **Gasoline Price**, defined as the price of 1 liter of Super gasoline in 2000 in Purchasing Power Parities; and (3) the **1900 Population Share**, defined as the share of the population of the city in 2000 that lived there in 1900, as a proxy variable for the share of the city built before the advent of the private automobile.

Hypothesis 5: *Ample and cheap agricultural lands on the urban periphery do not reduce average densities.* The variable used to test this hypothesis was **Arable Land**, defined as the national arable land and land in permanent crops per capita in 2000.

Hypothesis 6: *The availability of water from wells that may free new development from dependence on municipal water supplies does not reduce average densities.* The variable used to test this hypothesis was **Well Water**, defined as the share of households in the city that obtained their water from wells rather than from a public water supply in 2005.

Hypothesis 7: *Cities with larger households that may consume less land per person do not have higher average densities.* The variable used to test this hypothesis was the average **Household Size** in the city in 2005.

Studies in urban ecology have often noted that in some countries, the poor occupy the centers of cities while the rich move to the suburbs, while in other countries the rich stay in the center and the poor occupy the periphery. Schnore (1965), for example, comments on this difference as a key difference in urban spatial structure between North and South America. Chattergee (1960, 233, quoted in Berry, Simmons and Tennant 402) comments on a similar attractiveness of the center to rich people in India:

> The influence of the caste system is reflected in the usual concentration of the higher castes in the central areas of good residential localities, while the lower caste groups usually occupy the fringe.

The preference of the rich to live in urban centers would cause them to live at higher density and consume less land, and we should therefore expect cities where this pattern exists to have higher densities than cities where the rich live in suburbs. This has lead to the formulation of hypothesis 8:

Hypothesis 8: *Cities with unattractive centers do not have lower average densities.* The variable used to test this hypothesis was the **Attractive Center Index**, defined as a composite measure of survey answers to questions about income, gentrification and crime in the city center in 2005.

The traditional theory does not address additional factors that affect the average density in cities. Several of those merit consideration:

Hypothesis 9: *Cities that do not permit development in large areas around them do not have higher average densities.* The variable used to test this hypothesis was **No**

Development Allowed, defined as the percentage of the metropolitan plan area where no development was allowed in 2005.

Hypothesis 10: *While zoning regulations may act to limit density, cities with lax or corrupt regulatory enforcement do not have higher densities.* The variables used to test this hypothesis were: (1) **Subdivisions with No Permit**, defined as the average share of land subdivisions built without permit; and (2) **Corrupt Enforcement**, defined as a composite measure of survey answers to questions about corruption in the enforcement of zoning, land use and land subdivision regulations in 2005.

Hypothesis 11: *Metropolitan areas with a large number of jurisdictions that compete with each other for growth do not have lower average densities.* The variable used to test this hypothesis was **Municipal Fragmentation**, defined as the number of independent municipalities per 1,000,000 people in the metropolitan area in 2005.

Hypothesis 12: *While land consumption may be income elastic, cities with high-income inequality do not have lower average densities.* The variable used to test this hypothesis was **Income Inequality**, defined as the national Gini Coefficient for measuring income inequality nearest the year 1990.

Hypothesis 13: *Cities with large numbers of people in informal settlements do not have higher average densities.* The variable used to test this hypothesis was **Informal Settlements**, defined as the share of dwelling units in the city in informal settlements in 2005.

The descriptive statistics for all the independent variables used in estimating the models to explain density (as well as density change to be discussed later) are given in table 4.1.

Table 4.1: Variables used in modeling density and density change, 1990-2000

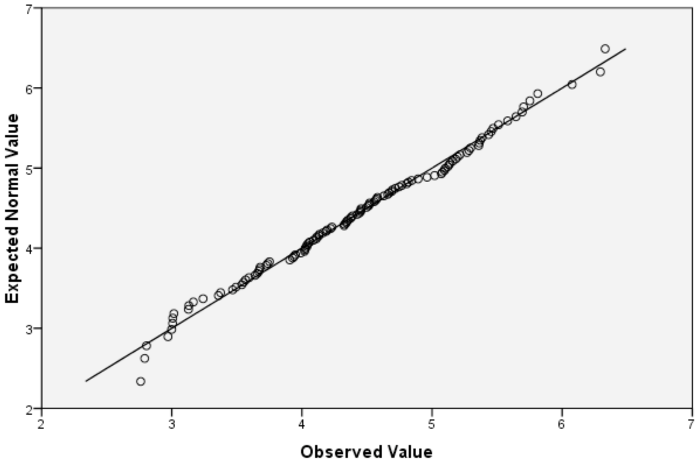
Variable	Average	Standard Deviation	Minimum	Maximum	Count
Built-up Area Density 2000 (persons per ha)	112.4	95.0	15.6	565.7	120
Built-up Area Density Change 1990-2000	-0.021	0.022	-0.099	0.040	120
1st Satellite image date (days)	26-Sep-89	829	13-Jun-84	19-Jan-95	120
2nd Satellite image date (days)	28-Nov-00	312	1-Jul-99	26-Dec-02	120
Time Elapsed Between Images (years)	11.17	2.24	5.19	16.97	120
City Population 2000	3,640,266	4,829,838	137,998	29,410,915	120
GDP Per Capita 1990 (national, in 2000 dollars)	9,641	9,390	762	30,568	120
Income Inequality (national Gini coefficient), ~1990	0.31	0.10	0.00	0.61	120
Arable Land + Permanent Crops Per Capita (m^2), 2000	3,223	4,461	0	36,697	120
Buildable land 2000	0.735	0.223	0.063	0.998	120
Household Size	4.0	1.3	1.8	8.2	120
Share of 2000 Population in 1900	0.10	0.18	0.00	1.19	112
Car ownership per capita (national), 1991	0.12	0.19	0.59	0.00	116
Gasoline price in 2000 in $ PPP	0.37	0.32	0.01	1.52	119
Well Water (percent)	0.15	0.21	0.00	1.00	90
Attractive Center Index	0.58	0.27	0.00	1.00	108
Independent Municipalities per million people	4.8	13.0	1.0	109.2	120
Average share of subdivisions built without permit	0.13	0.18	0.00	0.80	108
Percent of Population in Informal Settlements	15	20	0	80	103
Enforcement Subject to Corrupt Practices	2.92	1.20	1.00	5.00	101
Percent of Plan Area Where No Development Is Allowed	24.4	25.5	0	100.0	70

Multiple regression models that explain variations in density

To test each one of the hypotheses outlined earlier under *ceteris paribus* conditions—namely, all other things being equal—we constructed a series of multiple regression models using the statistical software SPSS 16.0 for Windows. These multiple regression models are expected to explain variations in average built-up area density in cities in the global sample in a comprehensive way, seeking to include a complete set of relevant factors that explain variations in density in each model and then determining the effect of each individual variable on density given the effects of all other variables on density. Only when no important independent variables are omitted from a particular model can the model be relied upon to produce correct estimates of the contribution of each independent variable to variations in density.

We opted for using both dependent and independent variables in logarithmic forms, and we did this for two reasons. First, the logarithmic forms of the density variable as well as a host of other independent variables were typically found to be normally distributed: a precondition for using multiple regression models. The results of the Q-Q test for normality of the Log Density variable, for example, are shown in figure 4.4 below. The fact that the observations for cities in the global sample line up along a straight line is a visual confirmation that the variable is indeed normally distributed. Second, the coefficients in the logarithmic models are, in fact, elasticities: they indicate the percent change in density for a given percent change in the independent variable. If the coefficient of the Log Income variable, for example, is -0.4 it means that a 10 percent increase in income is associated with a 4 percent decline in average density. This allows for a simple and ready interpretation of the coefficients of the different independent variables in the models.

Figure 4.4: Normal Q-Q Plot of the log of average built-up area density in 2000



Multiple regression models were used to test each one of the null hypotheses formulated above. Simply put, the null hypothesis that states that *Higher incomes that may increase the consumption of land by households and firms do not reduce average densities* (Hypothesis 3) must be rejected if the coefficient of Log Income 1990, the independent variable associated with income, is significantly different from 0. We reject this hypothesis with a 95 percent level of confidence if the probability that it is 0 if less than 0.05. This probability, denoted *Signif.* in the tables below, is shown in italics below the coefficients of each of the independent variables in the model.

The first set of five models is shown in table 4.2. The dependent variable, as noted above, is Log Density 2000 and all sets of independent variables contain Log Income, but do not contain Log Household Size or Log Car Ownership, as both these variables are known to be highly correlated with Log Income. In fact, the Pearson correlation between Log Household Size and Log Income in our sample is -.71 and it is different from 0 (sig. 0.001, 2-tailed). Similarly, the Pearson correlation between Log Car Ownership and Log Income in our sample is 0.902 and it is also different from 0 (sig. 0.001, 2-tailed). Log Household Size is used as an independent variable in Models 6-10 instead of Log Income and Log Car ownership is used as an independent variable instead of Log Income in Models 11-15.

Model 1, shown in the second column from the left in table 5.1, uses five independent variables to explain the variation in Log Density in the global sample of 120 cities. The R^2 and Adjusted R^2 of the model are 0.71 and 0.70, indicating that the model explains some 70 percent of the variation in Log Density. We can say with 99 percent confidence that the coefficients of all five independent variables are significantly different from zero (significance shown in italics below each variable).

Table 4.2: Logarithmic models that explain variations in density in 2000 with 1990 Log Income as the key independent variable

	Coefficients and levels of significance				
Independent Variables	Model 1	Model 2	Model 3	Model 4	Model 5
Log City Population, 2000	**0.192**	**0.182**	**0.179**	**0.178**	**0.177**
Signif.	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Log Arable Land	**-0.245**	**-0.269**	**-0.198**	**-0.233**	**-0.298**
Signif.	*0.000*	*0.000*	*0.002*	*0.001*	*0.000*
Log Income Inequality, 1990	**-0.564**	**-0.575**	**-0.859**	**-0.900**	**-0.761**
Signif.	*0.002*	*0.003*	*0.001*	*0.001*	*0.004*
Log Buildable Area	**-0.544**	**-0.555**	**-0.524**	**-0.483**	**-0.335**
Signif.	*0.000*	*0.000*	*0.000*	*0.000*	*0.025*
Log Income, 1990	**-0.404**	**-0.418**	**-0.227**	**-0.246**	**-0.227**
Signif.	*0.000*	*0.000*	*0.001*	*0.000*	*0.004*
Log Well Water		**-0.039**		**-0.027**	
Signif.		*0.561*		*0.705*	
Log Informal Settlements			**0.115**	**0.065**	
Signif.			*0.015*	*0.237*	
Log Corrupt Enforcement					**0.258**
Signif.					*0.077*
Log Subdivisions w. No Permit					**0.033**
Signif.					*0.490*
Constant	**6.287**	**6.743**	**4.719**	**5.024**	**5.152**
Signif.	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
No. of Observations	119[13]	94	74	65	74
R-Squared	0.709	0.761	0.638	0.655	0.649
Adjusted R-Squared	0.697	0.744	0.605	0.612	0.612

Model 1 therefore rejects five of the above null hypotheses. Hypothesis 2 is rejected, indicating that larger cities should be expected to have higher average built-up area densities than smaller cities, and that a 10 percent increase in city population is associated

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[13] The reader will notice that the number of observations varies between models because of missing data. However, when we tested Model 1, for example, with the limited data set of 74 observations available for Model 4, we obtain the same results. All the coefficients were still significantly different from zero and not very different in magnitude from those obtained in Model 1. We therefore tested all models with the largest available data set.

with a 1.9 percent increase in density. Hypothesis 5 is rejected, indicating that cities in countries with ample arable lands per capita should be expected to have lower average built-up area densities, and that a 10 percent increase in arable lands per capita is associated with a 2.5 percent decrease in density. Hypothesis 12 is rejected, indicating that cities in countries with high levels of income inequality should be expected to have lower average built-up area densities, and that a 10 percent increase in the Gini coefficient that measures national income inequality is associated with a 5.6 percent decrease in density. Hypothesis 1 is rejected, indicating that cities surrounded by ample buildable land should be expected to have lower average built-up area densities, and that a 10 percent increase in the share of buildable land on the urban periphery is associated with a 5.4 percent decrease in density. Finally, Hypothesis 3 is rejected, indicating that cities in richer countries should be expected to have lower average built-up area densities, and that a 10 percent increase in national per capita GDP in 1990 is associated with a 4.0 percent decrease in density in 2000.

The coefficients of the five independent variables in Model 1 are quite robust and do not vary appreciably when more independent variables are introduced into the model in models 2-5. When we look at all five models together, we can see that: (1) a 10 percent increase in city population is associated with a 1.8-1.9 percent increase in density; (2) a 10 percent increase in arable lands per capita is associated with a 2.0-3.0 percent decrease in density; (3) a 10 percent increase in the Gini coefficient that measures national income inequality is associated with a 5.6-9.0 percent decrease in density; (4) a 10 percent increase in the share of buildable land on the urban periphery is associated with a 3.4-5.6 percent decrease in density; and (5) a 10 percent increase in national per capita GDP in 1990 is associated with a 2.3-4.2 percent decrease in density in 2000.

The robustness of coefficients suggests that the models do not suffer from serious collinearity problems. Table 4.3 below displays the Pearson correlations for the independent variables used in models 1-5. The reader should note that the five variables in model 1 are not correlated with each other, except for a weak correlation between per capita income and ample arable land.

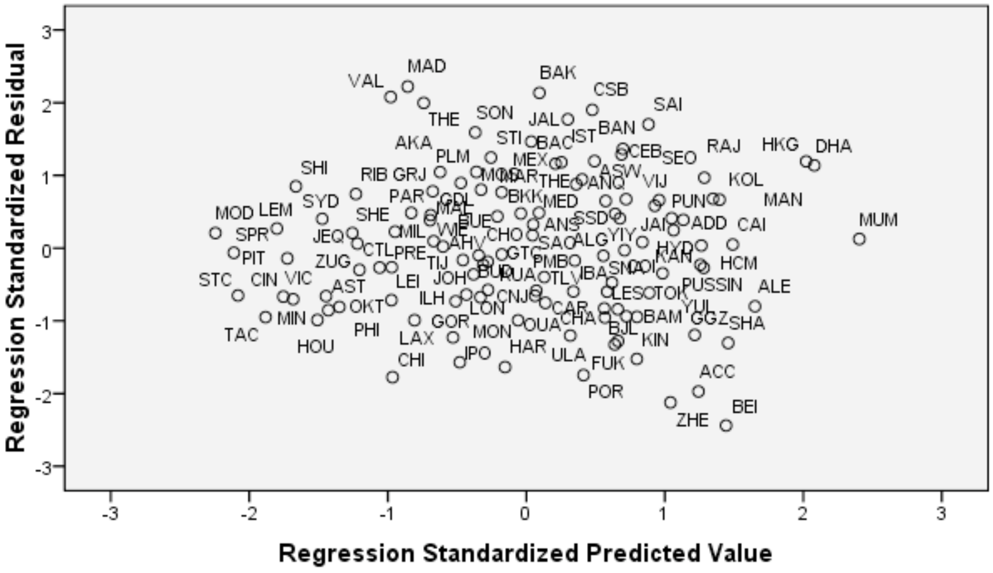
It is important to inquire whether the models presented here suffer from the absence of a key independent variable or, to use a statistical term, from Omitted Variable Bias. If an important independent variable were omitted from the model, then the error term would still include it, and the error term will be correlated with the dependent variable. Conversely, if no important variable were omitted, then the error term will not be correlated with the dependent variable. To test for Omitted Variable Bias we examine the scatter plots of the residual error of the model for each city in our sample against the predicted value for that city. More specifically, in Model 1, for example, we examine the standardized error in predicting the Log Density 2000 against the predicted value of Log Density 2000 for that city. The scatter plot for Model 1 is shown in figure 4.5, with 3-letter labels for each city in the sample. The values for each city are all within a clearly defined box: from -3 to +3 on both the X-axis and the Y-axis; they are also clustered together with no outliers. This suggests that the error terms in Model 1 are indeed random and we can therefore assume that the model does not suffer from heteroscedasticity or omitted variable bias. Scatter plots for other models are similar and will not be shown here.

Table 4.3: Correlations among Independent Variables Used in Density Models 1-5

Variable	Log City Population	Log Arable land	Log Income Inequality	Log Buildable land	Log GDP per capita	Log Well Water	Log Informal settlem'ts	Log Corrupt Enforcem't	Log Subdiv. w/o Permit
Log City Population	1.000								
Log Arable land	-0.164	1.000							
Log Income Inequality	-0.089	0.092	1.000						
Log Buildable land	-0.029	0.119	-0.177	1.000					
Log GDP per capita	0.005	0.225*	-0.005	-0.173	1.000				
Log Well Water	-0.088	-0.019	-0.078	0.029	0.335**	1.000			
Log Informal settlements	-0.032	0.059	0.050	0.011	-0.310**	-0.297*	1.000		
Log Corrupt Enforcement	0.127	0.051	-0.039	0.108	-0.494	-0.251*	0.414	1.000	
Log Subdivisions w. No Permit	-0.068	0.123	0.149	0.149	-0.550**	-0.259*	0.558**	0.489**	1.000

Note: * Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

Figure 4.5: Scatter plot of density model 1 showing no omitted variable bias



Model 2, by introducing Well Water as an independent variable has the highest R^2 and Adjusted R^2 among all five models, and explains some 75 percent of the variation in density in the global sample. However, while the coefficient of well water in negative, its significance does not allow us to reject the hypothesis that ample well water is associated with lower built-up area densities. The same is true of its coefficient in model 4.

Model 3 introduces the Log of the share of the population in informal settlements as an independent variable. The probability that its coefficient is different from 0 is 0.015, indicating that Hypothesis 13 can be rejected with a 95 percent level of confidence: cities with a large share of their population in informal settlements can indeed be expected to have higher densities, and a 10 percent increase in this share is associated with a 1 percent increase in built-up area density. It is worth noting that in model 4, where both informal settlements and well water are included together, neither of their coefficients can be said to be different from 0 with a sufficient level of confidence. Finally, the coefficients of the Log of Corrupt Enforcement and the Log of the Share of Subdivisions Built without Permit in model 5 have the right signs to suggest that the null hypothesis associated with them (Hypothesis 10) could be rejected, but the probability that their coefficients are different from 0 is not low enough to reject it with a sufficient level of confidence.

We now turn our attention to models 6-10 presented in table 4.4. As noted earlier, the key difference between models 1-5 and models 6-10 is that the first set of models uses Log Income as an independent variable and the second set uses Log Household Size as an independent variable. The correlation between income and household size was found to be significant at the 0.001 level (2-tailed). Indeed, it is well known that countries with higher per capita GDP have significantly lower average household sizes. Because of this high correlation, we avoided using both variables in the same model.

Table 4.4: Logarithmic models that explain variations in density in 2000 with Log Household Size as the key independent variable

	Coefficients and levels of significance				
Independent Variables	Model 6	Model 7	Model 8	Model 9	Model 10
Log City Population, 2000	**0.188**	**0.189**	**0.189**	**0.147**	**0.091**
Signif.	*0.000*	*0.000*	*0.000*	*0.006*	*0.080*
Log Arable Land	**-0.309**	**-0.235**	**-0.301**	**-0.307**	**-0.311**
Signif.	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Log Income Inequality, 1990	**-0.869**	**-0.988**	**-0.768**	**-0.759**	**-0.979**
Signif.	*0.000*	*0.000*	*0.001*	*0.002*	*0.003*
Log Buildable Area	**-0.357**	**-0.435**	**-0.393**	**-0.417**	
Signif.	*0.001*	*0.000*	*0.001*	*0.001*	
Log Household Size, 2005	**1.228**	**0.798**	**1.284**	**1.335**	**1.259**
Signif.	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Log Informal Settlements, 2005		**0.101**			
Signif.		*0.037*			
Log Attractive Center			**0.069**	**0.068**	
Signif.			*0.308*	*0.333*	
Log City Age				**0.078**	
Signif.				*0.374*	
Log No Development Allowed					**0.017**
Signif.					*0.746*
Constant	**1.482**	**1.716**	**1.494**	**1.674**	**2.880**
Signif.	*0.041*	*0.060*	*0.051*	*0.041*	*0.005*
No. of Observations	119	74	109	98	60
R-Squared	0.658	0.639	0.656	0.679	0.615
Adjusted R-Squared	0.643	0.607	0.635	0.654	0.579

The coefficient of average household size was found to be significantly different from 0 in all five models. This suggests that Hypothesis 7 must be rejected and that cities in countries with larger household sizes can indeed be expected to have higher average built-up area densities. The coefficient of Log Household size in the models varied between 0.80 and 1.34, suggesting that an increase of 10 percent in average household size is associated with an increase of 8.0-13.4 percent in density.

The coefficients of Log City Population, Log Arable Land, Log Income Inequality, Log Buildable Land, and Log Informal Settlements were all found to be significantly different from 0 in models 6-10 as they were in models 1-5. They were also found to have quite similar values to those in models 1-5. The explanatory power of this set of models was slightly lower than those of models 1-5: Its R^2 varied between 0.62 and 0.68 compared to a range of 0.65-0.76 in models 1-5.

Models 7-8 also failed to reject hypothesis 8, associated with the effects of an attractive city center on average built-up area densities. While the coefficient of Log Attractive center has the correct sign, suggesting that cities with more attractive centers may have higher average densities, we cannot say with any confidence that it is different from zero. This is an important finding. As we noted earlier, the preference of the rich to live in urban centers would cause them to live at higher density and consume less land, and we should therefore expect cities where this pattern exists to have higher densities than cities where the rich live in suburbs. For now, however, we must reject this hypothesis. Other things being equal, we cannot say with confidence that cities with attractive centers are denser than cities with unattractive centers.

Models 9 ands 10 failed to reject the hypotheses associated with the age of the city and the presence of plans prohibiting development on density. While their coefficients have the correct signs, the null hypotheses associated with them (8, 9, and 14) could not be rejected with a sufficient level of confidence. Neither the age of the city, nor plans prohibiting the conversion of peripheral rural land to urban use, appeared to have a significant effect on average built-up areas densities.

To conclude this section, we turn our attention to models 11-15 presented in table 4.5. As noted earlier, these models do not contain an income variable and instead introduce Log Car Ownership as the key explanatory variable for variations in density. The coefficient of Log Car Ownership in 1991 was indeed found to be significantly different from 0 in all five models. This suggests that Hypothesis 4 must be rejected, at least in part, and that cities in countries with higher levels of car ownership can indeed be expected to have lower average built-up area densities. The coefficient of Log Car Ownership in the models varied between -0.13 and -0.23, suggesting that an increase of 10 percent in car ownership is associated with an decrease of 1.3-2.3 percent in density.

The coefficients of Log City Population, Log Arable Land, Log Buildable Land, and Log Informal Settlements were all found to be significantly different from 0 as in models 1-5. They were also found to have quite similar values to those in models 1-5. In contrast to models 1-10, however, income inequality did not have a significant effect on density in models where car ownership was included, even though it was not found to be significantly correlated with car ownership in our sample. The explanatory power of this set of models was similar to those of models 1-5: Its R^2 varied between 0.63 and 0.72 compared to a range of 0.65-0.76 in models 1-5. Models 11-15 failed to reject the hypotheses associated with the effects of gas prices, the share of the 2000 population that lived in the city in 1990 before the advent of motorized transport, and municipal fragmentation on average densities. While their coefficients have the correct signs, the null hypotheses associated with them (4 and 11) could not be rejected with a sufficient level of confidence. More particularly, while higher levels of car ownership were found to be associated with lower densities, higher gas prices were not.

Table 4.5: Logarithmic models that explain variations in density in 2000 with 1990 Log Car Ownership as the key independent variable

	Coefficients and levels of significance				
Independent Variables	Model 11	Model 12	Model 13	Model 14	Model 15
Log City Population, 2000	**0.171**	**0.170**	**0.195**	**0.183**	**0.157**
Signif.	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Log Arable Land	**-0.191**	**-0.185**	**-0.191**	**-0.200**	**-0.137**
Signif.	*0.000*	*0.000*	*0.000*	*0.000*	*0.057*
Log Income Inequality, 1990	**-0.300**	**-0.262**	**-0.160**	**-0.302**	**-0.716**
Signif.	*0.106*	*0.165*	*0.423*	*0.102*	*0.009*
Log Buildable Area	**-0.498**	**-0.482**	**-0.484**	**-0.498**	**-0.518**
Signif.	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Log Car Ownership per capita	**-0.217**	**-0.224**	**-0.221**	**-0.225**	**-0.126**
Signif.	*0.000*	*0.000*	*0.000*	*0.000*	*0.001*
Log Gas Price		**0.023**	**0.004**		
Signif.		*0.667*	*0.935*		
Log 1900 Population Share			**0.033**		
Signif.			*0.307*		
Log Municipal Fragmentation				**0.060**	
Signif.				*0.184*	
Log Informal Settlements					**0.133**
Signif.					*0.004*
Constant	**2.149**	**2.179**	**2.041**	**1.984**	**2.317**
Signif.	*0.001*	*0.001*	*0.004*	*0.003*	*0.010*
No. of Observations	115	114	103	115	70
R-Squared	0.701	0.702	0.722	0.706	0.628
Adjusted R-Squared	0.687	0.685	0.701	0.690	0.592

To conclude this section, we review its key findings:

- Average built-up area densities in cities in land-rich developed countries in the 1990s were roughly *half* those of cities in other developed countries, and the latter were, in turn, roughly *half* those of cities in developing countries.

- More specifically, the average built-up area density in cities in land-rich developed countries (the U.S., Canada, Australia and the Russian Federation) was 34±7 persons per hectare (p/ha) in 1990 and 28±5 p/ha in 2000.

- The average built-up area density in cities in other developed countries (Europe and Japan) was 86±9 p/ha in 1990 and 70±8 p/ha in 2000.

- The average built-up area density in cities in developing countries was 174±14 p/ha in 1990 and 135±11 p/ha in 2000.

- Multiple regression models can explain some three-quarters of the variation in average built-up area density and do not appear to suffer from omitted variable bias. They show that:

- Cities in countries with higher incomes—because of a variety of causes such as higher land consumption, higher car ownership, and lower household sizes—have significantly lower densities.

- The average built-up area densities in more populated cities are significantly higher than those found in smaller cities.

- Cities in countries with ample arable lands per capita have significantly lower average built-up area densities.

- Cities with no geographical constraints on their expansion in all directions have significantly lower average built-up area densities.

- Cities in countries with high levels of income inequality have significantly lower average built-up area densities.

- But cities with a large share of their population in informal settlements have significantly higher average built-up area densities.

Thus far, we have concentrated our attention on a cross-sectional comparison of densities in a single point in time, the year 2000. Since the focus of this paper is on density *change,* we now turn to the discussion and explanation of the change in density in the global sample during the 1990s.

V. DENSITY DECLINE IN THE GLOBAL SAMPLE OF 120 CITIES, 1990-2000

The recent decline in average urban population densities has been amply recorded in the United States (see, for example, Fulton et al, 2001 quoted earlier, and El Nasser and Overberg, 2001; see also Demographia, 2000). This decline, typically manifesting itself as the land area of cities expanding at a faster rate than their population growth rate, has often been used as the very definition of *sprawl*. Europeans have tended to look at this decline, and more generally at *sprawl*, as a typically American phenomenon, but have recently come to understand that their cities have also become less dense than before. As a recent report by the European Environmental Agency attests:

> Classically urban sprawl is a US phenomenon…. In Europe cities have traditionally been much more compact…. However, European cities were more compact and less sprawled in the 1950s than they are today, and

> urban sprawl is now a common phenomenon throughout Europe (European Environmental agency, 2006, 5).

What has not been so evident to academics, planners, politicians and activists is that this phenomenon is now global in scope and includes the developing countries as well, and that urban densities are in decline in all world geographic regions. In fact, the evidence presented below contradicts the early findings of Berry, Simmons and Tennant (1963, 401) who claimed that

> whereas both degree of compactness and overcrowding diminish in Western cities through time, non-Western cities experience increasing overcrowding, constant compactness, and a lower degree of expansion at the periphery than in the West.

It also contradicts the more recent findings of Richardson, Bae and Buxamusa (2000, 25) that cities in developing countries "are not becoming significantly less compact in spite of decelerating population growth and the beginnings of decentralization". And it also contradicts the findings of Acioly and Davidson that "there was evidence that a general process of change was leading to more compact cities" in developing countries (Acioly and Davidson, 1996 quoted in Acioly and Davidson 2000, 127). While "the belief in the blessings of the compact city policy is now widespread" in developing countries (de Roo and Miller, 2000, 1), our findings do not bode well for those pursuing policies of urban densification and compact city development policies, in both developing and developed countries, as the way of the future. As we shall see, cities in the world over are becoming less, rather than more, compact over time.

This section presents the statistical evidence to this effect in the global sample of 120 cities presented earlier, where it has been studied for the period 1990-2000. It should be emphasized here that the decline in density may be difficult to visualize when looking at actual cities. Tall buildings abound, streets are crowded, and living spaces are at a premium. But the sheer amount of buildings in cities may mask the fact that homes now are less overcrowded, that roads are wider, and that workplaces, shops, schools and public buildings are more spacious than before. When we measure density in this study, we only measure the number of people per unit of built-up (or impervious surface) area, not the amount of floor area per unit of built-up area. And in many places the floor area has increased while the number of people occupying it has decreased. To take one extreme recent example:

> In Tianjin in 1988 the average living floor space per person in the city proper had reached around 6.5m^2 per person. In 2000 the living floor space was 19.1 m^2 per person and it has further increased to 25m^2 per person in 2005 (Tianjin Municipal Statistical Bureau, 2007, quoted in Bertaud, 2007, 5).

We also note that the analysis in this section is restricted to *built-up area* densities and does not include the urbanized area densities or the city footprint densities defined earlier.

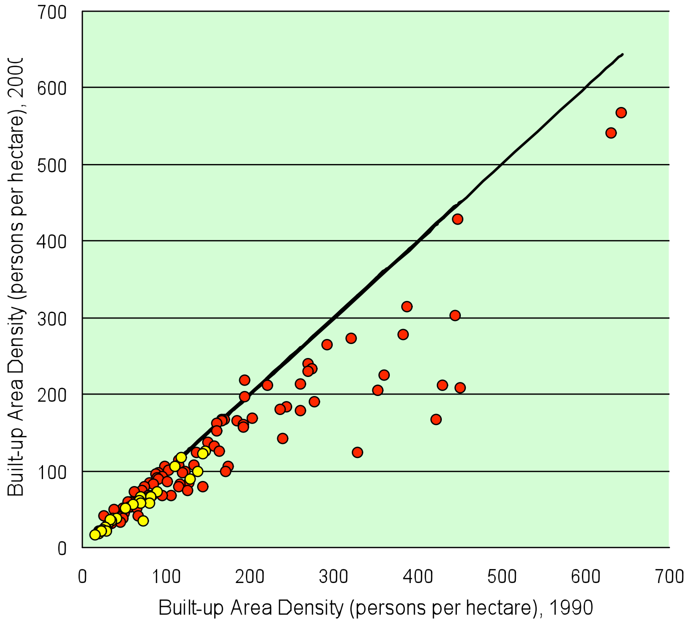
The former are the most rigorously comparable density metrics among the three because they do not involve arbitrary cutoff points to determine which open spaces should or should not be included in the calculation of density. It is true that the three densities are highly correlated (all their correlations in both 1990 and 2000 were higher than 0.95), but, as we shall see later their patterns of change were not the same between 1990 and 2000.

The decline of average built-up area densities in the universe of cities, 1990-2000

We conducted a paired-sample t-test to compare built-up area densities in the global sample of 120 cities for the two periods. The mean sample density in 1990 was found to be 144±12 persons per hectare (p/ha) and the mean sample density in 2000 was found to be 112±9 p/ha. We can say with a 95 percent level of confidence that built-up area densities in the universe of cities that had populations in excess of 100,000 in 2000 declined, on average, by 31±10 persons per hectare during this period, a 22 percent decline. We also conducted a one-sample t-test on the annual rate of decline in density during this period, assuming a constant rate of change. We can say with 95 percent confidence that, on average, densities in this universe of cities declined at an annual rate of -2.01±0.4 percent during this period.

The decline in densities between 1990 and 2000 can be seen graphically by looking at figure 5.1. The diagonal line in the figure is the 45° line where the density in 2000 exactly equals that of 1990. Each dot corresponds to one city, the red dots to cities in developing countries and the yellow ones to cities in developed countries. Clearly, most dots are located *below* the line, indicating that the density in 2000 was lower than the density in 1990 for the great majority of cities in the sample.

Figure 5.1: Density comparison in the global sample of cities, 1990-2000



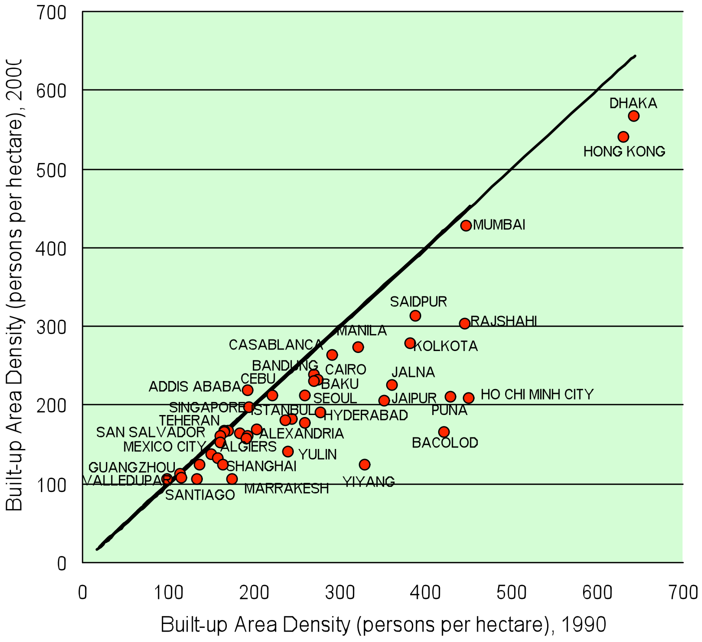
The small number of cities in the nine regional groupings in the global sample — in some regions there are only 8 cities in the sample—are too small to conduct statistical tests on the decline of densities for each of the nine regions. We can, however, test the global sample separately for developed-country and developing country cities as shown in table 2.1. There are 32 cities in the sample in developed countries. The rest of the cities in the sample are in developing countries and there are 88 cities in this category. We focus on the cities in developing countries first because this is where information on densities has been sorely lacking.

Built-up area density decline in developing-country cities between 1990 and 2000

Average built-up area densities declined in 75 out of the 88, or 6 out of 7, developing-country cities in the global sample between 1990 and 2000. To test whether this decline was statistically significant, we conducted a paired-sample t-test to compare built-up area densities in these cities between the two periods. The mean sample density in 1990 was found to be 174±14 persons per hectare (p/ha) and the mean sample density in 2000 was found to be 136±11 p/ha. We can say with a 95 percent level of confidence that the mean difference between the average built-up area density in the universe of developing-country cities between 1990 and 2000 was of the order of 39±13 p/ha. We also conducted a one-sample t-test on the annual rate of decline in density in developing-country cities during this period, assuming a constant rate of change. We can say with 95 percent confidence that, on average, densities in the universe of developing-country cities declined at an annual rate of 2.04±0.5 percent during this period.

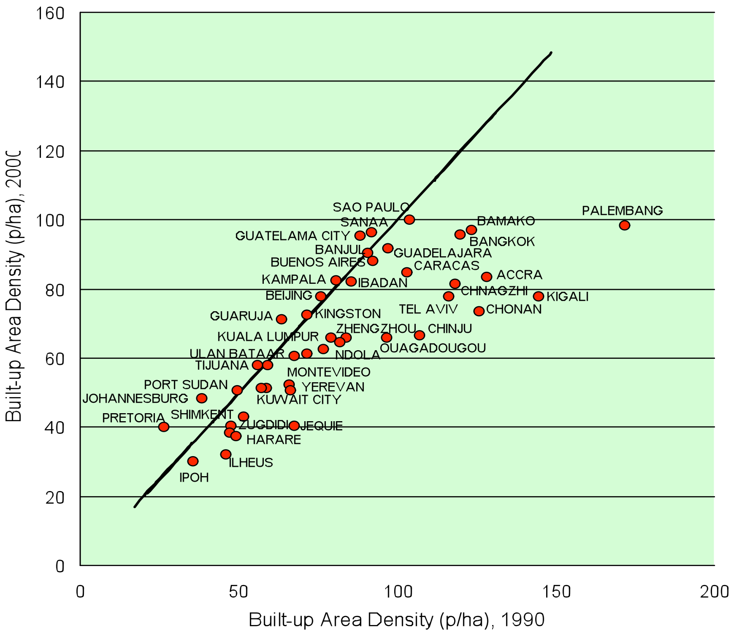
We illustrate the decline in densities in developing-country cities between 1990 and 2000 in two figures, rather than one, to make them more readable. Figure 5.2 shows the decline in developing-country cities that had built-up area densities higher than 100 persons per hectare in 2000, and figure 5.3 shows density decline in those developing-country cities that had densities lower than 100 p/ha in 2000.

Figure 5.2: The decline in density in denser developing-country cities, 1990-2000



Inspection of these two figures suggests that cities with very high densities appear to have registered more significant density declines than cities with lower density, indicating that an active process of decongestion in the densest cities is now taking place. As we shall see later, the higher the density was in 1990, the faster its decline. Only a few cities, most notable among them Johannesburg and Pretoria, registered a significant increase in density. The increase in density in these two cities can be attributed to changes in urban spatial structure associated with the end of apartheid in South Africa.

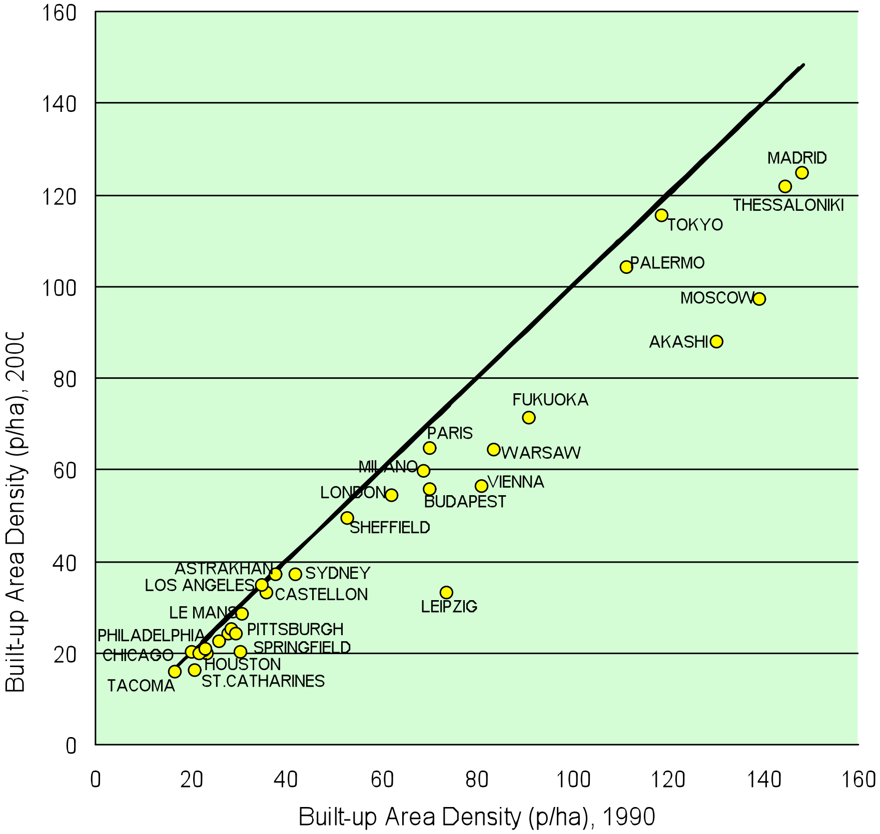
Figure 5.3: The decline in density in less dense developing-country cities, 1990-2000



Built-up Area Density decline in developed-country cities between 1990 and 2000

Built-up area densities declined in all 32 developed-country cities in the sample between 1990 and 2000. To test whether this decline was statistically significant, we conducted a paired-sample t-test to compare built-up area densities in these cities between the two periods. The mean sample density in 1990 was found to be 60±7 persons per hectare (p/ha) and the mean sample density in 2000 was found to be 49±6 p/ha. We can say with a 95 percent level of confidence that average built-up area densities in the universe of developed-country cities declined by 11±5 p/ha between 1990 and 2000. We also conducted a one-sample t-test on the annual rate of decline in density in developed-country cities during this period, assuming a constant rate of change. We can say with 95 percent confidence that, on average, densities in this universe of developing-country cities declined at an annual rate of 1.94±0.6 percent during this period. We illustrate the decline in density in developed-country cities between 1990 and 2000 in figure 5.4.

Figure 5.4: Density change in developed country cities, 1990-2000



We can further divide developed-country cities into two subgroups: cities in land-rich countries and cities other developed countries. Land rich developed countries are those with a large amount of arable land per capita and include the United States, Canada, Australia and the Russian Federation. These countries all had more than 6,000m^2 of arable land per capita in 2000. The group titled 'other developed countries' includes all of Europe (outside the Russian Federation) as well as Japan. An independent samples t-test confirmed that there was no statistically significant difference in the annual rate of decline in built-up area densities between cities in land-rich developed countries and cities in other developed countries.

To conclude, between 1990 and 2000 average built-up area densities were in decline in the entire universe of cities that had populations in excess of 100,000 in 2000. On average, densities in this universe of cities declined at an annual rate of 2±0.4 percent during this period. An independent samples t-test suggests that there was also no statistically significant difference in the annual rate of decline in these densities between developing and developed countries: the average annual rate of decline was found to be of the order of 2 per cent with a standard error of 0.5 percent in developing-country cities and in developed-country cities, be they land-rich developed countries or other developed countries.

At the present rates of decline of 2 percent per annum in the universe of cities, average built-up area densities in all three subgroups will be halved in approximately 30 years. It is important to question whether these rates of decline are likely to continue and we shall discuss this question later, but if present trends do continue, cities in other developed countries will reach densities similar to those of the land-rich countries like the United States today in 30 years and developing-country cities will reach densities similar to those of cities in Europe and Japan today in 30 years. The implications of these potential declines will be examined in the final section of this paper.

Explaining Built-up Area Density Change during 1990-2000 in the Universe of Cities

The findings introduced in the previous section demonstrated that there were no significant differences in the rate of decline in densities between the three sub-regions during the 1990s. This in itself is an indication that the level of development, measured, say, in per capita GNP, does not explain the rate of density decline: rates of decline are similar, on the whole, in both rich and poor countries. It also suggests that the ready availability of land for expansion in land-rich countries does not imply that urban densities in these countries now decline at a faster rate. What, then, accounts for the differences in the rate of decline among cities?

Traditional urban economic theory does not provide us with a ready explanation of the rate of decline in average built-up area density. We thus have to posit hypotheses based on the knowledge accumulated thus far from the comparative study of density and on common sense. Several of these hypotheses are introduced below:

The first hypothesis was based on the common observation that cities with rapidly growing populations typically experience an increase in built-up area densities because the provision of housing, infrastructure, workspaces, shopping areas, and public facilities cannot be supplied rapidly enough to accommodate the growing population. Stated as a null hypothesis, it becomes:

> Hypothesis 1: *Cities with rapidly growing populations and slow-growing populations have similar rates of change in average built-up area density*. The variable used to test this hypothesis was **Population Growth**, defined as the average annual rate of population growth in the administrative region defining the city between two census dates, one circa 1990 and one circa 2000, assuming a constant rate of change between these dates.

The second hypothesis was predicated on the observation that cities in countries with rapidly-growing incomes typically experience building booms that result in the massive provision of new housing, new infrastructure, and new workplaces, shopping areas and public facilities, resulting in the rapid expansion of their built-up area and therefore in a more rapid decline in built-up area density than in cities with slow-growing incomes. Stated as a null hypothesis, it becomes:

> Hypothesis 2: *Cities in countries with rapidly growing incomes and slow-growing incomes have similar rates of change in average built-up area density*. The variable used to test this hypothesis was **Income Growth**, defined as the average annual rate of per capita GNP growth in the country between 1990 and 2000, assuming a constant rate of change between 1990 and 2000.

The third hypothesis was based on the observation that cities with high initial densities, like Tianjin, are under more pressure to reduce densities than cities with low initial densities. High densities that result in overcrowding, as we noted earlier, are viewed as a serious social problem and great efforts are expanded to reduce them. Stated as a null hypothesis, it becomes:

> Hypothesis 3: *Cities with high initial densities and cities with low initial densities experience the same rate of density change over time*. The variable used to test this hypothesis was **Density 1990**, defined as the average built-up area density in 1990.

The fourth hypothesis was predicated on the observation that larger cities are better able to accommodate an influx of population without a major expansion of their housing stock, their infrastructure, and their building stock than smaller cities. More particularly, larger cities are more likely to respond to increased demand for building by densification than smaller cities. Stated as a null hypothesis, it becomes:

> Hypothesis 4: *More-populated cities experience the same rate of density change over time than less-populated cities*. The variable used to test this hypothesis was **City Population 1990**, defined as the total population within the administrative area(s) defining the city in 1990.

We have already determined in an earlier section that average built-up area density is negatively correlated with income: the higher the city's income, the lower its density. Since this correlation is rather high, it is not advisable, therefore, to use both density and income as explanatory variables in the same model. We have already argued earlier that income differences do not explain the rate of change in average density. If they do, however, it is probably because of their correlation with density. We therefore did test a model using initial income as an independent variable but excluding initial density. Stated as a null hypothesis, it becomes:

> Hypothesis 5: *Cities with high initial incomes and therefore high initial densities and cities with low initial incomes and therefore low initial densities experience the same rate of density change over time*. The variable used to test this hypothesis was **Income 1990**, defined as the per capita GDP in the country in 1990.

The sixth hypothesis was predicated on the observation that geographic constraints to urban expansion, such as water bodies of steep inclines, continue to constrict it over time. In other words, they are always there to make it more difficult for the city to expand. Stated as a null hypothesis, it becomes:

> Hypothesis 6: *Geographic constraints on urban expansion do not increase the rate of change of average densities over time*. The variable used to test this hypothesis was **Buildable Land**, defined as the share of dry land with a slope less than 15° in a circle about the center of the city with an area equal to four times the urbanized area of the city in 2000.

As noted earlier, ample land for expansion in land-rich countries did not lead to accelerated rates of density decline. We observed the same rates of decline in both land-rich and other developed countries. To test this contention statistically, we posited it as a null hypothesis thus:

> Hypothesis 7: *Ample and cheap agricultural lands on the urban periphery do not affect the rate of change in average densities.* Because the amount of arable land per capita does not change appreciably over time, the variable used to test this hypothesis was **Arable Land**, defined as the national arable land and land in permanent crops per capita in 2000.

It is commonly argued that high levels of car ownership are responsible for increased rates of urban sprawl. It is difficult to test this hypothesis because car ownership is typically highly correlated with income and thus indirectly with average built-up area density. We did posit this contention as a null hypothesis thus:

> Hypothesis 8: *Lower initial transport costs do not result in faster or slower rates of decline in average densities.* The variable used to test this hypothesis was **Car Ownership 1991**, defined as the national car ownership rate in 1991.

We tested these hypotheses as before, using a series of five multiple regression models with **Density Change**, defined as the mean annual rate of change in built-up area density during the 1990s as the dependent variable, assuming a constant rate of change during this period. In all models, we used density change, population change, and income change as annual percentage rates, and all other independent variables in their logarithmic form as in the models discussed in the previous section and for the same reasons cited earlier.[14]

Before introducing the models, we discuss the possibility of collinearity among the independent variables in the models. To examine collinearity, we introduce table 5.1 below. It should not be surprising that density in 1990 is highly correlated with city population, arable land, and income (and hence also with car ownership). This is the main result of the density models introduced in the previous section. What is surprising is that it is also correlated with income change: denser cities appear to have experienced a

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[14] Since we collected density data for two time periods for the global sample of cities, we could in principle subject these data to a two-period panel data analysis (Wooldridge, 2000, 419). However, since among the independent variables used in the models presented below only income and population data are available for the two periods, we opted to use the annual rate of change in density as a dependent variable rather than the difference in density between the two periods. This allows us to use the initial density as an independent variable in the models; it is independent from the rate of change but not independent from the difference in densities between the two time periods.

significantly higher increase in income between 1990 and 2000. It is also surprising that cities in land-rich countries appear to have experienced slower income growth than cities in other countries. And it is not surprising that cities in poorer countries grew faster than cities in richer countries. That said, the coefficients of the independent variables in the five models introduced below appear to be quite stable from one model to another, and are not disturbed by the correlations among them.

The five linear regression models with the change in average built-up area density between 1990 and 2000 as a dependent variable are displayed in table 5.2 below. The scatter plot for Model 3 is shown in figure 5.5, with 3-letter labels for each city in the sample. The values for each city are all within a clearly defined box: from -3 to +3 on both the X-axis and the Y-axis; they are also clustered together with no outliers. This suggests that the error terms in Model 3 are indeed random and we can therefore assume that the model does not suffer from heteroscedasticity or omitted variable bias. Scatter plots for other models are similar and will not be shown here.

Table 5.1: Pearson correlations for independent variables used in density change models 1-5

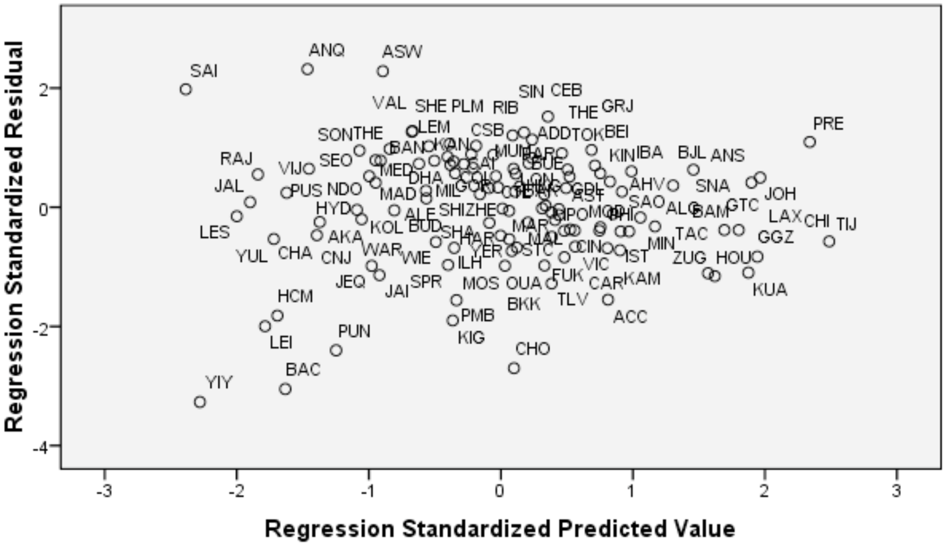
Independent Variable	Log City Population 1990	Log Density 1990	Log Arable land	Change in income 1990-2000	Change in population 1990-2000	Log car ownership 1991	Log Buildable land 1990	Log GDP per capita 1990
Log City Population 1990	1.000							
Log Density 1990	0.312**	1.000						
Log Arable land	-0.137	-0.554**	1.000					
Change in income 1990-2000	0.230*	0.274**	-0.393**	1.000				
Change in population 1990-2000	-0.011	0.154	-0.243**	0.213	1.000			
Log car ownership 1991	-0.009	-0.679**	0.371**	-0.271**	-0.402**	1.000		
Log Buildable land 1990	-0.039	-0.178	0.119	-0.011	0.079	-0.113	1.000	
Log GDP per capita 1990	0.052	-0.569**	0.225*	-0.129	-0.404**	0.921**	-0.173	1.000

Note: * Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed).

Table 5.2: Logarithmic models that explain density change, 1990-2000

Independent Variables	Coefficients and levels of significance				
	Model 1	Model 2	Model 3	Model 4	Model 5
Population Growth Rate	**0.687**	**0.771**	**0.721**	**0.708**	**0.703**
Signif.	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Income Growth Rate	**-0.228**	**-0.288**	**-0.225**	**-0.255**	**-0.218**
Signif.	*0.002*	*0.000*	*0.002*	*0.001*	*0.003*
Log Density, 1990	**-0.012**		**-0.013**	**-0.014**	**-0.013**
Signif.	*0.000*		*0.000*	*0.000*	*0.000*
Log City Population, 1990	**0.005**	**0.006**	**0.005**	**0.005**	**0.005**
Signif.	*0.000*	*0.002*	*0.000*	*0.000*	*0.000*
Log Income, 1990		**0.003**			
Signif.		*0.052*			
Log Buildable Area			**-0.011**	**-0.011**	**-0.011**
Signif.			*0.005*	*0.007*	*0.010*
Log Arable Land				**-0.002**	
Signif.				*0.270*	
Log Car Ownership, 1991					**0.000**
Signif.					*0.734*
Constant	**-0.045**	**-0.117**	**-0.046**	**-0.025**	**-0.048**
Signif.	*0.019*	*0.000*	*0.015*	*0.360*	*0.012*
No. of Observations	120	120	120	119	116
R-Squared	0.385	0.285	0.427	0.435	0.416
Adjusted R-Squared	0.364	0.260	0.402	0.404	0.384

Figure 5.5: Scatter plot for density change 1990-2000 model 3



Model 1, shown in the second column from the left, uses four independent variables to explain the variation in Density Change 1990-2000 in the global sample of 120 cities. The R^2 and Adjusted R^2 of the model are 0.39 and 0.36 respectively, indicating that the model explains some one-third of the variation in Density Change. We can say with 99 percent confidence that the coefficients of all four independent variables are significantly different from zero (significance shown in italics below each variable).

Model 1 therefore rejects four of the above null hypotheses. Hypothesis 1 is rejected, indicating that fast-growing cities should be expected to have higher rates of density increase, and that a 10 percent increase in the city population growth rate is associated with a 7 percent increase in the rate of change of density. Hypothesis 2 is rejected, indicating that cities in countries with higher rates of income growth should be expected to have higher rates of density decline, and that a 10 percent increase in the income growth rate is associated with a 2.3 percent increase in the rate of density decline. Hypothesis 3 is rejected, indicating that cities with high initial densities should be expected to have higher rates of density decline, and that a 10 percent increase in initial density is associated with a 1.2 percent increase in the density decline rate. The reader should recall that this was seen graphically in figure 5.1 earlier. Finally, Hypothesis 4 is rejected, indicating that larger cities should be expected to have lower rates of density decline, and that a 10 percent increase in the initial population of the city is associated with a 0.5 percent decrease in the rate of change of density.

The coefficients of the four independent variables in Model 1 are quite robust and do not vary appreciably when more independent variables are introduced in models 2-5. When we look at all five models together, we can see that: (1) a 10 percent increase in the rate of city population growth is associated with a 6.9-7.7 percent increase in the rate of change of density; (2) a 10 percent increase in the rate of income growth is associated with a 2.2-2.9 percent decrease in the rate of change of density; (3) a 10 percent increase in the initial density is associated with a 1.2-1.4 percent decrease in the rate of change of density; and (4) a 10 percent increase in the initial population of the city is associated with a 0.5-0.6 percent increase in the rate of change of density.

We already cautioned against using income and density as explanatory variables in the same model. Model 2 exchanges Log Income for Log Density and finds that Hypothesis 5 cannot be rejected at the 95 percent level of confidence and that the coefficient associated with income is rather small. We must conclude that the rate of density change does not vary appreciably between rich and poor countries, confirming our observations in the previous section. The explanatory power of this model is much reduced compared to model 1: The R^2 and Adjusted R^2 of the model are 0.29 and 0.26 respectively, compared to 0.39 And 0.36 in model 1.

Model 3 rejects Hypothesis 6 and finds that geographic constraints continue to impede urban expansion and that a 10 percent increase in buildable area is associated with a 1.1 percent decrease in the rate of density change. All five independent variables in model 3 have coefficients that are significantly different from zero and the model explains more than 40 percent of the variations in the rates of change in density in the global sample of 120 cities between 1990 and 2000: The R^2 and Adjusted R^2 of the model are 0.43 and 0.40 respectively.

Model 4 fails to reject hypothesis 7: the availability of ample arable lands in the country is not associated with more rapid rates of density decline, again confirming our observation in the previous section: Other things being equal, cities in land-rich developed countries, like the U.S. for example, do not consume peripheral lands at higher rates than other developed countries or developing countries.

In conclusion, we can now assert that the rate of built-up area density decline in the global sample of cities between 1990 and 2000 can be explained adequately by noting that fast-growing cities experienced a slower rate of decline than slow-growing cities; that cities in countries with rapidly-growing incomes experienced a steeper rate of decline in density that cities in countries with slow-growing incomes; that the rate of density decline in dense cities was faster than the rate of decline in less dense ones; that the rate of density decline in large cities was slower than the rate of decline in smaller ones; that the rate of density decline in cities subject to physical constraints was slower than that of cities that could freely expand in all directions; and that the rates of density decline in cities in land-rich countries were not significantly different than those of other countries. It is true that the overall explanatory power of the dynamic models discussed here is much lower than that of the static models discussed in the previous section, but that is to be generally expected in dynamic models. It is clear, however, that the models do not suffer from omitted variable bias and that they provide a good overall explanation of density change in the global sample.

A note on the decline in urbanized area densities and city footprint densities, 1990-2000

It is important to ask whether the observed decline in built-up area densities in the global sample of 120 cities could also be observed when we examine urbanized area densities and city footprint densities in the global sample of 120 cities. Independent sample t-tests showed that the rates of decline in urbanized area density and city footprint density were -2.02± 0.44 percent and -1.72±0.43 percent per annum respectively and they were both significantly different from zero at the 95 percent confidence level.

A paired sample t-test shows that the mean rates of decline built-up area density and urbanized area density were not significantly different from each other. The mean difference between them was 0.008±0.068 percent and it was not significantly different from zero at the 95 percent confidence level.

The mean rates of decline in built-up area density and urbanized area density, however, were both significantly different than the mean rate of decline in city footprint density. The latter averaged -1.72±0.4 percent per annum and the mean difference between that rate and the rate of decline in built-up area densities, for example, was -0.29±0.22 percent and it was significantly different from zero. In other words, the *share* of the open space fragmented and otherwise affected by the built-up areas of cities declined significantly between 1990 and 2000, a welcome development. Indeed, the ratio between the mean city footprint area and the mean built-up area in 1990 was 2.01±0.06 and it declined to 1.93±0.07 in 2000. The mean difference between the two ratios was 0.08±0.04 and it was significantly different from zero at the 95 percent confidence level. We can conclude, therefore, that the built-up areas of cities in 2000 affected or fragmented a smaller proportion of the open space around them that in 1990. If we consider open space fragmentation as a measure of sprawl, then we can say that, on average, sprawl as open space fragmentation declined between 1990 and 2000.

There were also differences in the mean rate of decline of city footprint densities between land-rich developed countries (-1.09±0.70 percent), other developed countries (-1.63±0.92 percent), and developing countries (-1.86±0.55 percent). Single sample t-tests show that the means of all three rates were negative and significantly different from zero at the 95 percent confidence level, while independent sample t-tests show that the differences between their means were not significantly different from zero at the 95 percent confidence level. That said, it may well be that further tests will show that cities in land-rich developed countries are now experiencing slower rates of decline in urban footprint densities than cities in other countries.

To conclude this section, we review its main findings:

- The average built-up area densities of the cities the world over declined from 144±12 persons per hectare (p/ha) in 1990 to112±9 p/ha in 2000.
- Average built-up area densities declined in 75 out of the 88, or 6 out of 7, developing-country cities in the global sample between 1990 and 2000.
- Average built-up area densities declined in all 16 cities in land-rich developed countries and in all 16 cities in other developed countries between 1990 and 2000.
- There was no significant difference in the average rate of decline in built-up area densities in cities in the three regional groupings.
- On average, mean built-up area densities in this universe of cities declined at an annual rate of 2.01±0.4 percent during this period.
- At present rates of decline, average built-up area densities in all three regional groupings can be expected to be halved in approximately 30 years.
- Multiple regression models can explain some 40 percent of the variation in the rates of density change in the universe of cities and appear to be free of omitted variable bias. They show that:
- Cities with rapidly growing populations have significantly slower rates of density decline.

- Cities in countries with rapidly growing incomes have significantly faster rates of density decline.

- Cities with high initial densities or low initial incomes have significantly faster rates of density decline.

- Cities with larger populations have significantly slower rates of density decline.

- Cities with no geographical constraints on their expansion in all directions have significantly faster rates of density decline.

- Densities in cities in land-rich countries do not decline at faster or slower rates than cities in other countries.

While these findings are quite robust, it is still possible to argue that the decline in density observed in the universe of cities between 1990 and 2000 was a fluke, or that it was the result of the particular economic, social, political and demographic conditions that prevailed during that decade. To test this contention, the next section explores the change in densities in 20 U.S. cities over a longer time period: 1910-2000.

VI. DENSITY DECLINE IN 20 U.S. CITIES, 1910-2000

As noted earlier, U.S. census data for 20 major cities—going back to 1910 for seven of them, to 1930 for 18 of them, and for 1940 for all of them—is available at the tract level on digital maps that can be interpreted using ArcGIS software. We used these data to explore the decline in average tract densities, to be distinguished from average built-up area densities for which data were not available, and to compare this decline with similar declines in three other density metrics: maximum tract density, and the gradient and intercept of the density curve. We also used these data, as well as data for 45 additional cities from 1950 onwards, to study changes in the rate of decline in tract densities over time. We report on these results in this section.

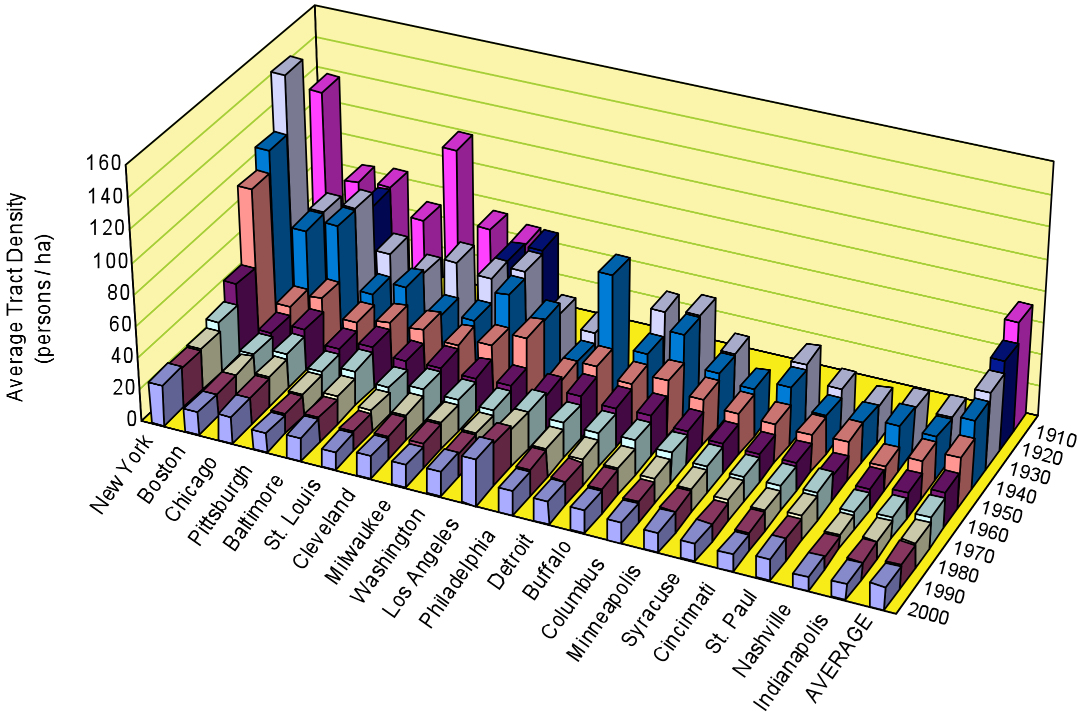
The decline in average tract density in U.S. cities, 1910-2000

Average tract density was defined as the ratio of the total population residing in census tracts with densities over 1,000 persons per square mile (3.86 persons/ha) to the total area of such tracts. New York, for example, had a population in such tracts of 16.39 million in the year 2000 and an urbanized area of 2,400 square miles or 621,500 hectares. Its average tract density was, therefore, 26.4 persons per hectare.

The reader should recall that average tract density equals the urban population divided by the total area of urban tracts, and that these tracts contain considerable amount of open space. Tract densities are thus considerably lower than built-up area densities, as we saw in table 2.1 earlier. They also change in a different way than built-up area densities. For example, if vacant lands in urban census tracts are filled by new built-up areas at lower-than-average built-up area densities, then the average built-up area density will decline, but the average tract density will increase. Thus it may well be that built-up area densities in U.S. cities continue to decline while increasing rates of infill of vacant lands slows down the rate of decline in average tract densities. Conversely, large amounts of leapfrogging development may lower tract densities even if the built-up area density of these new developments is quite high. The reader must therefore bear in mind, therefore, that the analysis in this section focuses on tract densities and not on built-up area densities and that comparing these results to the results concerning built-up area density in the previous section must be done with utmost care.

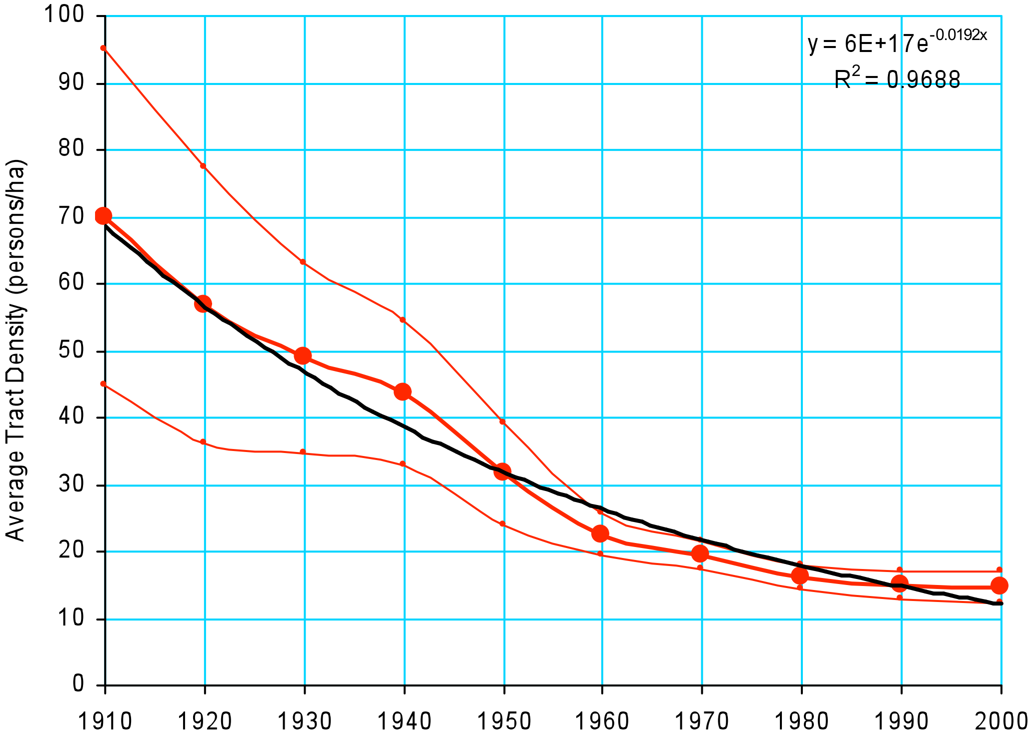
Average tract densities for all 20 U.S. cities in the years between 1910 and 2000 for which data were available are shown in figure 6.1.

Figure 6.1: Average tract densities in 20 U.S. cities, 1910-2000



Several important features of figure 6.1 merit our attention. First, the average tract density (shown in the row on the far right) declined in every decade since 1910, from 69.6 persons per hectare in 1910 to 14.6 per hectare in 2000, roughly a five-fold decline. Fitting an exponential curve to the average density in every decade from 1910 to 2000, we find that the average annual rate of decline for the entire period, assuming a constant rate, was 1.92 percent (see figure 6.2). The goodness of fit of the exponential curve to the data is very high, with an R^2 of 0.969. Second, average tract density declines (rather than increases) between two consecutive censuses were registered in 124 out of the 153 observations, or 81 percent of the time. Third, subjecting these 153 individual observations to a single sample t-test we can say with a 95 percent level of confidence that the average decline between two consecutive censuses was significantly different from zero, and that it averaged 1.55±0.29 percent per annum. Fourth, average tract densities declined, on the whole in 19 out of 20 cities. The single exception is Los Angeles, where average tract densities have been on the increase since 1940 and are now the highest among the 20 cities studied.

Figure 6.2: The decline in average tract density in 20 U.S. cities, 1910-2000



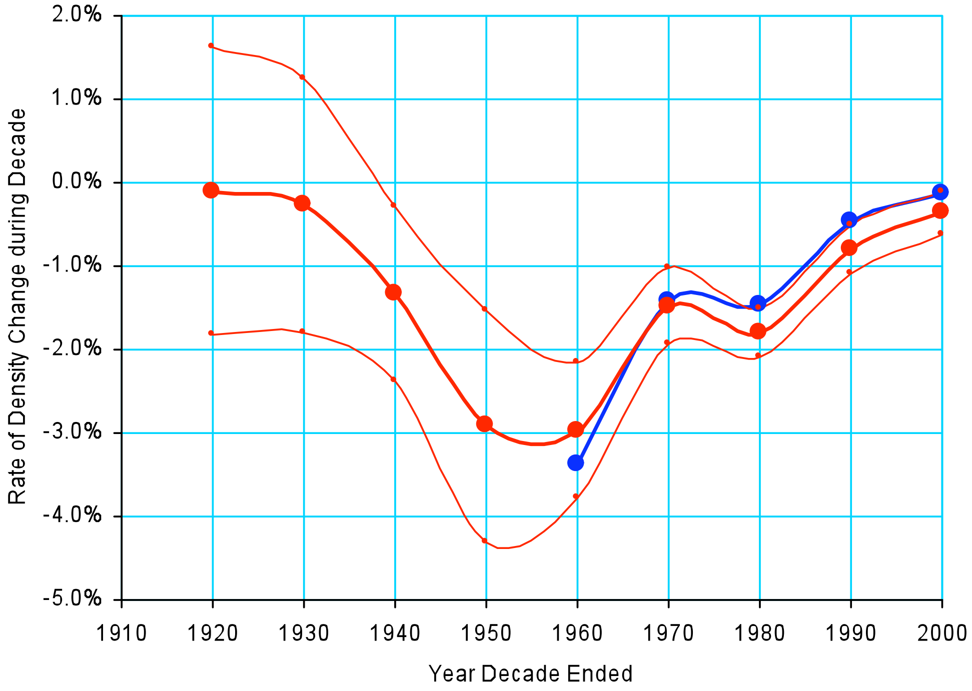
Note: Thinner lines indicate 95 percent confidence interval of average value; trend line is best-fit negative exponential curve with $R^2 = 0.9688$. The average annual rate of decline of this curve is 1.92 percent.

The changing rate of decline in average tract densities in U.S. cities, 1910-2000

Average tract density data only becomes available every ten years. To calculate annual rates of tract density decline we must therefore assume that the rate of decline between two census years is constant. We can then calculate an annual rate of decline based on two data points ten years apart, twenty years apart, and so on. Short-term rates of decline in average tract density, based on two data points ten years apart, appear to have peaked in 1940s and 1950s, when they averaged 3 percent per annum and are now on the decrease: they averaged only 0.3 percent per annum in the 1990s (see figure 6.3). In fact, between 1990 and 2000 six out of 20 cities registered an increase in average tract density: New York, Washington, Los Angeles, St. Paul, Syracuse, and Nashville. Hence, while average densities in U.S. cities have been in general decline for almost a century, they may slowly be reaching a plateau. This is shown graphically in figure 6.3 below. The points on the thick lines in the graph correspond to the average annual rate of change in density, shown on the Y-axis, for the decade ending in the year shown on the X-axis. The thin lines indicate 95 percent confidence intervals for these average values.

The data shown in red in the graph are for the 20 U.S. cities for which we have data from 1910 to 2000. The data shown in blue is for a larger set of 65 cities and metropolitan areas for which average tract densities could be calculated from 1950 onwards. The data for the larger set of cities shows lower rates of density decline from 1970 onwards, but these lower rates are still within the error band of the 20-city data set. These lower values may be due to the fact that this larger list includes many newer cities, and that the older 20 cities are still experiencing faster declines in average tract densities than newer ones. This conjecture will need to be examined in greater detail in future studies. What is important to note here is that the pattern of decline is the same for both sets of cities. The rate of decline began to slow down rapidly during the 1950s; it reversed itself in the 1960s, but then continued to decline from the 1970s onwards. It is quite possible that mean tract densities in the U.S. are slowly reaching a plateau and we already know that some metropolitan areas are experiencing densification. This densification is observable in increasing average tract densities, and may be the result of infill rather than the result of increasing built-up area densities. In fact, in all 10 U.S. cities in the global sample, average built-up area densities—to be distinguished from average tract densities—decreased, rather than increased, between 1990 and 2000.

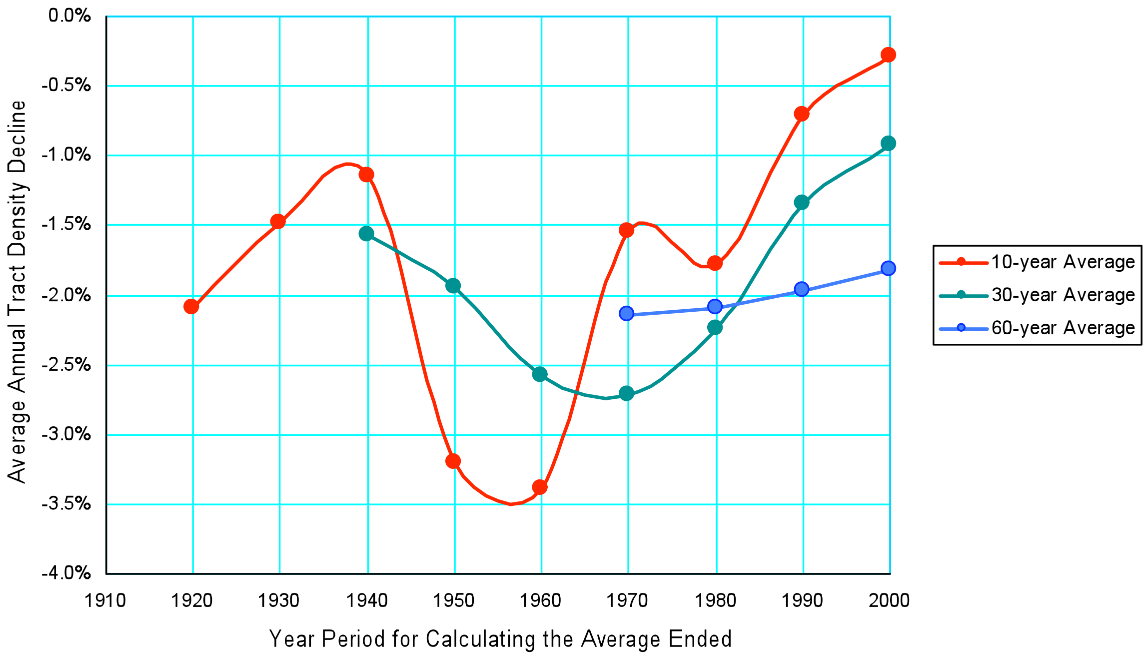
Figure 6.3: Average rate of annual tract density change in 20 cities (red) and 65 cities (blue) in the U.S., 1910-2000



Note: Thinner lines red indicate 95 percent confidence interval of average values for the 20-city data set. The blue line indicates the values for the larger 65-city data set.

For purposes of long-term projections of density decline, it may not be advisable to use short-term rates of change in density to determine the projected rate of density change in future years. In figure 6.4 we present the average annual rate of change in density during a 10-year, 30-year, and 60-year period. The average 10-year rates of decline in average tract densities in U.S. cities since 1970 are shown to vary between 0.3 and 1.8 percent per annum. The average 30-year rates of decline in average tract densities in U.S. cities since 1970 are shown to vary between 1.0 and 2.7 percent per annum. The average 60-year rates of decline in average tract densities in U.S. cities since 1970 are shown to vary between 1.8 and 2.1 percent per annum. In a later section, we will discuss data on rates of change in urbanized area density—again, not necessarily identical to tract density—in the historical sample of cities between 1800 and 2000 and compare them to rates of change in U.S. cities. As we shall see later, the long-term rates of decline in urbanized area density in the global sample of historical cities are similar to longer-term rates of decline in average tract density in U.S. cities.

Figure 6.4: The average rate of density decline in 20 U.S. cities, 1910-2000



The tract density data available for U.S. cities for 1910-2000 makes it possible to calculate several other density metrics and to see whether the pattern of decline in the average tract density discussed in the previous section is paralleled by similar declines in the other density metrics defined earlier in chapter 2[15]: maximum tract density, the tract density gradient, and the tract density curve intercept. In general, we can say that all three-density metrics display parallel declines to those of average tract density. We examine this observation in greater detail in the following sections.

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[15] The examination of the median tract density did not yield any interesting insights and will not be explored further in this paper.

The decline in maximum tract densities in U.S. Cities, 1910-2000

We defined maximum tract density earlier, not as the population density in the single tract that had the highest density in the city, but as the average density in the one percent of tracts in the city with the highest tract density. We calculated this value as the ratio of the total population and the total area of these tracts. As expected, maximum tract density declined over time in the cities studied.

This decline is examined graphically in figures 6.5 and 6.6 below. In general, maximum tracts densities declined from an average of 600 persons per hectare in 1910 to an average of 100 persons per hectare in 2000, a six-fold decline. Only one city in the U.S., New York, had and still has high maximum tract densities in comparison to other cities. Maximum tract density in New York City reached 1,496 persons per hectare in 1910, an exceptionally high number by all standards. It declined to 419 persons per hectare by the year 2000, a 3.5-fold decline. Again, Los Angeles was the only city in this sample where maximum tract densities increased over time, albeit only slightly, in parallel with the increase in average tract density reported earlier.

In general terms, as figure 6.6 shows, there was a precipitous decline in mean maximum tract density in the first decade of the twentieth century, when maximum densities declined at an average rate of almost 9 percent per annum. That was indeed the time when American cities were still rapidly decongesting, mostly with the advent of the horsecar on rails and the electric trolley that enabled the first wave of suburbanization. Maximum tract densities fell, on average, below 250 persons per hectare by the second and third decade of the century and then continued to decline slowly over time to an average of 100 persons per hectare.

Figure 6.5: The decline in maximum tract densities in 20 U.S. cities, 1910-2000

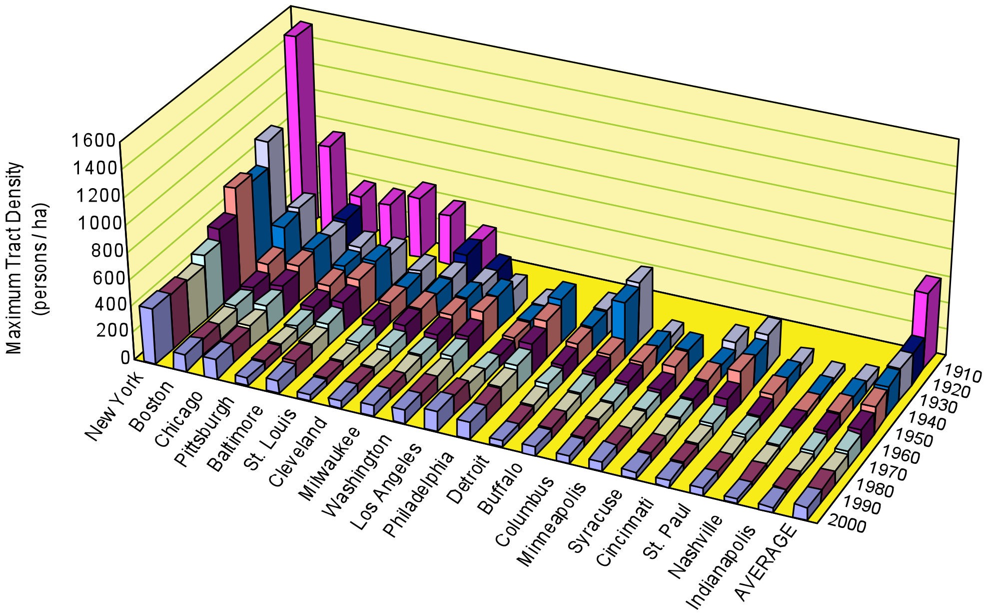
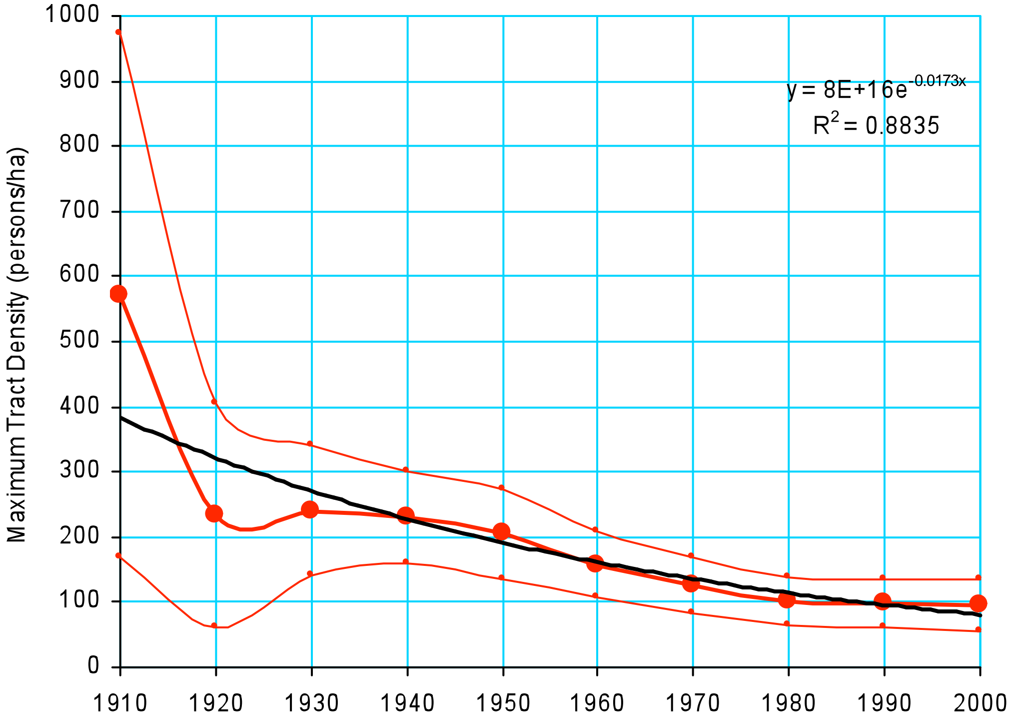


Figure 6.6: The mean decline in maximum tract densities in 20 U.S. cities, 1910-2000



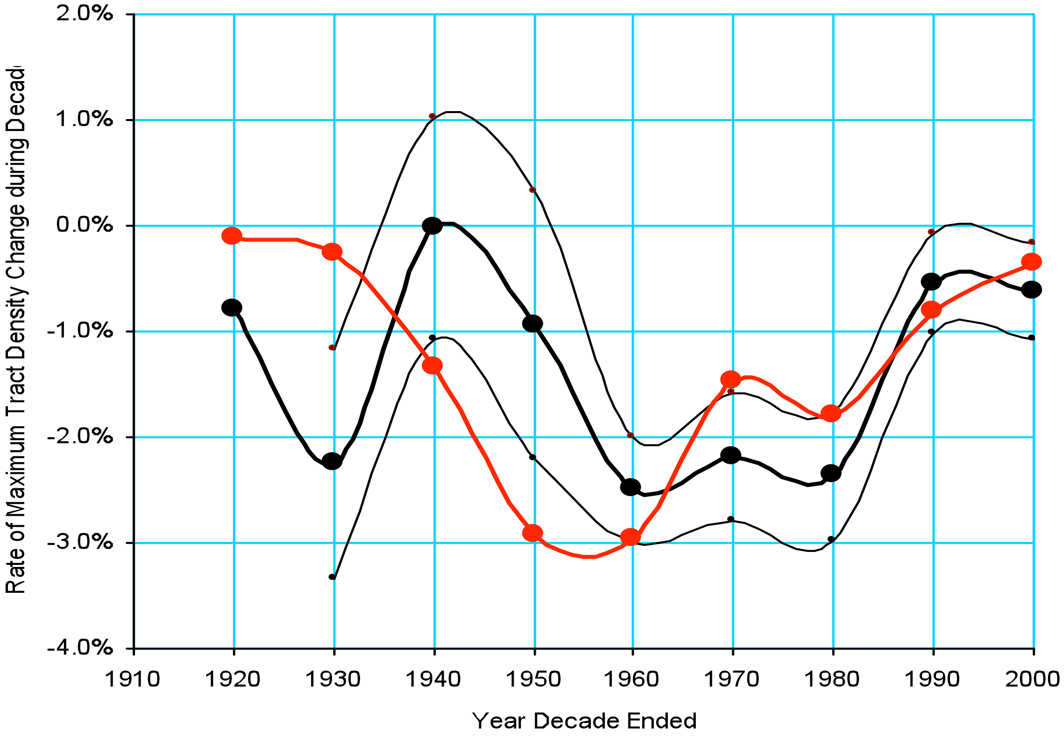
Note: Thinner lines red indicate 95 percent confidence interval of the mean values. The intervals for 1910 and 1920 are wide because data was available for only 7 and 3 cities respectively.

Towards, the end of the twentieth century, the rate of decline in maximum tract density in U.S. cities slowed down to a rate close to zero (-0.35 percent). Except for New York City, only five other cities had maximum tract densities higher than 100 persons per hectare: Los Angeles (153), Chicago (145), Boston (128), Philadelphia (126), and Washington (109).

Finally, we can ask: To what extent did the decline in average tract densities mirror the decline in maximum tract densities in this group of cities? When we look at the change in density in every decade in every city in this data set, we find a total of 150 cases of change in density. In 122 of these cases, or 81 percent, a change in average tract density was accompanied by a change in the same direction in maximum density. We can conclude that, in general, declines in average tract density were accompanied by parallel declines in maximum tract density.

Figure 6.7 shows that the rate of change in the average levels of mean maximum tract density generally followed the rate of change in average tract density during the period studied. Once the deconcentration of dense neighborhoods in the early decades of the century was completed, the rate of decline of maximum densities proceeded along with the rapid suburbanization in the 1940s and 1950s and then slowed down to near zero in the later decades of the twentieth century, closely paralleling the rate of change in average tract density.

Figure 6.7: the rate of change of maximum tract density (in black) compared to the rate of change in average tract density (red) in 20 U.S. cities, 1910-2000

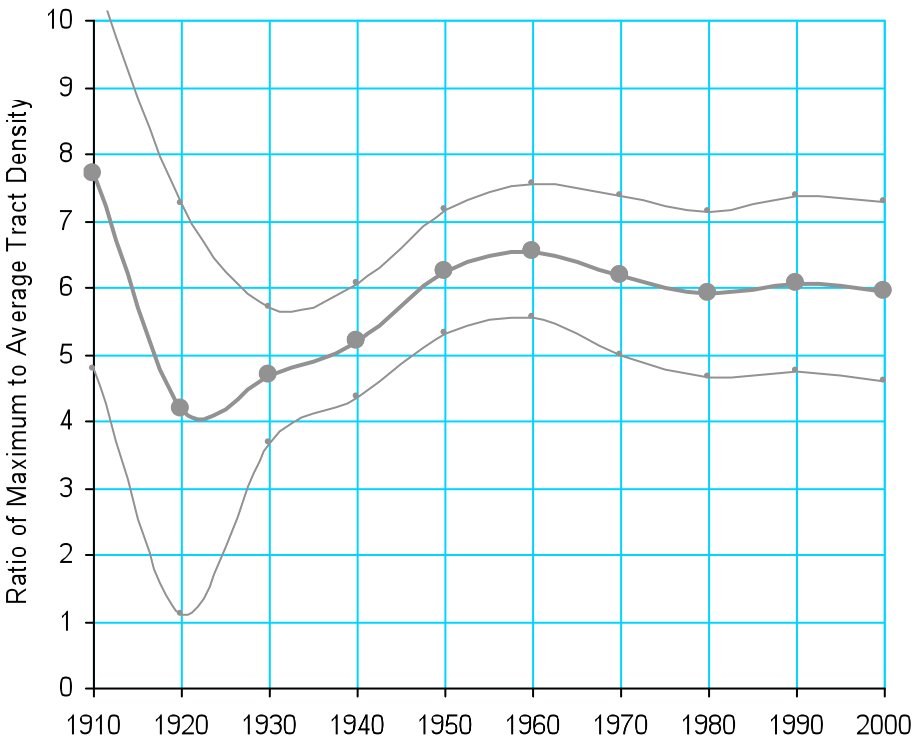


Note: Thinner black lines display the 95 percent confidence intervals for the mean values of maximum tract density in a given decade. Confidence intervals for 1920 are not shown because there were only 2 observations for the change in maximum density between 1910 and 1920.

In more general terms, we found that the Pearson correlation between average tract density and maximum tract density in this data set was 0.829. We can also say with a 95 percent level of confidence that the mean ratio between the two for the period studied was 5.91±0.37. We can conclude, therefore, that information about average densities does tell us something about maximum tract densities. That said, there are outliers that do not conform to this relationship. New York, of course, is a case in point. Its average tract density in 2000 was 26.4 persons per hectare, some 80 percent above the average for the cities studied. Its maximum density was 419 persons per hectare, more than four times the average for the cities studied.

It may well be that small areas with high concentrations of people are gradually becoming a thing of the past and that the urban population is becoming more evenly spread out. This appears to be the case in Boston, as the illustration on the cover of this paper shows. If that were the case for all cities, then the ratio between maximum tract density and average tract density in these cities should tend to decline over time. Figure 6.8 displays this ratio.

Figure 6.8: The ratio of maximum to average tract density in 20 U.S. cities, 1910-2000



An examination of this figure suggests that once the deconcentration of high-density neighborhoods in the early decades of the twentieth century was complete, the relationship between maximum tract density and average tract density became remarkably constant. In the second half of the twentieth century, maximum tract density became a fixed multiple—of the order of 6—of average tract density. The contention that maximum tract densities tend to become more similar to average tract densities over time does not appear to be supported by this evidence. It may be that both are declining at similar rates and that therefore the ratio between them tends to remain the same.

A more traditional way to look at the decline in the spatial variation in density across urban space is to examine the parameters of the density gradient and their change over time. We turn to this discussion in the next section.

Suburbanization or the decline in the gradient and intercepts of the density curves of 20 U.S. cities, 1910-2000

Edwin Mills, who has written extensively on sprawl and prefers to refer to it with the non-pejorative term *suburbanization*, has observed that "the deconcentration of urban areas is a long-run phenomenon that results from basic economic and technological forces and not from social forces that are specific to a single country" (paraphrased in McDonald, 1989, 378-9):

> The pervasiveness and persistence of suburbanization over long time periods and among countries with very different government and private institutions indicate that suburbanization results from powerful forces and is, presumably, deeply embedded in the urban growth process. Suburbanization's critics might show some humility (Mills, 1999, 1-2).

Colin Clark (1951) observed that urban population densities decline as the distance from the city center increases.[16] He postulated a decline at constant rate and that made it possible to calculate a density gradient. A steep gradient is associated with a city where the population density falls rapidly as distance from the city center increases. A shallow gradient is associated with a city where population densities are not very different in the center and everywhere else. The density gradient can be calculated by measuring the average population density in rings about the city center, plotting this average on the Y-axis with the distance of the ring from the center on the X-axis, and fitting a negative exponential curve[17] to this set of points. Another way of measuring the density gradient, and the one used here, is to plot the average density of each census tract against the distance of its centroid from City Hall, and fitting a negative exponential curve to this set of points

As we noted in the introduction, there is good, though scattered, empirical evidence to support the claim that population density gradients have fallen in absolute value over time. Mills and Peng (1980, tables 2, 4 and 8, 315-8) present evidence that the density gradients of U.S. metropolitan areas, London, and Mumbai have been decreasing steadily since the nineteenth century. Ingram and Carroll (1981, table 5, 266) report on the decline of density gradients from 1950 to 1970 in 10 Latin American cities. Jordan, Ross and Usowski (1998, 614) report on more recent declines in U.S. cities: "[d]ensity gradients became smaller in absolute value from 1970 to 1980 and from 1980 to 1990 indicating continuing decreases in centralization (increases in suburbanization) in virtually all metropolitan areas". These declines are predicted by the classical economic models of the monocentric city developed by Alonso (1964), Muth (1969) and Mills (1972), models that assume that all employment is concentrated at the center and all trips take place to and from the center. When transport costs decline relative to incomes and incomes increase relative to land prices on the urban fringe, cities become more spread out. In general, then, there is accumulated evidence to show that central and outlying densities have become more similar, and the metropolitan center has thus decreased in importance as a preferred location for residences.[18]

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[16] For a review of the literature on urban population densities see McDonald (1989).

[17] The curve typically has the function $d_r = d_o e^{-\square r}$, where d_r is the average density in a ring at a distance r from the city center, d_o is the intercept or the estimated density at the center, and □ is the density gradient.

[18] It is important to note here that the metropolitan center has decreased in importance not only for residences but also for jobs. The urban core is no longer the primary location of employment and its share of total urban employment continues to decline. In 2000, for example, only 17.4% of all commuting trips in U.S. metropolitan areas were from the suburbs to the central city (U.S. Census data cited in Hanson, 2004, table 1.3, 22). The average share of total metropolitan employment in the Central Business Districts (CBDs) of 38 international cities declined from 23.4% in 1960 to 20.4% in 1970, to 18.3% in 1980 and to 15.8% in 1990 (Demographia, 2000).

We examined the data set for the 20 U.S. cities to see whether the gradients and intercepts of the density curves of cities declined over time in parallel with the declines in average tract densities.

Figures 6.9 and 6.10 show the declines in the gradients and intercepts of the density functions for the 20 U.S. cities studied. Figure 6.9 shows that the density gradients in the U.S. cities studied have definitely become flatter over time and that the high values that were typical in the first half of the twentieth century can no longer be observed anywhere. It appears that larger cities now tend to have smaller density gradients than smaller ones. Except for Syracuse, Minneapolis, St. Paul, and Milwaukee, all cities have gradient values less than 0.05, and Los Angeles has the lowest gradient value: 0.02. The mean value for the density gradient has clearly declined over time, but this decline is also observable in all individual cities, even in New York. In fact, with the exceptions of Syracuse and St. Paul in 1990, no city in the U.S. has had any increase in its density gradient in the second part of the twentieth century.

Figure 6.9: The decline in density gradients in 20 U.S. cities, 1910-2000

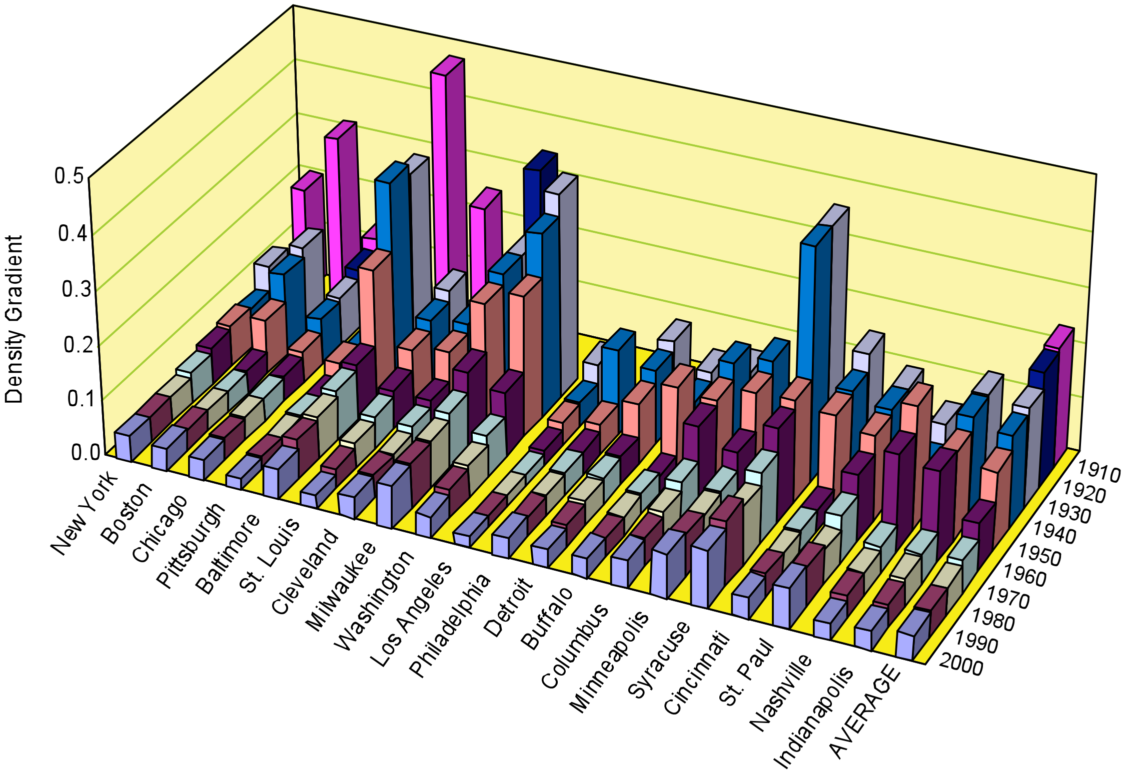
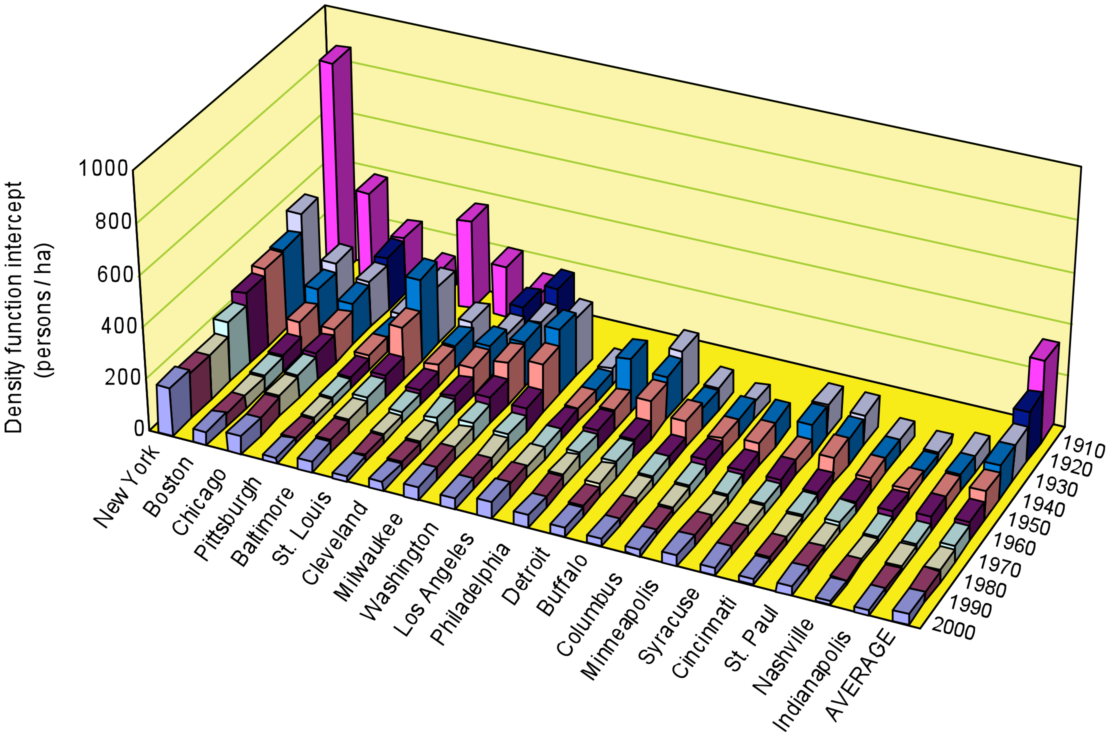


Figure 6.10 shows that the density curve intercepts, which are, in fact, the expected population density at the centers of cities have also declined substantially in the twentieth century. In fact, except for New York that still has a substantial population density at its center, with an intercept of 190 persons per hectare in 2000, all other cities had intercepts

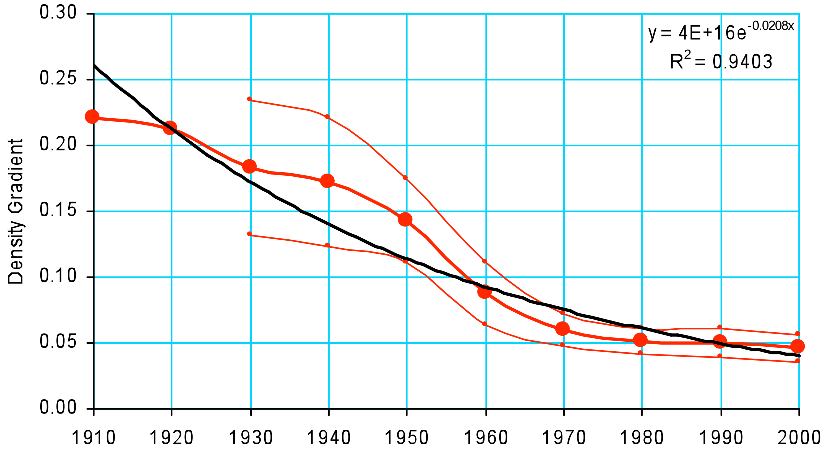
below 75 persons per hectare in that year. Nashville had the lowest intercept in 21000—14 persons per hectare.

Figure 6.10: The decline in the intercepts of the density functions of 20 U.S. cities, 1910-2000



The graphs showing the average declines in the values of the gradients and intercepts of the 20 cities studied are shown in figure 6.11 and 6.12. As figure 6.11 shows, the average density gradient declined significantly over time in U.S. cities, to one-fourth or one-third what it was in the earlier decades of the twentieth century. In other words, the difference between central city densities and peripheral densities is now much smaller than it used to be. This is, as we noted earlier, one of the five measurable attributes of urban expansion or ‘sprawl’: Suburbanization. When we fit a negative exponential curve to the average values of the density gradient in different decades, we can estimate that density gradients have been losing value, on average, at the rate of 2 percent per annum during the twentieth century.

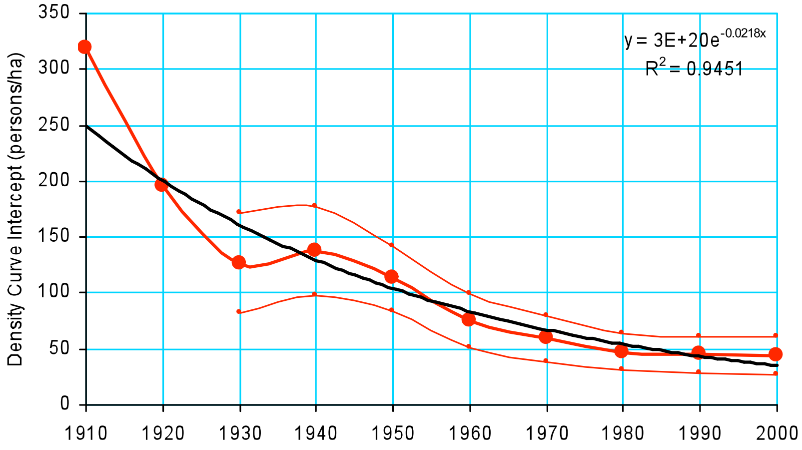
Figure 6.11: The decline in the average density gradient in 20 U.S. cities, 1910-2000



Note: Thinner lines display the 95 percent confidence intervals for the average values of the density gradient in a given decade. Confidence intervals for 1910 and 1920 are not shown because there were only 7 and 2 observations respectively for these two decades.

The reader should note that it is possible for the density gradient to decline and for average density to go up, rather than down, if the density curve intercept increases sufficiently. This, however, did not happen. As figure 6.12 shows, the mean value of the density curve intercept declined, also probably to one-fourth or one-third of its value in the early decades of the twentieth century. A comparison of the negative exponential curves fitted to average tract density, the density curve gradient and the density curve intercept suggest that all three declined, on average, by 2 percent per annum during the twentieth century. In short, while U.S. cities became less dense, their spatial structure also became more uniform.

Figure 6.12: The average decline in the density curve intercept in 20 U.S. cities, 1910-2000

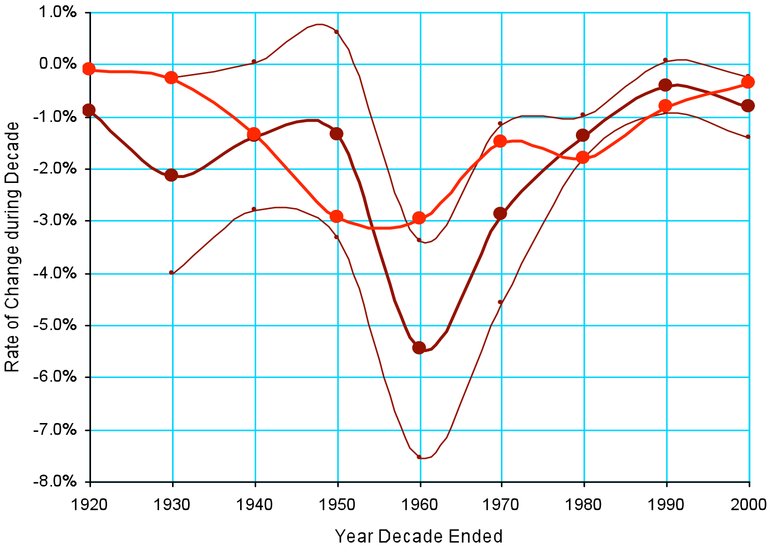


Note: Thinner lines display the 95 percent confidence intervals for the average values of the density gradient in a given decade. Confidence intervals for 1910 and 1920 are not shown because there were only 7 and 2 observations respectively for these two decades.

Did the changes in rates of change in the gradient and intercept of density function of U.S. cities parallel the changes in the rate of change in average tract density? When we look at the change in average tract density and in the density gradient in every decade in every city in this data set, we find a total of 150 cases of change in density and gradient. In 115 of these cases, or 77 percent, a change in average tract density was accompanied by a change in the same direction in the density gradient. The same was true for the intercept of the density curve. In 127 of these cases, or 85 percent, a change in average tract density was accompanied by a change in the same direction in the density curve intercept.

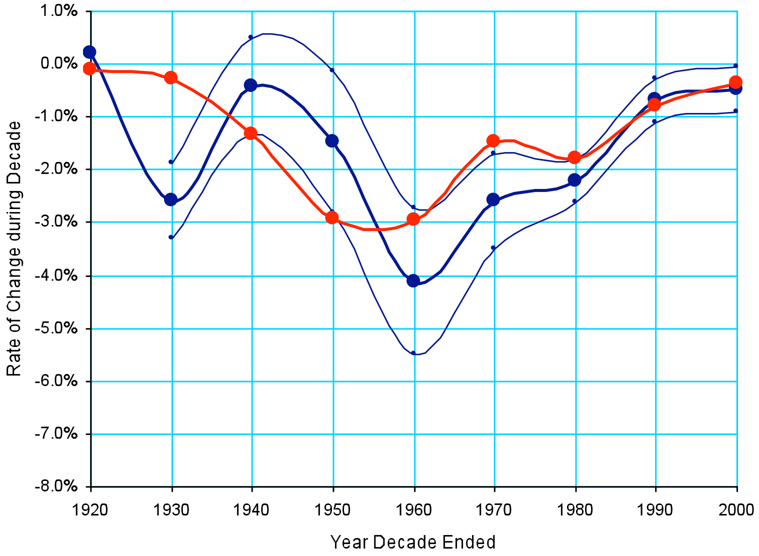
We can examine whether suburbanization and density decline paralleled each other in U.S. cities in the twentieth century in more detail by looking at their respective rates of change over time. Figures 6.13 and 6.14 examine the average rates of change in every decade in the density gradient and intercept (shown in dark red and dark blue respectively) in comparison to the rates of change in average tract density (shown in red in both figures). Both figures show that suburbanization started early in the twentieth century, before average densities began to decline. It slowed down slightly in the 1930s, and when average densities began to decline at a rapid rate in the 1940s and 1950s, suburbanization followed with a short time lag of a decade of less. Both rates of decline were at their maximum in the 1950s. Then both suburbanization and average density decline started to slow down to rates below 1 percent per annum in the 1990s.

Figure 6.13: the rate of change of the density gradient (dark red) compared to the rate of change in average tract density (red) in 20 U.S. cities, 1910-2000



Note: Thinner lines display the 95 percent confidence intervals for the average values of the density gradient in a given decade. Confidence intervals for 1920 are not shown because there were only 2 observations for the change in the gradient between 1910 and 1920.

Figure 6.14: the rate of change of the density function intercept (dark blue) compared to the rate of change in average tract density (red) in 20 U.S. cities, 1910-2000



Note: Thinner lines display the 95 percent confidence intervals for the average values the density curve intercept in a given decade. Confidence intervals for 1920 are not shown because there were only 2 observations for the change in the intercept between 1910 and 1920.

We can summarize the findings in this section as follows:

- Average tract density in the 20 U.S. cities studied declined from 69.6 persons per hectare in 1910 to 14.6 per hectare in 2000, roughly a five-fold decline.

- Average tract densities declined in 19 out of 20 cities studied, and the average rate of decline for the entire period was 1.92 percent per annum.

- The single exception was Los Angeles, where average tract densities have been *on the increase* since 1940 and are now the highest among the 20 cities studied.

- The rate of decline in average tract density appears to have peaked in 1940s and 1950s, when it averaged 3 percent per annum and; it declined to 0.3 percent per annum in the 1990s.

- Six out of 20 cities studied registered an increase in average tract density in the 1990s: New York, Washington, Los Angeles, St. Paul, Syracuse, and Nashville.

- Hence, while average densities in U.S. cities have been in general decline for almost a century, they may slowly be reaching a plateau.

- Maximum tracts densities declined from an average of 600 persons per hectare in 1910 to an average of 100 persons per hectare in 2000, a six-fold decline.

- Towards the end of the twentieth century, the decline in maximum tract density in U.S. cities slowed down to a rate close to zero (-0.35 percent).

- In general, declines in average tract density in U.S. cities in the twentieth century were accompanied by parallel declines in maximum tract density.

- From 1950 onwards, maximum tract density in U.S. cities became a fixed multiple—of the order of 6—of average tract density.

- The average density gradient in U.S. cities declined over time to one-fourth or one-third what it was in the earlier decades of the twentieth century.

- In fact, density gradients in U.S. cities have been declining, on average, at the rate of 2 percent per annum during the twentieth century.

- The mean value of the density curve intercept also declined, to one-fourth or one-third of its value in the early decades of the twentieth century.

- Average tract density, the density curve gradient and the density curve intercept all declined, on average, by 2 percent per annum during the twentieth century.

- In general, therefore, we can confirm that declines in average tract density were accompanied by suburbanization.

We conclude this section by repeating our assertion that average tract densities in U.S. metropolitan areas have been in decline for almost a century, and certainly for more than the single decade 1990-2000. This suggests that the global decline in average built-up area density is more than a decade old and that it is possibly a century old. To test this suspicion in a more rigorous manner, we explored the change in urbanized area density in a global sample of thirty cities during the last two centuries. We now turn to the discussion of our findings regarding this historical sample of cities.

VII. DENSITY DECLINE IN THE GLOBAL SAMPLE OF 30 CITIES, 1800-2000

Urban expansion maps, 1800-2000

For this phase of our study, we focused on thirty cities in all geographic regions. Twenty-seven of these cities were a subset of our global sample of 120 cities and three cities—Jeddah, Nairobi, and Santiago—were added to lend this smaller sample a better regional balance (see list of cities in table 3.2 above). We collected historical maps of the built-up areas of these cities, at roughly 25-year intervals, from 1800 or thereabouts or, in the case of newer cities, from the year their population first reached 20,000. These maps were then digitized and geo-referenced with a focus on including all built-up areas, as well as the open spaces within them. In general, therefore, the digitized maps are maps of the *urbanized area* of cities, as defined earlier, to be distinguished from the built-up area, the city footprint, or the urban tract area of cities. We then constructed a composite map of the urbanized area for each city with ArcGIS software, showing its expansion over time. The composite maps for Buenos Aires, Cairo, Paris and Bangkok are shown in Figures 7.1-7.4, and the composite maps for all 30 cities, their populations, their urbanized areas, and their urbanized area densities are shown in Annex II.

Figure 7.1: The expansion of Buenos Aires, 1809-2000

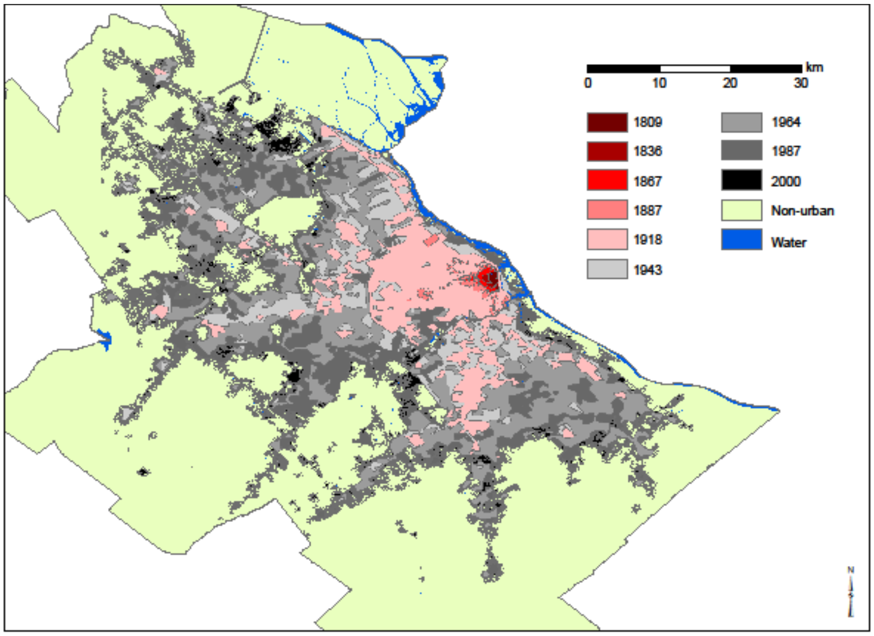


Figure 7.2: The expansion of Cairo, 1800-2000

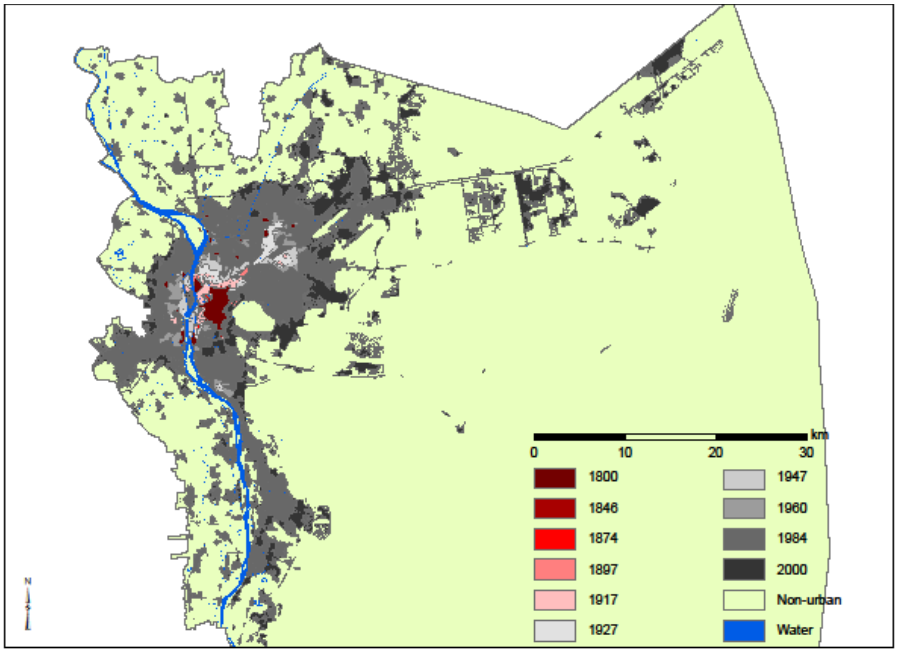


Figure 7.3: The expansion of Paris, 1800-2000

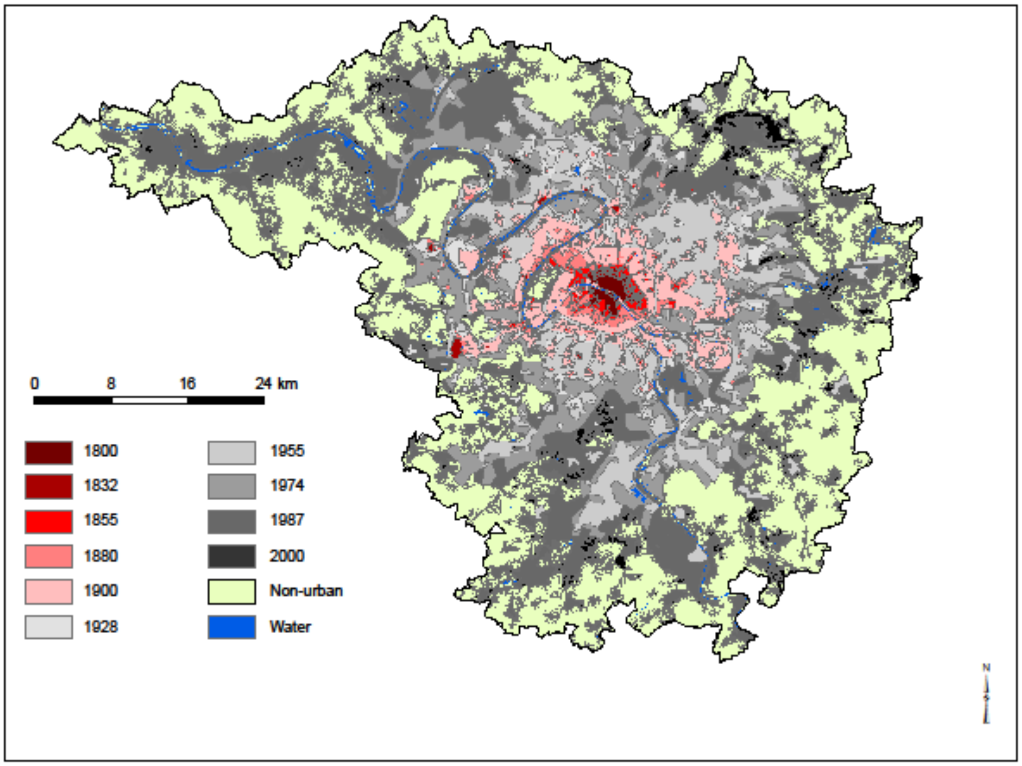
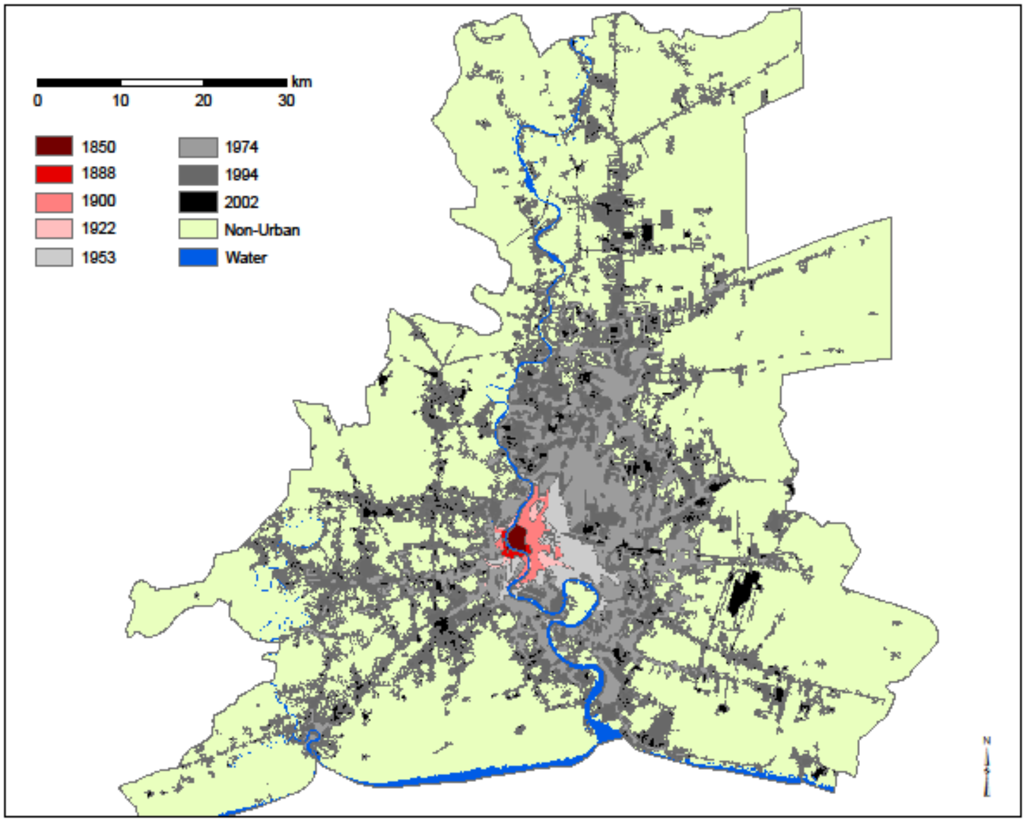


Figure 7.4: The expansion of Bangkok, 1850-2002



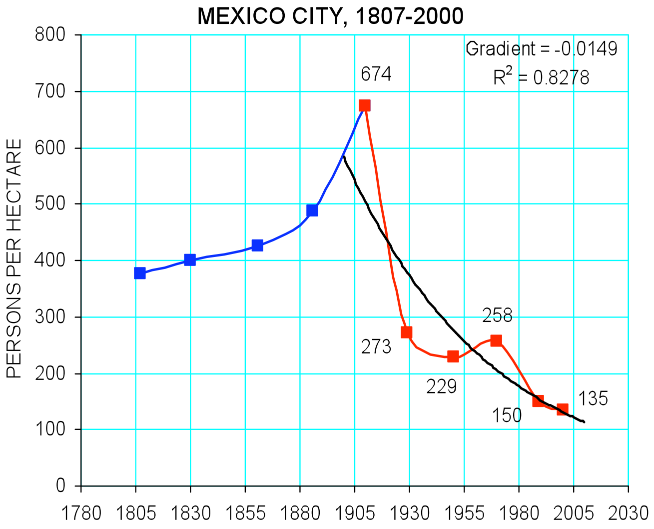
Between 1809 and 2001, the area of Buenos Aires shown in figure 7.1 increased from 190 hectares to 160,500 hectares—and 845-fold increase. Similarly, between 1800 and 2000, the area of Cairo shown in figure 7.2 increased from 1,300 hectares to 66,500 hectares—a 65-fold increase. The area of Paris shown in figure 7.3 increased from 1,200 to 18,000 hectares—150-fold increase—between 1800 and 2000, and the area of Bangkok shown in figure 7.4 increased from 600 to 135,000 hectares—a 235-fold increase—between 1850 and 2000. In short, there was a massive expansion in the area of these cities. Similar levels of expansion can be observed in the rest of the cities in this global historical sample.

Density change, 1800-2000

What is of interest to us is whether the growth in area in any given city between two time periods was faster or slower than the growth of the population of this city during this period. If it was faster, its density increased and the city became more sprawled. If it was slower, its density decreased and the city became more compact. To explore this question, we obtained population figures for each city at different time periods and interpolated the population figures of each city at the various times corresponding to the dates of its various urbanized area maps. This made it possible to calculate the urbanized area density for each city for each time period corresponding to each of its maps.

Figure 7.5 illustrates this calculation for Mexico City from 1807 to 2000. In this and in all other density figures, we identified the highest density peak—in this case 674 persons per hectare in 1910—and showed the density in later periods in red and in earlier periods in blue. In Mexico City, densities increased in a regular fashion in the nineteenth century and declined in a regular fashion in the twentieth century. If we fit a negative exponential curve to the declining densities from their peak in 1910 to the year 2000, we find that the average rate of density decline during this period was 1.49 percent per annum, and that the fit of the negative exponential curve is good (R^2=0.83). All in all, we can observe a 5-fold decline in the density of Mexico City between 1901 and 2000.

Figure 7.5: Density change in Mexico City, 1807-2000



Figures 7.6-7.10 show the density curves for each of the 30 cities in the historical sample. The 30 cities are divided informally into groups based on the characteristics of their density curves.

Figure 7.6 shows the density curves for six cities that experienced relatively continuous density declines during the past two centuries.

Figure 7.7 shows the density curves for six cities that experienced increases in density during the nineteen century (and in the case of Kuwait City until 1950) and then experienced density declines during the twentieth century.

Figure 7.8 shows the density curves for six cities that had an additional density peak before their highest peak.

Figure 7.9 shows the density curves for six cities that are in decline, but appear to be declining at a slower rate in recent decades.

Finally, figure 7.10 shows the density curves for six cities that had only minor and irregular density declines over the years.

The notes at the bottom of each figure present the multiple of the decline in density from its peak and the dates where there were sizable increases in density, where ‘sizeable’ is defined as a rate of density increase in excess of one percent per annum.

Figure 7.6: Density change 1800-2000 ─ Cities with continuous declines

Algiers: 10-fold decline in density from 1800 peak; no sizeable increases in density.

London: 7-fold decline in density from 1830 peak; no sizeable increases in density.

Manila: 6-fold decline in density from 1802 peak; sizeable increase in density 1945-1971.

Bangkok: 5-fold decline in density from 1888 peak; sizeable increases in density 1900-1922 and 1984-1994.

Tel Aviv: 8-fold decline in density from 1917 peak; sizeable increase in density 1944-1956.

Accra: 4-fold decline in density from 1903 peak; sizeable increase in density 1929-1943.

Figure 7.7: Density change 1800-2000 ─ Cities with single density peaks

Moscow: 4-fold decline in density from 1914 peak; sizeable increase in density 1836-1914.
Mexico City: 5-fold decline in density from 1910 peak; sizeable increase in density 1807-1910.
Tokyo: 3-fold decline in density from 1910 peak; sizeable increase in density 1858-1910.
Teheran: 3-fold decline in density from 1925 peak; sizeable increase in density 1850-1899.
Kuwait City: 5-fold decline in density from 1942 peak; sizeable increase in density 1900-1942.
Chicago: 4-fold decline in density from 1915 peak; sizeable increase in density 1850-1915.

Figure 7.8: Density change 1800-2000 – Cities with twin density peaks

Shanghai: 6-fold decline in density from 1944 peak; sizeable increase in density 1914-1944.
Beijing: 7-fold decline in density from 1974 peak; sizeable increases in density 1900-1929.
Cairo: 3-fold decline in density from 1897 peak; sizeable increases in density 1800-1897 and 1927-1947.
Warsaw: 14-fold decline in density from 1794 peak; sizeable increases in density 1831-1936 and 1978-1992.
Guatemala City: 2-fold decline in density from 1950 peak; sizeable increase in density 1900-1950.
Nairobi: 2-fold decline in density from 1978 peak; sizeable increase in density 1926-1978.

Figure 7.9: Density decline 1800-2000 ─ Cities with flattening density declines

Sao Paulo: 2-fold decline in density from 1881 peak; sizeable increase in density 1974-1988.
Buenos Aires: 3-fold decline in density from 1867 peak; sizeable increase in density 1918-1943.
Paris: 9-fold decline in density from 1800 peak; no sizeable increases in density.
Jeddah: 10-fold decline in density from 1900 peak; sizeable increase in density 1964-1973.
Istanbul: 3-fold decline in density from 1872 peak; sizeable increase in density 1960-1987.
Sydney: 21-fold decline in density from 1860 peak; sizeable increase in density 1808-1860.

Figure 7.10: Density change 1800-2000 ─ Cities with low rates of density decline

Mumbai: 2-fold decline in density from 1865 peak; sizeable increases in density 1814-1865, 1931-1954, and 1968-1992

Kolkota: 2-fold decline in density from 1909 peak; sizeable increases in density 1817-1839, 1858-1909, and 1961-1990.

Santiago: 2-fold decline in density from 1906 peak; sizeable increase in density 1850-1906 and 1970-1989.

Los Angeles: 40 % decline in density from 1877 peak; minor increase in density 1950-2000.
Lagos: 25 % decline in density from 1850 peak; sizeable increase in density 1952-1978.
Johannesburg: 20 % decline in density from 1900 peak; sizeable increases in density 1938-1957 and 1984-2000.

Global patterns of density change, 1800-2000

Ten general patterns emerge from the examination of the graphs presented in the previous section and the data underlying them:

1. Urban densities peaked circa 1890

Peak densities are a thing of the past. This can be seen graphically in figure 7.11 that shows the year that different cities attained their latest peak density.[19] As the figure shows, the latest city in our sample to attain its peak density was Guatemala City, and it attained it in 1950, some sixty years ago. In fact, we can say with 95 percent confidence that the average year that a city was likely to attain its peak density was 1890±15, namely more than a century ago.[20] If this sample of cities is indeed representative, then we can conclude that urban densities the world over have now been in decline for a century.

Peak densities also tended to decline over time and cities that attained their peak density later had lower peak densities than cities that attained their peak density earlier. The red line in figure 7.11 indicates that peak densities were significantly lower in later periods than in earlier ones. Although the overall fit of the line to the data is low (R^2=0.183), we can say with a 95 percent level of confidence that both the intercept at the Y-axis and the coefficient in the regression equation were significantly different from zero.

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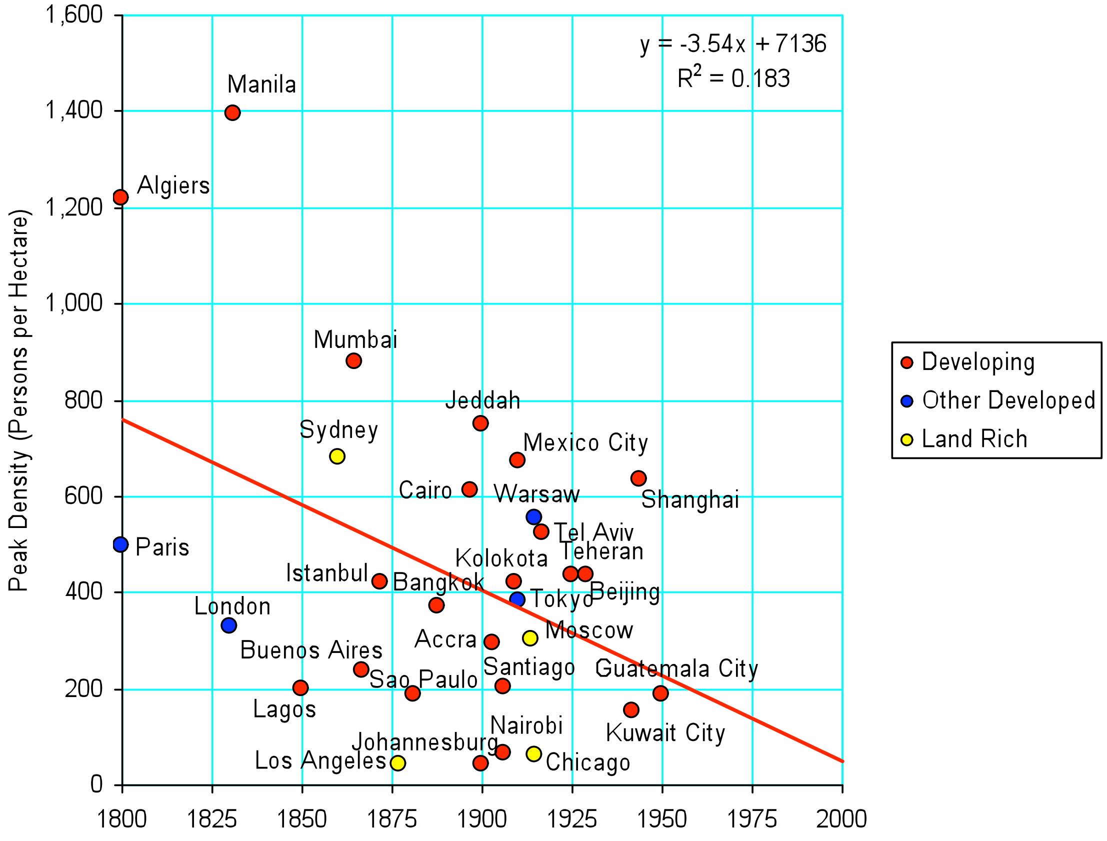
[19] If there were two peak densities within 5 percent of each other, the chose the later density as the peak density.

[20] Since only 8 of the 30 cities are in developed countries, we cannot say with any confidence that cities in developed countries reached their peak densities earlier than cities in developing countries. We can only say with 95% confidence that the former reached their peak density in 1878±37 and the latter in 1895±16.

Figure 7.11: The year cities in the global historical sample attained their peak density



2. Peak densities were preceded by periods of densification

We note than in two thirds of the cities in the sample, peak density was preceded by a period of increasing density (shown in blue). In some cities, this period of increasing density may have started earlier—in the seventeenth century—but for dates earlier than 1800 we did not obtain any data for this study. With the data we have we can, however, distinguish between the average 10-year annual rates of density change in cities before and after they attained their peak density, and when we do we find that they were significantly different. We can say with 95 percent level of confidence that the average 10-year annual rate of density change *before* cities attained their peak density was positive and different from zero, and was indeed 0.86±0.23 percent per annum. We can therefore conclude, together with Mumford and Clark quoted earlier, that cities experienced significant increases in density before their densities began to decline.

3. Cities experienced both increasing and declining densities in the nineteenth century and mostly declining densities in the twentieth century

We can say with 95 percent level of confidence that the average 10-year rate of density change in the nineteenth century was not different from zero, and was indeed 0.00±0.24

percent per annum. We can also say with 95 percent level of confidence that the average 10-year rate of density change in the twentieth century was significantly different from zero, and was indeed -1.00±0.29 percent per annum. For simplicity's sake, therefore, we can consider the turn of the century—the year 1900—to be the turning point when urban population densities began to decline in earnest as new transportation technologies became ubiquitous. The year 1900 is also within the margin of error of the average peak year in the sample, 1890±15.

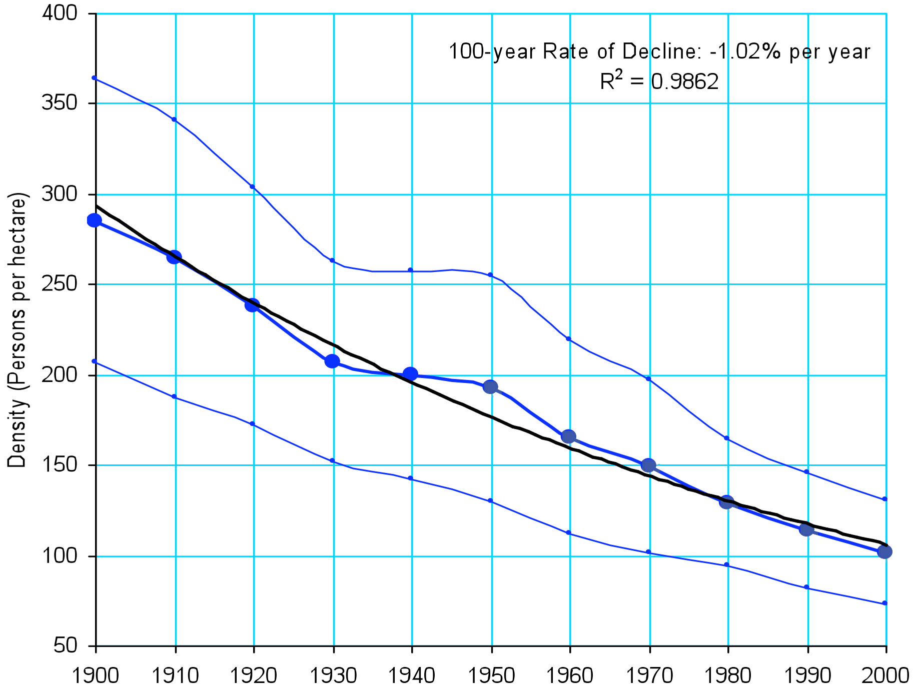
4. Densities declined threefold from their peaks

We observe that average density at the peak for the historical sample was considerably higher than average density in the year 2000. In fact, we can say with a 95 percent level of confidence that average peak density in this sample was 429±121 persons per hectare and by the year 2000 it declined to 101±21 persons per hectare. These averages are clearly significantly different from each other, and we can also say with 95 percent level of confidence that average density in 2000 was 31.4±8.0 percent of peak density. We can therefore conclude that there was a threefold decline in average urban population density between peak densities and densities in the year 2000.

5. Density declined threefold in the twentieth century

This is illustrated graphically in figure 7.12. It shows the average density for the cities in the sample in every decade from 1900 to 2000, as well as the 95 percent confidence levels for this average. The figure shows that urban population densities declined 3-fold, on average, from 285±79 to 102±29. When we fit a negative exponential curve to the average densities from 1900 to 2000 in figure 7.12, we obtain a very good fit ($R^2 = 0.986$) and we can determine that the average annual 100-year rate of density decline in the twentieth century was of the order of 1.0 percent per annum. When we fit a negative exponential curve to the average densities from 1950 to 2000 in figure 7.12 (not shown), we also obtain a very good fit ($R^2 = 0.998$) and we can determine that the average annual 50-year rate of density decline from 1950 to 2000 was of the order of 1.27 percent per annum.

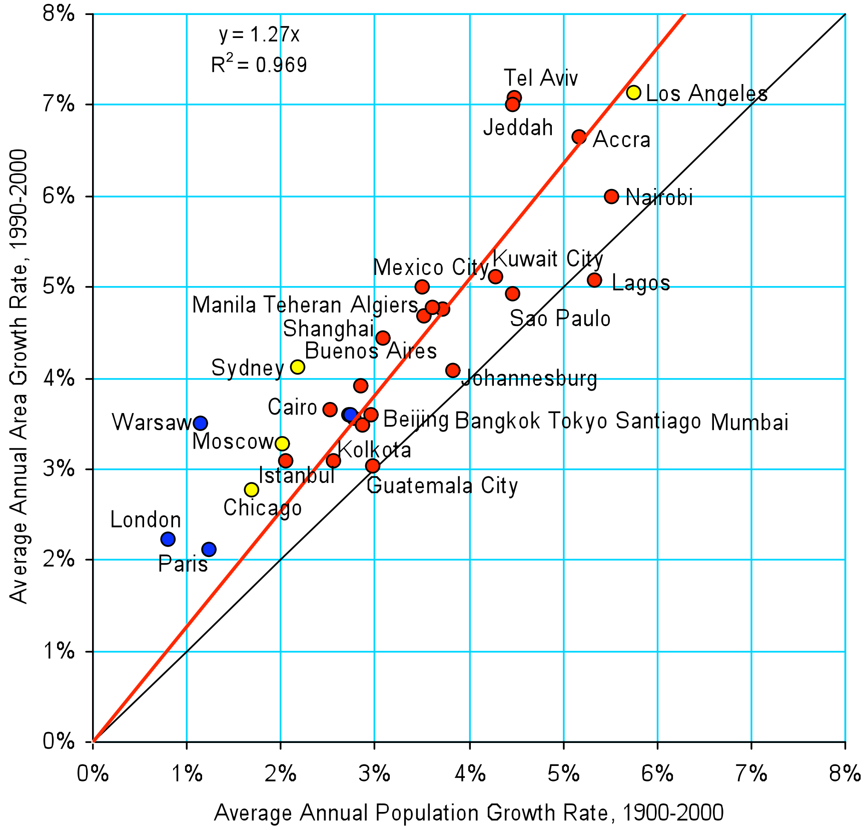
Figure 7.12: The decline in average density in the historical sample of cities, 1900-2000



6. The areas of cities grew 27 percent faster than their populations in the twentieth century

Another way to look at density decline in the twentieth century is to note that, on the whole, the rate of expansion of the urban areas of cities in this century typically exceeded their population growth rate, a key indication of sprawl. If, as some authors do — Brueckner and Fansler (1983), Brueckner (2000), Ewing et al (2002), Fulton et al (2001), and El Nasser and Overberg (2001), to cite a few examples — we define sprawl as the expansion of an urban area at a faster rate than its population growth rate, then we can say that almost all cities sprawled during the twentieth century taken in its entirety, i.e. from 1900 to 2000. This is illustrated graphically in figure 7.13 that compares the average rate of population growth to the average rate of area growth for every city in the sample from 1900 to 2000. These rates were calculated assuming a constant rate of growth in both population and area for the entire century.

Figure 7.13: A comparison of population and area growth rates, 1900-2000



The thin black diagonal line in figure 7.13 is the 45° line. If the rate of area growth were equal to the rate of population growth for any city, its marker would fall exactly on that line. As it turns out, all city markers except that of Lagos are above the line, indicating that the rate of growth of their areas exceeded the rate of growth of their populations in the twentieth century. London's rate of physical expansion, for example, was more than double its rate of population growth and Warsaw's was more than triple. On the whole, it appears that population growth in cities in developed countries (except for Los Angeles) was slower than that of developing countries, but that they expanded at a faster rate. On average, the rate of urban expansion for all cities was 1.27 times the population growth rate, shown here as the slope of the red line, which is the regression line of best fit to the data (R^2=0.969).

7. The global deconcentration of cities started in the last two decades of the nineteenth century

We can look at the change in density over time in more detail by examining the average 10-year rates of change in density and their 95 percent confidence levels in every decade, from 1800 to 2000, displayed in figure 7.14 below. We must preface our discussion of figure 7.14 by noting that the margins of error are too wide to draw any solid statistical conclusions about the 10-year rates of change decade by decade. That said, we note that in several decades in the nineteenth century—from 1840 to 1880—the average rates of change in density were positive, i.e. cities, on the whole, became denser. In contrast, during the twentieth century, the rates of change in density have always been negative, i.e. cities, on the whole, became less dense. In fact, slightly more than half (54 percent) of the 10-year rates of change in density observed in the nineteenth century were positive, while only a third (33.1 percent) were positive in the twentieth century.

Figure 7.14: The 10-year rate of change in average density, 1800-2000

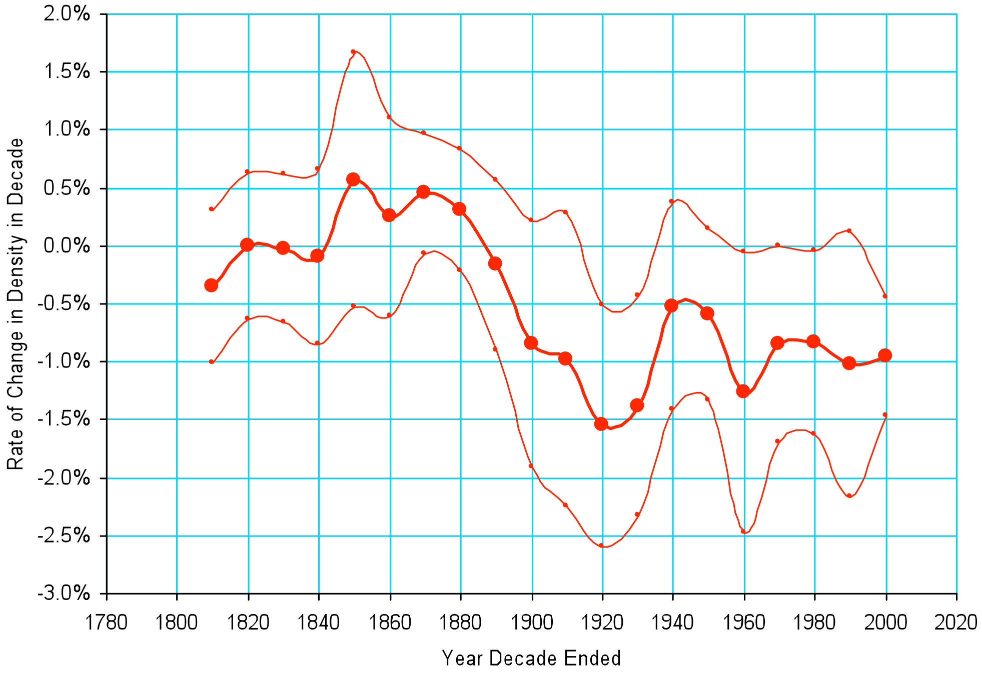


Figure 7.14 shows that the global deconcentration of cities appears to have started in the last two decades of the nineteenth century and accelerated during the first two decades of the twentieth century. Jackson, in his important 1972 study titled "Urban Deconcentration in the nineteenth Century: A Statistical Inquiry," already pointed this out in the case of U.S. cities:

> Despite the wide publicity given to the post-World War II suburban trend and to the population decline of central cities, it is here suggested that the large-scale dispersal of urban residents into exurbia and suburbia is not a new phenomenon, but is rather a direct continuation of a spatial pattern characteristic of metropolitan America for 125 years. Five indicators of deconcentration—higher peripheral rates of growth, leveling of densities, absolute loss of population at the center, movement of the upper and middle classes to the periphery, and lengthening of the average journey to work—were all present in the largest American cities before the introduction of the electric streetcar in the 1890s. (Jackson 1972, 140)

Clearly, this early period of global urban deconcentration had nothing to do with the adoption of the private automobile as a means of urban transport, since automobiles did not come into wide use anywhere during this period. It was most likely due to the introduction of earlier transport innovations, mostly public transport in the form of the ferry, the omnibus, the horse car, the electric streetcar, the cable car, and the commuter train. The rate of deconcentration of cities slowed down during the 1920s and 1930s, possibly as a result of the aftermath of the First World War and then of the Great Depression, and accelerated again in the 1950s and the 1960s as economies recovered, a period of global prosperity followed, and private automobiles became ubiquitous. From the 1970s onwards, the short-term global rate of decline in density appears to have settled at the annual rate of 1 percent per annum.

8. There are similarities and differences in the timing of changes in density in the U.S. and elsewhere

We can compare the 10-year rates of density change in the sample of 20 U.S. cities with the global historical sample of 30 cities to examine if the changes in density were parallel to each other.[21] This comparison is shown in figure 7.15, and, as before, we note that because of the paucity of data, we cannot make statistically significant statements about their commonalities or differences. We must also be aware that in the U.S. cities we measured average tract densities and in the global historical sample we measure urbanized area densities. That said, we can see that the rates of decline are negative in the twentieth century in both groups of cities.

We have collected the nineteenth century ward maps and the population data for each ward for this group of cities, but they have not yet been geo-referenced and digitized and their analysis will unfortunately need to be postponed. From the examination of the available data from 1910 onwards it may appear as though the beginning of the fast decline in densities in the U.S. started later than in other parts of the world: at the early decades of the twentieth century it was almost zero while in the world at large densities were already declining at the rate of 1.0-1.5 percent per annum. But then, while declines in the rest of the world slowed down in the 1920s and 1930s and stabilized in the 1940s, U.S. cities lost density rapidly during this period, at much faster rates than in cities elsewhere, a pattern due in large part to the fact that widespread automobile ownership in the U.S. (as well as in Canada and Australia) occurred much earlier than elsewhere in Europe and Japan or in developing countries (U.N. Statistics Division, various years). In U.S. cities and in the cities in our historical sample there was acceleration in the rate of decline in density in the 1950s and the 1960s, slowing down in later decades. But while the rate of decline in U.S. cities slowed down to less than 0.5 percent, cities elsewhere continued and still continue to support declining densities of the order of 1.0 percent per annum.

We can only speculate on the beginning of massive deconcentration in U.S. cities. Hawley, for example, suggested that "urban America moved toward concentration before 1920 and toward deconcentration after that date" (Jackson 197, 113, quoting

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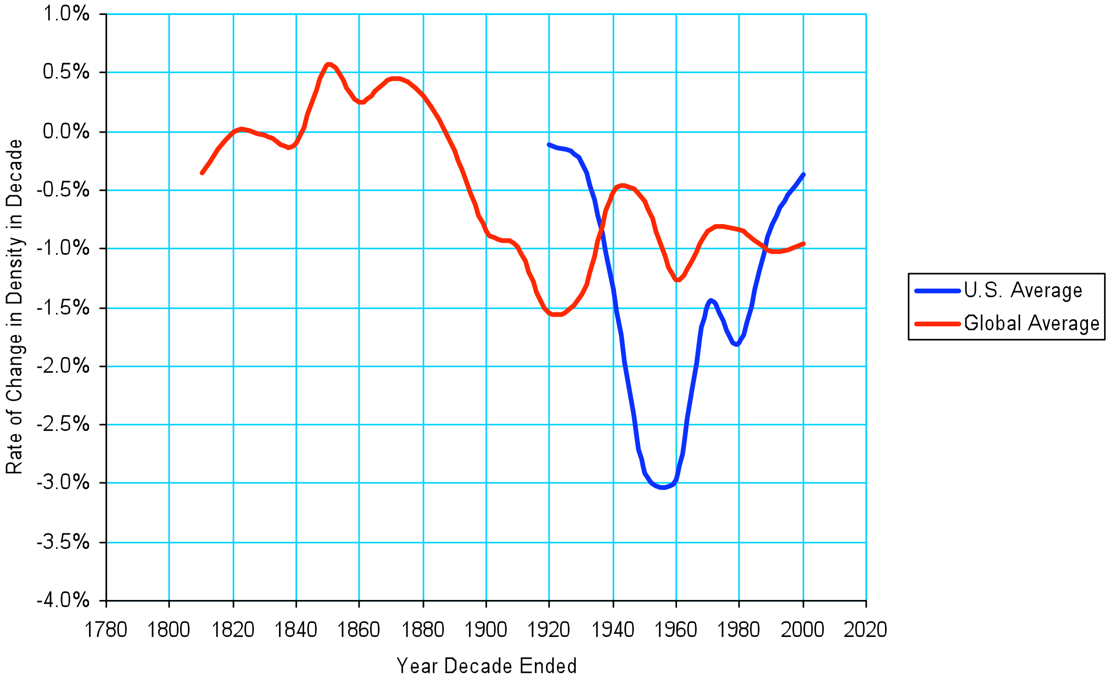
[21] The comparison of the two graphs was suggested to us by Greg Ingram.

paraphrasing Hawley, 1956). Unfortunately, the missing data for the nineteenth century in figure 7.14 make it difficult to examine Schnore's assertion that ten American cities began to deconcentrate earlier: "New York City began to experience suburbanization in the 1850s, followed by Cincinnati, San Francisco and New Haven in the 1870s, Boston and Albany in the 1880s, and Baltimore, St. Louis, Scranton and Duluth in the 1890s" (Jackson 1972, 113, paraphrasing Schnore, 1959). As noted earlier, Jackson (1972, 140), employing several indicators of deconcentration, contended that it can be traced back to the middle of the nineteenth century (Jackson 1972, 140). Whether the changes in his five indicators were sufficient to cause a decline in average tract densities—our key measure of deconcentration—in U.S. cities in the nineteenth century is a question that remains unanswered at the present time. If further research shows that this was indeed the case, then we may be able to conclude that deconcentration in the U.S. started at the same time as in cities in other countries.

Figure 7.15: A comparison of 10-year average rates of density decline in 20 U.S. cities and 30 global cities



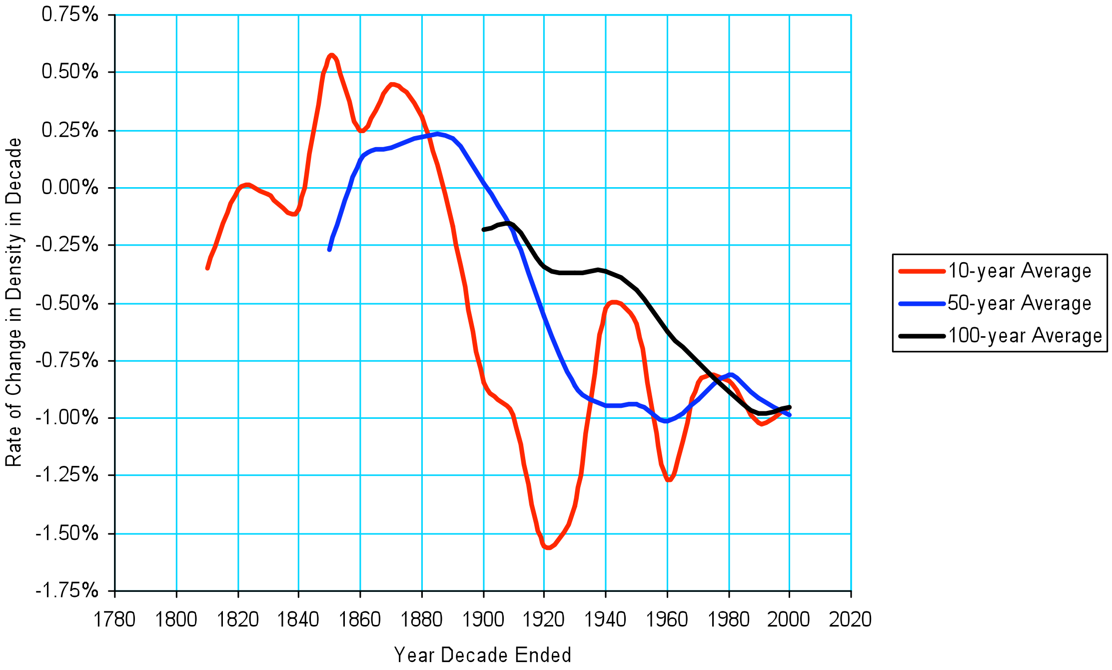
<u>9. Average short-term and long-term rates of decline from peak density were of the order of 1.2 percent and 1.5 percent per annum respectively</u>

We can say with 95 percent level of confidence that the average 10-year annual rate of density change *after* cities in the global historical sample attained their peak density was negative and significantly different from zero, and was indeed -1.17±0.24 percent per annum. When we focus attention on the negative exponential curves that estimate the long-term rate of density declines from their peak to the year 2000 for each city in the sample, more evidence emerges regarding the long-term rate of density decline. The negative exponential curves shown for every graph in figures 6.6.-6.10 have a gradient that measures the mean annual long-term rate of decline between the peak density and the density at the end of the twentieth century. We can say with 95 percent confidence that the *average gradient* of these curves for the cities in the historical sample is 1.53±0.33 percent. That is, when we look at the individual long-term declines in density in each city from its peak density to its density circa 2000, we see that, on average, these densities declined by an average of 1.5 percent per annum from peak densities. This is a more rapid rate of decline than the rate of 1.17 percent per annum observed earlier for the decline in the average 10-year after-peak density in this sample.

10. By the end of the twentieth century, short-term and long-term rates of density decline converged to 1.0 percent per annum

When we look at the average 10-year rate of density change and longer-term rates of change in density—say the 50-year rate and the 100-year rate—together, we can see that in the year 2000 they converged to a rate of decline of the order of 1 percent per annum. This is illustrated in figure 7.16 below. The longer-term rates of density decline show smaller fluctuations (and smaller error terms, not shown) than the 10-year rate. Both longer-term rates became negative at the beginning of the twentieth century and gradually settled down at approximately -1.0 percent per annum, the 50-year rate at -1.0±0.51 percent and the 100-year rate at -1.0 ±0.23 percent.

Figure 7.16: Average rates of decline in density in the historical sample



We conclude this section by repeating our assertion that average urbanized area densities in cities the world over declined significantly, in fact by a factor of three, during the twentieth century. Average urban population densities increased significantly during the nineteenth century to a peak around 1890, and, on the whole, cities became more compact in the nineteenth century and more sprawled in the twentieth century. The rates of decline in average urban densities are somewhat different, depending on the way they were calculated. The average long-term rates of decline are of the order of 1.0-1.5 percent per annum and the average short-term rates of decline are now of the order of 1.0 percent per annum.

These rates of decline, while they appear to be small, are not insignificant: In general, we can predict that if densities continue to decline at the average annual rate of 1 percent per annum, they would be 74 percent of their present value in 30-years time, 61 percent of their present value in 50-years time, and 37 percent of their present value in 100-years time. If they continue to decline at 1.5 percent per annum, they would be 64 percent of their present value in 30-years time, 47 percent of their present value in 50-years time, and 22 percent of their present value in 100-years time.

Explaining density change in the global sample of 30 cities, 1800-2000

In parallel with our attempt to explain density change in the 1990s in the global sample of 120 cities, we now turn to explaining the variations in the rate of change in density in the 30 cities in our historical sample of cities with the help of multiple regression models. As noted earlier, for each city in this sample, we have a set of maps at different dates between 1800 and 2000. For each map date, we have data on the total area and the total population of the city, and hence for the average density of the city at that date. The dependent variable in our analysis is the average annual rate of change in density between two consecutive map dates in every city in the sample. For example, between 1900 and 1922, average population density in Bangkok increased from 172 to 247 persons per hectare, at an average rate of 1.6 percent per annum. This average rate is the dependent variable in our models. There were altogether 204 consecutive map dates in this sample and we thus have 204 observations for our dependent variable.

What explains the rate of change in density between two map periods? Six of the eight hypotheses advanced to explain density change in the 1990s were tested here as well:

> Hypothesis 1: *Cities with rapidly growing populations and slow-growing populations have similar rates of change in average built-up area density*. The variable used to test this hypothesis was **Population Growth**, defined as the annual rate of population growth in the administrative region defining the city between two map periods.
>
> Hypothesis 2: *Cities in countries with rapidly growing incomes and slow-growing incomes have similar rates of change in average built-up area density*. The variable used to test this hypothesis was **Income Growth**, defined as the average annual rate of per capita GNP growth in the country between the two map periods, assuming a constant rate of change between 1990 and 2000.
>
> Hypothesis 3: *Cities with high initial densities and cities with low initial densities experience the same rate of density change over time*. The variable used to test this

> hypothesis was **Log Initial Density**, defined as the logarithm of the average built-up area density in the initial map period.
>
> Hypothesis 4: *More-populated cities experience the same rate of density change over time than less-populated cities*. The variable used to test this hypothesis was **Log Initial Population**, defined as the population of the city in the initial map period.
>
> Hypothesis 5: *Geographic constraints on urban expansion do not increase the rate of change of average densities over time*. The variable used to test this hypothesis was **Log Buildable Land**, defined as the logarithm of the share of dry land with a slope less than 15° in a circle about the center of the city with an area equal to four times the urbanized area of the city in 2000.
>
> Hypothesis 6: *Ample and cheap agricultural lands on the urban periphery do not affect the rate of change in average densities.* Because the amount of arable land per capita does not change appreciably over time, the variable used to test this hypothesis was **Log Arable Land**, defined as the logarithm of the national arable land and land in permanent crops per capita in 2000.

Two additional hypotheses were introduced into the models to account for variations in transport cost, assuming that the availability of cheap transport decreased the rate of change in density. Since automobiles did not come into use until the early twentieth century, car ownership was not used as a transport variable. Instead, we assumed that most new transport technologies came into wide use in the twentieth century. This lead to the formulation of

> Hypothesis 7: *Lower transport costs do not result in faster or slower rates of decline in average densities.* The variable used to test this hypothesis was **Before 1900? Yes or No**, as a proxy for the availability of long-range transport for commuting to work.

In addition, we assumed that as long as cities were walking cities ─ defined as being less than 50 square kilometers of 5,000 hectares in area ─ there was a tendency for densities to increase. This resulted in the formulation of

> Hypothesis 8: *Walking cities do not result in faster or slower rates of decline in average densities*. The variable used to test this hypothesis was **Walking City? Yes or No,** and it attained the value of 1 if the city was less than $50km^2$ in area and the value of 0 otherwise.

As before, independent variables were introduced into the models either as rates of change or in their logarithmic form, so as to insure normality. Figure 7.17 shows the Q-Q normality test for the rate of change in density between two map periods as the dependent variable. Except for a few outliers, most of the expected normal values for given observed values lie around the straight line, suggesting that we can assume that the dependent variable is indeed normally distributed.

The five models we tested are shown in table 7.1 below. Model 1 tests only hypotheses 1 and 2. Both are rejected. Cities with populations growing at faster rates do experience increasing rates of density change. Cites that experience economic booms accompanied by increasing incomes, experience more rapid decreases in density. But while both variables are significant at the 95 percent level, the model only explains 9 percent of the variation in the rates of density change in the sample ($R^2 = 0.094$).

Figure 7.17: Normality test for the rate of change in density as dependent variable

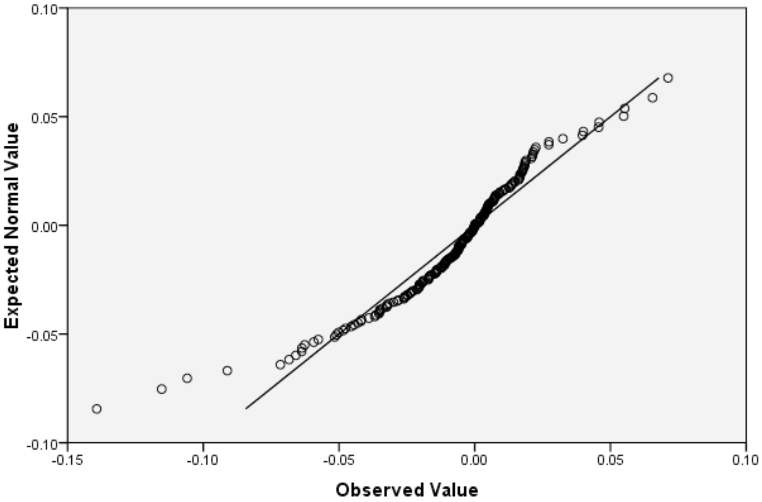


Table 7.1: Logarithmic models that explain long-term density change, 1800-2000

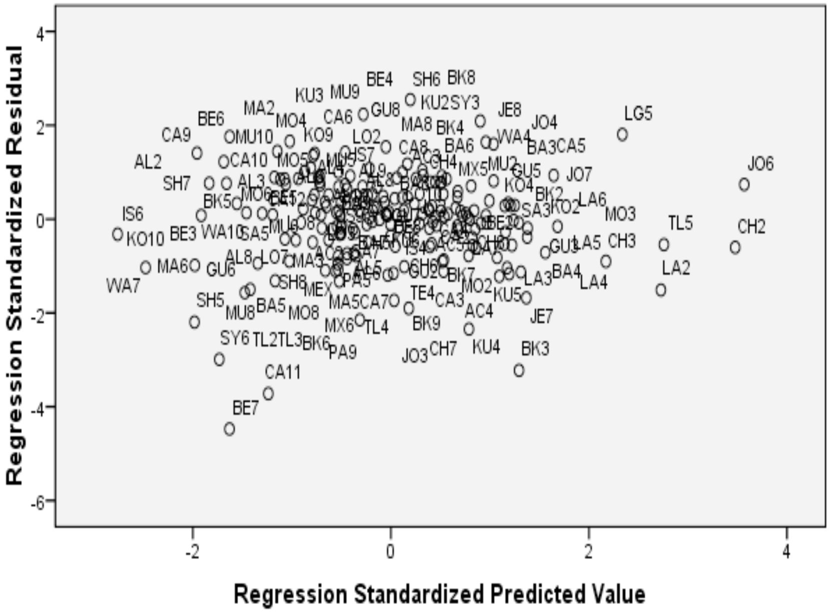
Independent Variables	Coefficients and levels of significance Model 1	Model 2	Model 3	Model 4	Model 5
Population Growth Rate	**0.424**	**0.298**	**0.439**	**0.542**	**0.403**
Signif.	*0.000*	*0.007*	*0.000*	*0.000*	*0.000*
Income Growth Rate	**-0.224**	**-0.262**	**-0.177**	**-0.175**	**-0.080**
Signif.	*0.033*	*0.012*	*0.079*	*0.077*	*0.340*
Log Initial Density		**-0.008**	**-0.010**	**-0.013**	**-0.014**
Signif.		*0.001*	*0.000*	*0.000*	*0.000*
Log Initial Population		**-0.001**	**0.002**	**0.006**	**0.005**
Signif.		*0.314*	*0.159*	*0.003*	*0.005*
Before 1900? Yes/No			**0.026**	**0.023**	**0.016**
Signif.			*0.000*	*0.000*	*0.001*
Walking City? Yes/No				**0.022**	**0.027**
Signif.				*0.004*	*0.000*
Log Buildable Land					**0.000**
Signif.					*0.987*
Log Arable Land					**0.000**
Signif.					*0.991*
Constant	**-0.018**	**0.050**	**-0.005**	**-0.054**	**-0.028**
Signif.	*0.000*	*0.078*	*0.877*	*0.113*	*0.292*
No. of Observations	204	204	204	204	196
R-Squared	0.094	0.143	0.217	0.250	0.309
Adjusted R-Squared	0.085	0.126	0.198	0.227	0.279

Model 2 tests these two hypotheses together with hypotheses 3 and 4. Hypothesis 3 is rejected: cities with high initial densities experience faster rates of density decline than cities with lower initial densities. Hypothesis 4 cannot be rejected, as the coefficient of the log of the initial population of the city cannot be said to be different from zero. All in all, this model explains 14 percent of the variation in the dependent variable ($R^2 = 0.14$).

Model 3 tests hypothesis 7 and it is rejected: As we saw in the previous section, densities in the nineteenth century tended to increase, on the whole, while in the twentieth century they tended to decline. Although we can show no proof, it is quite likely that this difference was due to the vast expansion of urban transportation options that made suburbanization possible. The initial population of the city still has a coefficient that is not significantly different from zero and income growth coefficient is now significant only at the 90 percent level. All in all, this model explains 22 percent of the variation in the dependent variable ($R^2 = 0.22$).

Model 4 tests hypothesis 8 and it is rejected: Densities in cities during their walking city stage tended to increase at a more rapid rate than when cities expanded beyond their walking range. Both transport variables are significant at the 95 percent level and income growth is still significant at the 90 percent level, and in this model the log of the initial population is also found to be significant at the 95 percent level. Larger cities are found to have steeper increases in density than smaller cities. All in all, this model explains 25 percent of the variation in the dependent variable ($R^2 = 0.25$). Model 4 is also found to be quite comprehensive and does not appear to suffer from heteroscedasticity or omitted variable bias, as can be seen from figure 7.18: the standardized residual values in the model are randomly distributed with respect to their corresponding standardized predicted values.

Figure 7.18: Scatter plot for long-term density change model 4



Finally, model 5 introduces hypotheses 5 and 6 and neither of them is rejected: cities with plentiful buildable areas around them in countries with plentiful arable lands are not likely to experience faster rates of density decline than cities elsewhere. In this model, the coefficient of the income growth rate cannot be said to be different from zero, but the population growth rate, the initial density, the initial population and the two transport variables are all significant at the 99 percent level. All in all, this model explains 31 percent of the variation in the dependent variable ($R^2 = 0.31$).

We can summarize the findings of this section as follows:

- Urban densities peaked circa 1890.
- Peak densities were preceded by periods of densification.
- Cities experienced both increasing and declining densities in the nineteenth century and mostly declining densities in the twentieth century.
- Densities declined threefold from their peaks.
- Density declined threefold in the twentieth century.
- The areas of cities grew 27 percent faster than their populations in the twentieth century.
- The deconcentration of cities started in the last two decades of the nineteenth century.
- There are similarities and differences in the timing of changes in density in the U.S. and elsewhere.
- Average short-term and long-term rates of decline from peak density were of the order of 1.2 percent and 1.5 percent per annum respectively.
- By the end of the twentieth century, short-term and long-term rates of density decline converged to 1.0 percent per annum.
- Rates of change in density tended to increase in the nineteenth century before the advent of cheap transport and to decline in the twentieth after the introduction of many forms of cheap transport.
- While cities were still walking cities, densities were more likely to increase rather than decrease than after cities expanded beyond their walking range.
- Rapid population growth typically results in increasing densities, while rapid income growth typically results in declining densities.

- Cities with high densities were more likely to experience density declines than cities with lower densities.
- Larger cities were more likely to experience increasing densities than smaller ones.

This brings our discussion of the historical sample of cities to an end.

We have now examined the differences in built-up area density in the year 2000 among cities the world over, the global decline in built-up area density during the 1990s, the decline in average tract density in U.S. cities between 1910 and 2000, and the rise followed by the decline in urbanized area densities in a global sample of 30 cities between 1800 and 2000. We now turn to a discussion of the policy implications of our analysis.

VIII. CONCLUSION: THE POLICY IMPLICATIONS OF THE STUDY

As the reader may recall, we started this essay with the premise that the worldwide efforts to contain urban sprawl would benefit from being grounded in a solid empirical foundation that focused on urban population densities, and our study sought to provide this empirical foundation. We now know how densities vary from place to place, how they vary over time, and what accounts for these variations.

What can we learn from our analysis about the efficacy and appropriateness of urban containment and compact city strategies, the strategies aimed at limiting and reversing urban expansion or sprawl?

In this paper, we gave a few examples of the pace of urban expansion in the past two centuries: Between 1800 and 2000 the area of Cairo increased 65-fold and the area of Paris increased 150-fold. Between 1850 and 2000 the area of Bangkok increased 235-fold and between 1809 and 2001 the area of Buenos Aires increased 845-fold. There is little reason to believe that urban expansion will come to a halt anytime soon, especially while the processes driving it ─ global population growth and the increasing share of that population residing in urban areas, rising per capita incomes, ample lands for urban expansion, affordable transport, and income inequality to name a few ─ continue unabated.

As we noted in our introduction, however, the scale of global urban land cover, the rate of global urban expansion, the projected areas needed to accommodate cities in the twenty-first century, the factors that determine urban land consumption in different countries, and the implications of these findings for urban containment and compact city strategies will be the subject of a second, separate paper. The measurement and explanation of fragmentation and its recent decline will be the subject of a third, separate paper.

Our discussion here thus focuses mainly on the findings related to urban densities and their implications for urban containment and compact city strategies. We have identified a number of important policy implications from different parts of our analysis:

- Urban containment and compact city policies may be less relevant in rapidly-growing cities with much higher densities than those prevailing in the U.S.
- Efforts to make cities denser require the reversal of a very powerful and sustained global tendency for densities to decline.
- The impact of existing policy regimes and attractive city centers on density and density decline may be negligible.
- In some developing-country cities, densities are too high, and calling for containing their expansion so as to increase densities is misplaced.
- Average densities in developing-country cities are high enough ─ and densities in land-rich developed countries are too often too low ─ to sustain public transport.
- The rate of density decline has slowed down over time, and densities in cities in land-rich developed countries may soon reach a plateau: a welcome development.
- The rate of land fragmentation on the urban fringe is on the decline, also a welcome development.
- Anti-sprawl policies that target low-density development should be clearly distinguished from anti-sprawl policies that target fragmentation.
- As a rule of thumb for planning purposes, when the population of a city doubles, its area triples.

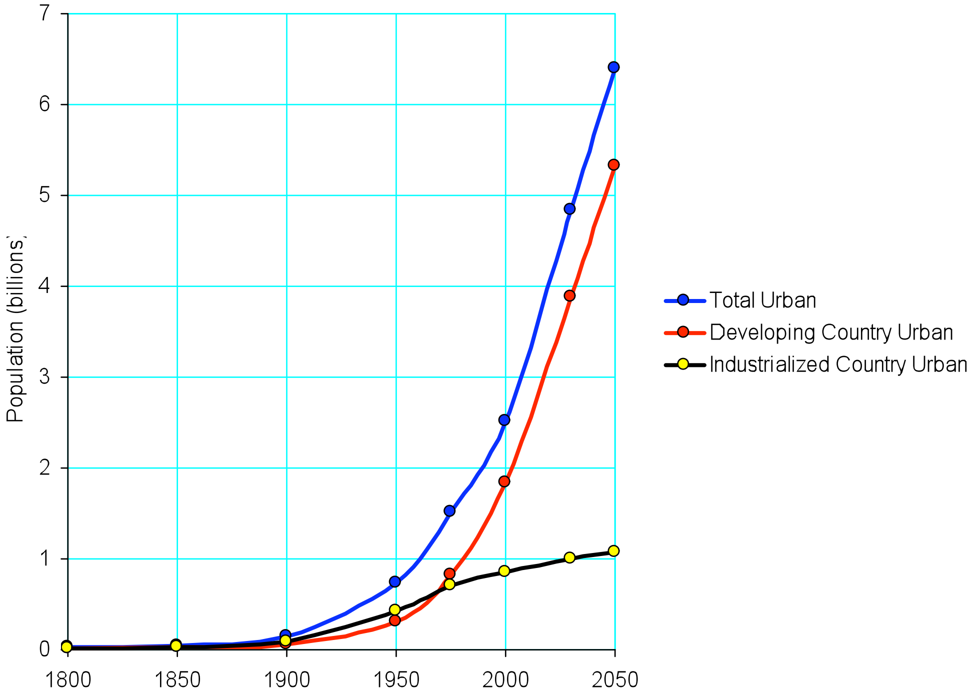
These policy implications are discussed in greater detail below.

Urban containment and compact city policies may be less relevant in rapidly-growing cities with much higher densities than those prevailing in the U.S.

Urbanization in the developed countries has now reached a plateau and urban population growth is projected to be minimal in the years to come. The United Nations Population Division estimates that between 2000 and 2050 the urban population in developed countries will only grow by 22 percent, at the rate of 0.4 percent per annum, stabilizing around 1 billion people (U.N. Population Division, table F3). Future urban expansion in these countries will largely be driven by immigration from abroad, by rising incomes, by changing housing and commuting preferences, by transport costs, and by fiscal and financial incentives. The urban population in developing countries, on the other hand, is expected to grow by 168 percent at more than 5 times the rate in developed countries ─ 1.98 percent per annum ─ from 2 billion in 2000 to 5.3 billion in 2050 (see figure 8.1).

Even at existing densities, not to mention at lower densities, cities in developing countries will increase their areas 2.5-fold, on average, during this period. Future urban expansion in developing countries will be driven, first and foremost, by urban population growth and by rising incomes.

Figure 8.1: Global urban population growth, 1800-2000



The average built-up area density in cities in land-rich developed countries like the U.S. was 28±5 p/ha and it was significantly different from that of other developed countries, 70±8 p/ha, and from that of developing countries, 135±11 p/ha. In general terms, we can conclude that in both 1990 and 2000 average built-up area densities in developing countries were roughly double those in cities in other developed countries, and that densities in other developed countries were roughly double, in turn, those of land-rich developed countries. These relationships among densities in the three regional sub-groups were illustrated graphically in figure 4.3.

There is no doubt, therefore, that sprawl, defined in absolute terms as a pattern of urban development at low densities, is now more extensive in land-rich developed countries — the United States, Canada, Australia and Russia — than in other countries. On average, urban dwellers in the former consume twice the built-up land per person than persons in Europe and Japan and four times the built-up land per person in developing countries.

Concerns about sprawl, especially as they relate to global warming or global energy reserves, are surely global in scope. Still, to the extent that they involve recommendations about containing urban expansion or encouraging urban development at higher density, we should be wary of applying them in places where population is still growing rapidly or where urban development already takes place at high densities.

Efforts to make cities denser require the reversal a very powerful and sustained global tendency for densities to decline.

On average, built-up area densities declined in 2.1±0.5 percent per annum in the 1990s. Long-term density declines in both the U.S. and in the global historical sample were of the order of 1.0-1.5 percent per annum in the twentieth century. Densities are now declining in land-rich developed countries, in other developing countries, and in developing countries and they have been shown to be in decline for a century or more.

As we stated earlier, these findings contradict the early findings of Berry, Simmons and Tennant (1963, 401) who claimed that

> whereas both degree of compactness and overcrowding diminish in Western cities through time, non-Western cities experience increasing overcrowding, constant compactness, and a lower degree of expansion at the periphery than in the West.

Our findings also contradict the more recent findings of Richardson et al, given their limited sample of cities, claiming that cities in developing countries "are not becoming significantly less compact in spite of decelerating population growth and the beginnings of decentralization" (Richardson, Bae and Buxamusa, 2000, 25). And they also contradict the findings of Acioly and Davidson that "there was evidence that a general process of change was leading to more compact cities" in developing countries (Acioly and Davidson, 1996 quoted in Acioly and Davidson 2000, 127).

At the very least, those championing urban containment and compact city policies could try to abstain from claiming that history, or the urban history of the last century, is on their side. Admittedly, it would be easier to champion such policies if cities already tended to become denser and now only needed a gentle policy push to become more compact. Unfortunately, as we have shown, this is not the case. While "the belief in the blessings of the compact city policy is now widespread" (de Roo and Miller, 2000,1), our findings suggest that efforts to make cities denser require the reversal a very powerful and sustained global tendency for densities to decline. For as long as a century, cities in the world over have become less, rather than more, dense and less, rather than more, compact.

The impact of existing policy regimes and attractive city centers on density and density decline may be negligible

The multiple regression models tested in this study could not find any existing policy or policy regime that had a significant effect on urban population density, or, more specifically, on the average density of the built-up areas of cities. Our survey of the planning and policy regime in each of the 120 cities in the global survey identified many policy variables that could potentially affect densities: municipal fragmentation, the share of zoning plans where no development was allowed, the corrupt or non-corrupt enforcement of planning regulations, subdivisions built with or without permits, and the possibility of drilling and using well water without requiring access to the municipal water supplies. None of these policy variables was found to have a statistically significant effect on density. In addition, whether the centers of urban areas were attractive and occupied mainly by the rich or unattractive and occupied mainly by the poor did not appear to have a significant effect on the overall average density of cities.

Given that the models that explain variations in density do not appear to suffer from omitted variable bias, we can conclude that, on the whole, the density of cities is not amenable to effect by existing planning policies of one kind or another. Surely, several cities in the global sample do employ urban containment and compact city policies, but, on the whole, these do not appear to have significant influence on density. Density is surely affected by income, by city size, by the cost and ease of transport, by the availability of land for expansion, and by the distribution of income, and by the share of informal settlements in the housing stock. But it does not appear to be affected, to any appreciable extent, by existing planning policies of one kind or another.

In some developing-country cities, densities are too high, and calling for containing their expansion so as to increase densities is misplaced

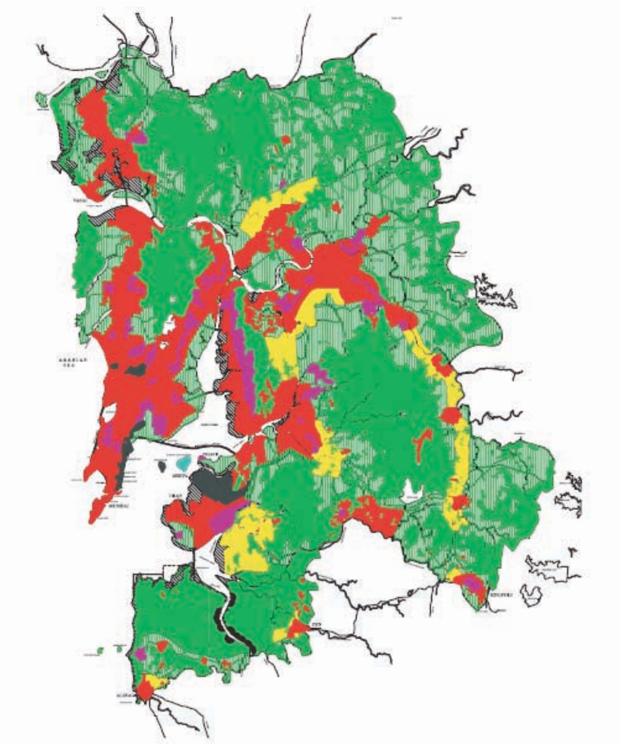
In the same way that reformers deplored the high-density neighborhoods in U.S. cities like New York at the turn of the twentieth century and welcomed the decongestion of the city by the opening up of suburbs, so must modern-day activist reformers welcome the decongestion now taking place in high-density cities in developing countries. Average built-up area densities in 2000 in Dhaka and Mumbai, for example, were 550 and 440 persons per hectare respectively, compared to 54 p/ha in London and 20 p/ha in Chicago. The appropriate urban expansion policy in these cities is to allow them to spread out, rather than to contain them or make them more compact.

Burgess, for example, in framing the debate on the merits of compact city strategies in developing countries sounds the same note:

> What is the sense, it is frequently asked, of further densification given that densities are already high and associated with a range of problems including infrastructure overload, overcrowding, congestion, air pollution, severe health hazards, lack of public and green space and environmental degradation? The sustainability gains from further densification will be limited under conditions where densities are already high. Under these circumstances the merits of urban densification postulated for developed country cities seem far less convincing in the context of developing countries (Burgess, 2000, 15).

It is interesting to note that, as figure 8.2 shows, the 1996-2011 Regional Plan for the Mumbai Metropolitan Region, for example, in a radical reversal of earlier policies to contain urban growth and expansion, envisions a tripling of the urbanized area ─ from 418km^2 to 1194km^2 ─ while its population is projected to increase by only 50 percent ─ from 14.4 to 22.1 million─ during this period (MMRDA 1999, 335, table 13.3 on page 357 and figure 13.8 on page 354).

Figure 8.2: Urban land Use (in red and yellow)
in the 2011 Regional Plan for Mumbai



Average densities in developing-country cities are high enough ─ and densities in land-rich developed countries are too often too low ─ to sustain public transport

Numerous authors have claimed that there is a relationship, or a correlation, between urban population density and transit use. Nelson and Nygaard (1995, 3-1), for example, analyzing variations in transit demand in Portland, Oregon note that

> Of 40 land use and demographic variables studied, the most significant for determining transit demand are overall housing density per acre and overall employment density per acre. These two variables alone predict 93 percent of the variance in transit demand among different parts of the region.

Parsons et al (1996, 13) report a similar finding in Chicago:

> Analysis in the Chicago area found that transit trips per person are strongly related to residential density. A doubling of residential densities

> more than doubles transit use… People in denser areas also use transit for more trip purposes… (Parsons et al, 1996, 13)

This does not necessarily mean that higher densities are the cause of more intensive transit use. In fact, some studies (e.g. Datz et al, 2008) suggest that causality goes both ways: the greater availability of transit increases densities while higher densities increase transit patronage. If that were the case, then policies simply aimed at increasing density may not necessarily reduce the reliance on private automobiles. Datz at al note that both transit use and living at higher densities may be lifestyle choices of self-selected individuals and families, and that these choices are also subject to change over time. For the purposes of this study, however, we need not concern ourselves with the direction of causality between density and transit use and simply observe that they go hand-in-hand, namely that higher densities are typically associated with higher levels of transit use.[22]

Several studies compiled by Holtzclaw (1974), for example, suggest that average densities of 30 persons per hectare can sustain local bus service and densities of 50 persons per hectare can sustain high-frequency bus service. Our study shows that average densities in developing country cities were of the order of 135 persons per hectare in 2000, clearly high enough to sustain public transport. We also found that the existence of informal settlements in developing-country cities tends to increase average density, namely that poor people consume less land than people with higher incomes. While incomes in developing-country cities can be expected to increase in the decades to come, the bulk of their areas are still expected to have densities that are high enough to support public transport. Calling for their densification in the name of the energy savings and the reduced levels of greenhouse gases associated with public transport thus appears to be misguided.

Cities in land-rich developed countries, on the other hand, face the opposite problem: densities there may already be too low in substantial portions of these cities to sustain public transport. And it is highly unlikely that densities can be sufficiently increased in areas now not served by public transport, so as to serve them effectively with public transport in the years to come.

If densities are to increase, they will only increase slowly as existing dwellings are expanded or subdivided, as additional units are added to single-family plots, as vacant lands are built-upon, and as multi-family dwellings replace single-family ones. And this is only likely to happen if restrictions on the expansion and subdivision of dwellings are removed, if restrictions on building additional units on occupied plots of land are removed, and if restrictions on introducing multi-family dwellings are removed. It can also happen if commercial corridors are opened to high-density residential development and served with good public transport. In short, densification in low-density suburbs may

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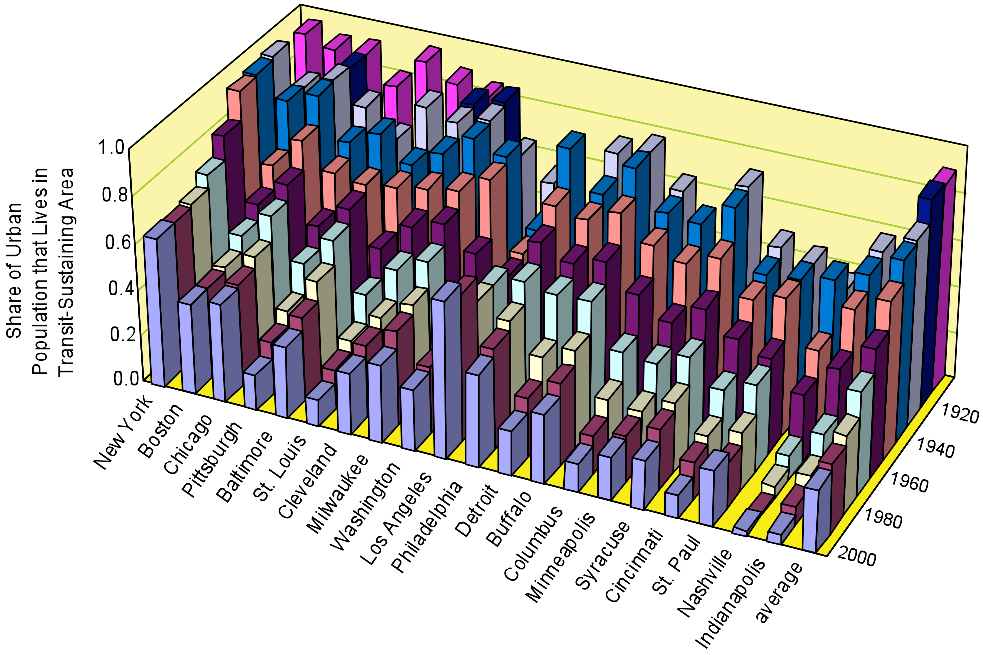
[22] Even this assertion needs to be more carefully examined. There are special cases, e.g. Ottawa and Toronto, where large areas with comparatively low residential densities are adequately served by public transport. In contrast, there are large areas of Los Angeles, for example, where densities that are clearly adequate for sustaining good bus transport and do not have access to good bus transport.

require a radical regulatory reform, a reform that is likely to face stiff resistance from sitting residents.

Figure 8.3 documents the decline in the share of the urban populations in U.S. cities that inhabits areas with high enough densities to sustain public transport.[23] The average share of the urban population in transit-sustaining areas declined from 90 percent in 1910-1920 to 27 percent in 2000, a 70 percent decline. In some cities, like Nashville and Indianapolis, less than 5 percent of the population lives in areas with high enough densities to sustain public transport. Bertaud (2002), in commenting on Atlanta, which had similar average densities to those of Nashville and Indianapolis in 2000, calculates that the bulk of the Atlanta metropolitan area will never reach the minimum densities necessary to sustain public transport:

> We have seen that, first, because of the very low density of and the spatial dispersion of jobs, transit in Atlanta cannot capture any significant share of trips; second, that density is unlikely to ever increase significantly and that the dispersion of jobs is likely to increase with time. It is therefore unrealistic to hope that the serious congestion and pollution problems of Atlanta will be solved by an increase in the number of transit trips and a comparable decrease in car trips. (Bertaud, 2002, 18)

Figure 8.3: The decline of the share of the population living in areas with transit-sustaining densities (above 30 persons per hectare), 1910-2000



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[23] Assumed here to be a census tract density of 30 persons per hectare in a circle with a radius equal to a walking distance of 0.5km.

In short, we can conclude that densities in most developing-country cities may be high enough to sustain public transport and that these cities do not require urban containment and compact city strategies to make them transit friendly. We can also conclude that densities in many land-rich developed country cities may now be too low to sustain extensive networks of adequate-frequency public transport. The densification of low-density areas to a point where they may be able to sustain public transport can either be limited to selected commercial corridors or to selected transit-oriented developments (TODs) that can be connected by good public transport; or it can occur gradually over a long period of time with a deliberate relaxation of the regulations that now make densification difficult if not impossible.

The rate of density decline has slowed down over time, and densities in cities in land-rich developed countries may soon reach a plateau: a welcome development

We have found some evidence that the rate of decline in urban densities is slowing down everywhere from its highs in the middle decades of the twentieth century, and that it may be slowing down in the U.S. more rapidly than elsewhere. This is welcome news for those worried about densities in U.S. cities becoming even lower and further removed from those of the ideal landscapes of the New Urbanism or from those capable of sustaining public transport. It may well be that the period of rapid density decline is now slowly coming to an end, and that in the near future rates of density decline will slow down even further, possibly becoming positive again as they were in the nineteenth century.

Our study of the global sample of 120 cities only provided data for two points in time in every city, one circa 1990 and one circa 2000. These data were sufficient to explore whether densities increased or declined, but they were not sufficient to examine whether the *rate* of increase or decline was accelerating or decelerating. We did obtain data on the changes in the rate of decline in urban tract densities in our long-term study of 20 U.S. cities from 1910 to 2000 and 65 U.S. cities from 1950 to 2000, and on the changes in the rate of decline in urbanized area densities from our historical study of 30 cities from 1800 to 2000.

Looking at historical census tract data for 20 U.S. cities, we found that short-term rates of decline in average tract density appear to have peaked in 1940s and 1950s, when they averaged 3 percent per annum and are now on the decrease: they averaged only 0.3 percent per annum in the 1990s. In fact, between 1990 and 2000 six out of 20 U.S. cities studied registered an *increase* in average tract density: New York, Washington, Los Angeles, St. Paul, Syracuse, and Nashville.

When we look at the larger set of 65 U.S. cities between 1950 and 2000, we find that the recent rates of density decline are even lower. Average density decline rates were -3.4 percent per annum in the 1950s and they declined to -0.46 percent in the 1980s and -0.14 percent in the 1990s. 28 cities, or 43 percent of the total, registered a positive rate of urban tract density change in the 1990s averaging +0.54 percent per annum, while 37 cities registered a negative rate of density change averaging -0.66 percent per annum.

Hence, while average urban tract densities in U.S. cities have been in general decline for almost a century, they may be slowly reaching a plateau.

The data from the 30 cities in the historical sample provides a slightly different picture. Density rates indeed became negative in the twentieth century, but they did not reach the high rates of -3 percent per annum as did U.S. cities. Peak short-term rates in the 1920s were of the order of -1.5 percent per annum. They declined to a rate of -1.0 percent per annum and now seem to have stabilized there. There are no indications, given our present data, that the rates of density decline in the world at large are now reaching zero, let alone that they are becoming positive.

From a theoretical point of view, it makes perfect sense for densities in land-rich countries ─ where they are now the lowest ─ to eventually reach a plateau, because densities simply cannot continue to decline forever lest they become zero or negative, a clearly impossible outcome. Densities must eventually reach a minimum, stay there, or increase again. Whether such a minimum plateau will be different in the three sub-regions or whether densities in all cities will eventually converge to the densities prevailing in the U.S. at the present time is a question that for now must remain unanswered.

From a policy perspective, a slowing down of the rate of decline in urban density may signal a new period of increasing densities, welcome news for those advocating compact city strategies. But it may also signal a state of affairs where densities reach an all-time low and then stay there, at levels too low to be of comfort for those same advocates or for those hoping for a revival of public transport.

In this context it is worth noting that tract densities in the Los Angeles metropolitan area have been on the increase since 1970 and are now among the highest in the United States. While Los Angeles is partly surrounded by natural barriers that limit its expansion, it does not have an urban growth boundary. Nor does it have especially strict development controls. And nor does it have an extensive public transport system although densities in much of its area are high enough to sustain it. Further study may be needed to shed more light on why Los Angeles of all places has been able to increase its density over time, as it may offer clues for those in pursuit of effective compact city policies.

The rate of land fragmentation on the urban fringe is on the decline, also a welcome development

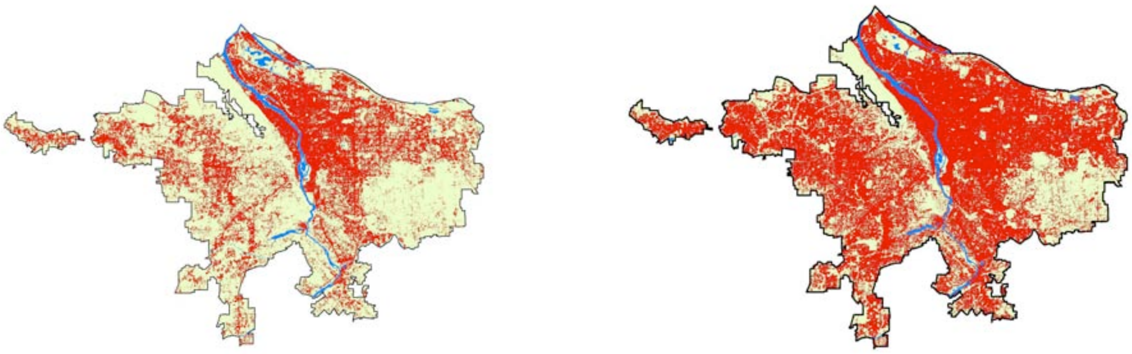
Our study found significant differences in the rate of decline of different densities. In particular, while average built-up area density in our global sample of cities declined at similar rates of 2.1 percent per annum between 1990 and 2000 in all three sub-regions, we found that city footprint density declined at a significantly slower average rate of 1.7 percent per annum. There were also differences in the rate of decline of city footprint densities between land-rich developed countries (-1.09±0.70 percent), other developed countries (-1.63±0.92 percent), and developing countries (-1.86±0.55 percent). We can conclude, therefore, that the built-up areas of cities in 2000 affected or fragmented a smaller proportion of the open space around them that in 1990, surely a welcome development. If we consider open space fragmentation as a measure of sprawl, then we can say that, on average, sprawl as open space fragmentation declined between 1990 and 2000.

We noted before that average city footprint densities are quite similar to average census tract densities. Portland, Oregon ─ that had adopted an Urban Growth Boundary in 1973 (see figure 8.4) to increase its city footprint density ─ ranked 11th highest among 65 U.S. cities in terms of its rate of increase in average urban tract density, 0.7 percent per annum, in the 1990s. Austin scored the highest with 1.3 percent per annum, followed by Durham, San Diego, San-Francisco-Oakland, San José, Miami, Atlanta, Los Angeles, and Houston. Given that a number of these cities do not practice urban containment in any form, it is difficult to conclude that a high score on this metric was associated with aggressive smart growth policies.

It is interesting to note that the average built-up area density in Portland continued to decline between 1973 and 2000, from 23.9 to 21.5 persons per hectare, while its city footprint density increased from 10.8 to 14.2 persons per hectare. The growth of the built-up area within its Urban Growth Boundary continued to be at relatively low (and decreasing) built-up area densities, but it was certainly more in the form of infill rather than of leapfrogging. In short, urban expansion in Portland, like urban expansion everywhere, now appears to engender less open space fragmentation than in the recent past.

It is also important to note that there was a rapid decline in the ratio of the city footprint and the built-up area within Portland's Urban Growth Boundary between 1973 and 2005. It declined from 2.2 in 1973 to 1.7 in 2000 and 1.5 in 2005. Its low ratio in recent years would rank it in the second decile in the global sample of 120 cities, similar to its rank among U.S. cities. We can conclude, therefore, that Portland has been pursuing a policy of accelerated infill, but that this infill is taking place at built-up area densities, which will still be too low to sustain an extensive network of public transport.

Figure 8.4: The expansion of the built-up area (in red) within Portland's Urban Growth Boundary (UGB), 1973-2005



Those scholars who hold the view that, in the long run, urban areas tend to fill in anyway (e.g. Peiser, 1989) would argue that infill is only a matter of time, and that the effect of Portland's Urban Growth Boundary is only temporary. Indeed, when we look at the average ratio of the urbanized area of cities and their built-up area in the global sample of 120 cities, we find that it was 1.22±0.01 in 1990 and 1.21±0.01 in 2000 and that it did not change significantly between the two periods. One could argue that, on average, some 20 percent of the urbanized area should or could remain vacant over time, with new vacant areas added on the urban fringe as previously vacant areas are filled in. It would be an argument similar to the one advanced for having a certain amount ─ typically of the order of 3-5 percent ─ of the housing stock remain vacant so as to ensure the smooth functioning of the housing market.

This argument is more difficult to make when we look at the sheer amount of open space that is fragmented by city footprints. When we look at the average ratio of *city footprints* and their built-up area, we find that it was 2.01±0.03 in 1990 and 1.93±0.03 in 2000 and that it did decline significantly between the two periods. Still, on average, city footprints fragmented as much open space as entire built-up areas. It would be more difficult to argue that cities need an amount of open space in and around them that is roughly equivalent to their built-up areas to remain vacant, so as to ensure the proper functioning of their land markets. In short, it would be quite reasonable to argue that present forms of urban expansion fragment *too much* of the countryside, temporary or not, and that campaigns that aim at reducing this kind of fragmentation are in order. Indeed, it may very well be that the increase in global environmental activism may already be bearing fruit, and that the expansion of cities has become a bit more conscious of ─ and possibly even more gentle with ─ their surrounding countryside.

Anti-sprawl policies that target low-density development should be clearly distinguished from anti-sprawl policies that target fragmentation.

Our parallel studies of built-up area densities and built-up area fragmentation in the global sample of cities have convinced us that the two are quite distinct. Densities and levels of fragmentation are quite independent from each other, as are the observed declines in density and the parallel declines in fragmentation. In our view, there is no viable theory for linking the two together. Hence we find fault with studies of sprawl that lump the two together and then proceed to offer remedies that typically address one and neglect the other. We believe it is more valuable to study them separately and to address them separately. This separation acquires additional value of we acknowledge that the policy instruments available for increasing built-up area densities are quite different from those that address excessive fragmentation.

For example, if the aim is to reduce sprawl by increasing built-up area densities, then the restrictions on higher-density developments should be removed; homeowners should be allowed to add an additional story to their home or build an additional unit on their plot; homeowners should be allowed to subdivide their homes into two or more units and to offer one of more unit for rent; there should be fiscal incentives for building on small plots and disincentives for building on large ones; restrictions on mixed-use development should be removed; and so on.

If, on the other hand, the aim is to reduce sprawl by reducing fragmentation, then there can be restrictions on conversion of land from rural to urban use; there can be impact fees for development at longer distances away from built-up areas; there can be conservation easements for keeping green areas from development; there can be exchanges of development rights to direct development into desirable areas; or there can be purchases of public open spaces, to give a few examples. And if in some cases the aim is to increase built-up area densities and to decrease fragmentation at the same time, then in those cases there would be a need to address both, each with an appropriate set of policy instruments.

As a rule of thumb for planning purposes, when the population of a city doubles, its area triples

Cities need realistic plans for charting and guiding their expansion in the coming decades. These plans would stand a better chance of guiding development on the ground if they were simple and minimalist rather than comprehensive in nature. At the very minimum, must contain a projection of the population at the plan horizon and the identification of adequate areas to accommodate that population. They must also contain plans for the location of arterial infrastructure grids in expansion areas, as well as plans for protecting specific open spaces from undesired development.[24] It is important to ensure that projected density declines are taken into account in projecting the areas needed for urbanization at future dates.

The projection of density declines can be done in a careful manner by looking at each of the factors in our multiple regression models that affects density and density decline, projecting the expected changes in these factors, and drawing appropriate conclusions about projected density change. They can also be done by looking at the rates of decline in density in the specific city in question and projecting them into the future. And they can also be done by looking at regional densities or global densities and their decline over time. On average, built-up area densities have recently been declining at 2 percent per annum in our global sample of 120 cities. Longer-term declines were found to be of the order of 1.0-1.5 percent per annum. If we assume, conservatively, that density will decline by 1.35 percent per annum when the population of developing country cities doubles in the next 30 years, we can estimate that the land area required to accommodate that population will triple. As a rule of thumb, therefore, we can say that given what we know about the expected global rate of density decline, *when the population of a city doubles its area triples*, unless we have more specific and better information about the rate of density decline in a particular city or country.

Refusing to prepare adequate areas for planned expansion in the belief that expansion at lower densities is undesirable is likely to fail in the long run and to the formation of large areas of unplanned expansion. In the short run it is also likely to result in creating

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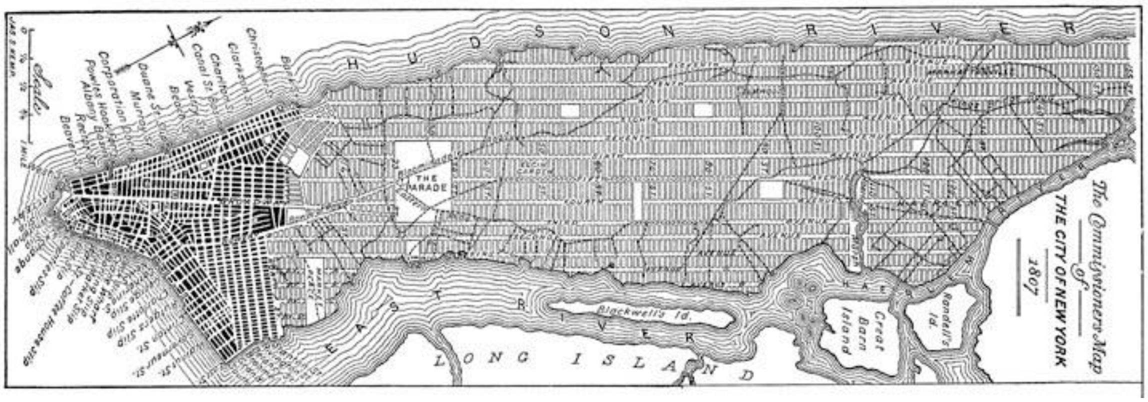
[24] For an extensive discussion of the making minimal preparations for urban expansion in developing countries see Angel, 2008.

artificial shortages of urbanized land with the consequent shortages in the supply of land for housing and other uses and the resulting appreciation of land and housing prices, making land unaffordable for large numbers of low-income families.

There is no doubt that the areas of many cities are going to grow by several multiples, as they have indeed grown in the past. These cities would do well by preparing adequate areas for their expansion. There are very few examples of bold preparations for the massive expansion of cities. Notable among them are the 1859 *Ensanche* plan for the ten-fold expansion of Barcelona and the 1811 plan for the ten-fold expansion of New York City (see figure 8.5: the built-up area is shown in black). The three commissioners presenting the plan noted:

> To some it may be a matter of surprise that the whole island has not been laid out as a city. To others it may be a subject of merriment that the Commissioners have provided space for a greater population than is collected at any spot on this side of China. (Morris, de Witt Clinton and Rutherford, 1811)

Figure 8.5: The commissioners' plan for New York City, 1807



More recently, President Sarkozy of France has unveiled one of several plans for the expansion of Paris, a plan that calls for its extension all the way to the English Channel (see figure 8.6). Surely, this plan envisions not only a growth in population, which may be quite modest, but also a substantial decline in urban density.

Figure 8.6: A plan for the expansion of Paris, 2009

Concluding Remarks: Making Generalizations about Cities in the Twenty-First Century

We believe that the methods employed in this study — the collection and analysis of comparable satellite data from a global sample taken from the universe of cities, the collection and analysis of survey data by local consultants in a global sample of cities, the collection and analysis of historical maps and populations, the integration of these data in a common spatial framework using Google Earth and ArcGIS software, and the analysis of these data in multiple regression models using statistical software, open new horizons for future of research on cities in the twenty-first century. We have shown that when we study a global sample of cities in a rigorous fashion, we can make new and important generalizations about cities that were not possible before. Indeed, using the methods we employed here or variations thereof, urban scholars can now begin to test many novel hypotheses about cities and to anchor the fields of urban planning, urban economics, urban geography, and urban history in a more solid empirical foundation. It is our hope and conviction that this would make possible the drawing out of important lessons on how to run or not to run our cities in a more efficient, more equitable and more sustainable manner, lessons that — given the projected expansion of cities the world over in the coming decades — are now urgently needed.

* * *

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The second phase of the study involved the administration of a survey by local consultants in each of the cities in the global sample of cities. The survey included questions on the latest census, on the status of metropolitan area planning, regulation and enforcement; on generals housing market conditions, on informal settlements, and on financial institutions that provide mortgage loans. This phase was supported by a grant from the National Science Foundation. The team that worked on this phase of the study included Shlomo Angel, Stephen Sheppard and Daniel Civco as principal investigators, assisted by Lucy Gitlin, Alison Kraley, Jason Parent, and Anna Chabaeva.

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The fourth phase of the study involved the collection, geo-referencing, and digitizing of maps at 20-25 year intervals for the period 1800-2000 for a global sample of 30 cities; the analysis of census data for 20 U.S. cities for the 1910-2000 period and 65 cities for the 1950-2000 period; the statistical modeling of the results of the all phases; and the preparation of this research report. It was supported by a one-year fellowship and research support given to Shlomo Angel by the Lincoln Institute of Land Policy. The team that worked on this phase of the study included Alejandro Blei who prepared all the historical data, Jason Parent, and Daniel Civco. Chun Il Kim helped with the statistical models. We are grateful to Gregory Ingram, the President and CEO of the Institute for supporting our work, and for his constructive comments during this phase of the study. We are also grateful to the staff of the Institute for their active support of this study as well as for their gracious hospitality.

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ANNEX I: DENSITY METRICS FOR THE GLOBAL SAMPLE OF CITIES, 1990-2000

The average ***Built-up Area Density*** is calculated as the ratio of the total population in the smallest set of administrative districts containing the city and the total area of the built-up pixels within these districts. *Urbanized open space* is defined as the set of open space pixels that have a majority of built-up pixels in a circle of 1-km^2 area around them. The Urbanized Area of a city includes its built-up area and its urbanized open space. The average ***Urbanized Area Density*** is the ratio of the total population in the set of districts containing the city and the total urbanized area in these districts. The *city footprint* is defined as the sum of the urban and suburban built-up areas, the affected open space fringe within a 100-meter buffer of these areas, and the internal open spaces captured by both. The average ***City Footprint Density*** is the ratio of the total population in the set of districts containing the city and the total city footprint area in these districts.

		Built-up Area Density (Hectares)		Urbanized Area Density (Hectares)		City Footprint Density (Hectares)	
City	Country	1990	2000	1990	2000	1990	2000
Eastern Asia							
Anqing	China	164.7	162.7	144.9	138.4	84.1	71.4
Beijing	China	73.5	75.5	62.6	64.7	34.1	36.5
Changzhi	China	127.2	80.5	111.9	68.8	59.3	36.7
Guangzhou	China	118.7	111.8	105.8	93.2	53.1	45.5
Hong_kong	China	629.5	543.0	532.7	462.9	399.7	346.8
Leshan	China	175.8	102.7	158.2	92.8	71.7	42.5
Shanghai	China	162.9	125.2	141.4	102.9	78.3	59.5
Yiyang	China	375.8	115.9	341.1	102.2	187.8	45.0
Yulin	China	243.8	138.7	224.8	125.7	96.6	51.2
Zhengzhou	China	81.3	66.3	70.1	55.0	30.4	23.3
Ulan_bator	Mongolia	67.3	61.1	57.7	53.8	41.1	36.9
Ansan	Republic of Korea	94.6	109.9	72.9	87.8	57.7	56.2
Chinju	Republic of Korea	108.2	65.5	98.4	58.3	57.5	27.2
Chonan	Republic of Korea	141.5	71.6	129.9	59.3	47.6	26.6
Pusan	Republic of Korea	263.1	175.2	222.9	147.5	163.3	108.3
Seoul	Republic of Korea	260.0	211.6	217.2	174.9	157.4	124.3
South-East Asia							
Bandung	Indonesia	278.3	241.8	219.1	188.9	134.7	127.0
Medan	Indonesia	190.9	156.1	160.4	125.4	92.3	80.5
Palembang	Indonesia	167.9	98.1	139.8	78.9	72.6	49.1
Ipoh	Malaysia	35.9	30.5	29.2	23.9	15.8	15.5

Kuala_lumpur	Malaysia	76.4	68.0	60.2	52.7	40.4	37.6
Bacolod	Philippines	446.6	159.9	351.5	130.7	142.3	93.2
Cebu	Philippines	206.8	232.4	167.4	191.3	98.9	114.0
Manila	Philippines	347.6	284.1	264.4	230.9	154.9	146.4
Singapore	Singapore	170.9	174.8	128.6	130.3	78.7	87.3
Bangkok	Thailand	139.4	100.3	107.5	77.1	47.9	44.4
Songkhla	Thailand	159.1	131.0	138.6	113.5	76.0	61.9
Hochimin_city	Vietnam	440.4	197.7	368.4	166.4	224.5	105.7
South and Central Asia							
Dhaka	Bangladesh	630.7	551.4	477.8	450.9	295.1	246.9
Rajshahi	Bangladesh	442.3	301.2	434.0	287.7	153.8	85.0
Saidpur	Bangladesh	391.1	317.1	344.7	289.1	212.0	154.9
Coimbatore	India	149.6	132.6	119.6	108.0	64.1	55.7
Hyderabad	India	276.4	189.6	228.7	155.8	128.5	95.0
Jaipur	India	347.9	200.4	282.8	158.6	179.5	127.2
Jalna	India	357.4	221.6	311.2	182.0	174.4	108.1
Kanpur	India	159.2	151.7	132.5	128.5	78.4	73.7
Kolkota	India	386.9	276.7	321.4	226.4	172.6	110.4
Mumbai	India	474.5	440.3	407.3	384.5	310.7	286.3
Puna	India	466.9	201.6	362.9	158.1	181.0	124.3
Vijayawada	India	246.9	181.5	199.7	157.2	133.3	98.3
Ahvaz	Iran	57.6	57.4	52.0	51.4	36.3	32.7
Gorgan	Iran	50.1	43.2	43.8	37.1	23.3	20.0
Teheran	Iran	161.3	165.4	130.6	135.4	103.8	106.0
Shimkent	Kazakhstan	48.1	39.9	41.5	33.8	27.1	21.4
Sanaa	Yemen	89.9	95.0	74.0	84.9	57.9	69.8
Western Asia							
Yerevan	Armenia	66.7	49.9	57.1	41.4	29.7	22.5
Baku	Azerbaijan	265.6	226.4	218.3	184.4	109.6	96.9
Zugdidi	Georgia	44.9	38.0	36.4	30.4	21.6	15.7
Tel_aviv	Israel	111.5	76.6	92.3	62.0	54.2	34.0
Kuwait_city	Kuwait	57.5	51.1	45.1	40.7	34.0	31.8
Istanbul	Turkey	190.7	165.9	144.6	129.5	107.1	94.0
Malatya	Turkey	77.3	62.2	66.9	53.9	31.2	26.2
Northern Africa							
Algiers	Algeria	183.3	157.7	146.9	126.6	85.8	74.8
Tebessa	Algeria	69.3	61.4	63.2	56.3	41.2	35.2
Alexandria	Egypt	230.9	177.6	203.8	155.7	155.0	119.8
Aswan	Egypt	183.6	196.1	172.2	184.2	112.5	118.3
Cairo	Egypt	259.7	231.1	221.3	198.2	167.7	143.1
Casablanca	Morocco	279.1	263.8	209.0	211.7	151.4	146.5
Marrakech	Morocco	127.6	103.9	113.1	94.0	73.3	55.0
Port_sudan	Sudan	55.6	51.4	47.0	43.7	38.0	34.4
Sub-Saharan Africa							
Ouagadougou	Burkina Faso	91.1	66.0	77.2	57.8	61.8	45.9
Addis_ababa	Ethiopia	204.6	211.3	157.7	164.5	110.8	111.8

Banjul	Gambia	79.6	90.0	65.8	73.5	42.9	45.5
Accra	Ghana	116.1	81.1	98.9	71.4	87.5	58.7
Bamako	Mali	113.0	94.4	96.1	80.0	70.8	54.5
Ibadan	Nigeria	76.9	80.9	66.3	71.5	56.8	55.5
Kigali	Rwanda	136.5	74.5	114.0	58.6	56.5	37.7
Johannesburg	South Africa	39.8	47.4	28.9	34.8	17.2	22.5
Pretoria	South Africa	28.0	38.9	20.0	27.6	12.3	19.2
Kampala	Uganda	109.4	89.9	85.6	72.2	29.9	36.0
Ndola	Zambia	82.6	63.7	66.1	49.3	38.2	31.5
Harare	Zimbabwe	49.3	36.9	40.1	30.1	20.4	15.4
Latin America and the Caribbean							
Buenos_aires	Argentina	91.7	88.0	77.5	74.4	60.9	58.0
Guaruja	Brazil	70.0	74.9	59.2	65.1	35.6	44.0
Ilheus	Brazil	46.3	31.6	41.2	28.6	20.5	14.2
Jequie	Brazil	67.4	39.6	56.6	34.4	37.9	26.7
Ribeirao_preto	Brazil	48.7	50.9	41.9	43.5	33.7	32.1
Sao_paulo	Brazil	101.7	99.6	87.9	88.1	72.1	71.5
Santiago	Chile	136.1	121.5	112.9	102.0	85.2	77.9
Valledupar	Colombia	116.4	107.8	106.4	98.2	83.0	70.4
San_salvador	El Salvador	160.5	157.0	129.9	132.1	87.0	93.1
Guatemala_city	Guatemala	100.5	93.2	80.7	75.7	47.5	56.0
Kingston	Jamaica	72.5	73.2	57.0	58.7	37.3	38.0
Guadalajara	Mexico	96.9	90.2	80.1	76.4	57.6	55.8
Mexico_city	Mexico	182.2	162.3	148.1	134.8	109.4	104.1
Tijuana	Mexico	52.9	56.5	41.2	48.4	34.8	39.4
Montevideo	Uruguay	65.8	52.1	55.8	43.9	31.0	26.5
Caracas	Venezuela	104.1	84.8	82.2	70.1	47.7	42.2
Land Rich Developed Countries							
Sydney	Australia	43.0	37.3	32.5	29.5	22.6	21.5
St_catharines	Canada	21.3	15.7	18.4	13.1	11.6	7.7
Victoria	Canada	30.2	23.9	23.1	18.9	15.1	13.6
Astrakhan	Russia	38.0	36.7	30.7	29.5	17.7	17.2
Moscow	Russia	139.1	95.5	109.4	76.9	62.3	47.4
Oktyabrsky	Russia	28.0	23.8	23.6	20.3	12.0	10.0
Cincinnati	United States	20.3	20.2	16.7	16.4	12.1	11.9
Minneapolis	United States	23.4	19.4	17.8	14.3	9.7	8.1
Modesto	United States	23.4	19.8	16.8	14.7	10.9	11.5
Philadelphia	United States	35.0	34.3	28.3	28.4	24.0	24.5
Tacoma	United States	22.8	20.0	16.2	14.2	10.1	9.9
Chicago	United States	24.7	20.4	19.0	16.4	12.0	10.4
Houston	United States	26.1	22.2	19.6	16.5	12.5	10.9
Los_angeles	United States	29.1	24.8	21.9	18.6	11.2	10.0
Pittsburgh	United States	30.8	19.9	26.0	15.0	11.0	8.4
Springfield	United States	17.1	15.7	12.3	11.7	7.4	8.1

Other Developed Countries							
Wien	Austria	81.8	55.8	64.0	44.7	33.3	27.1
Le_mans	France	31.3	28.3	28.0	25.4	16.6	15.0
Paris	France	70.2	64.4	55.7	53.1	40.8	39.5
Leipzig	Germany	74.7	31.9	62.0	25.9	32.2	15.6
Thessaloniki	Greece	142.5	122.0	115.7	97.2	78.3	64.8
Budapest	Hungary	70.3	55.4	59.0	46.7	46.1	35.6
Milano	Italy	69.2	59.3	55.1	46.7	34.2	31.1
Palermo	Italy	111.6	103.8	89.3	83.8	56.1	53.4
Akashi	Japan	130.0	87.1	91.8	70.3	59.7	60.2
Fukuoka	Japan	95.0	71.7	80.1	60.1	59.5	45.8
Tokyo	Japan	117.6	115.7	91.5	93.0	80.1	81.7
Warsaw	Poland	84.1	64.0	62.0	49.2	41.0	33.2
Castellon	Spain	36.9	32.8	31.1	26.4	15.1	13.3
Madrid	Spain	147.1	124.5	119.7	98.9	74.4	63.7
London	United Kingdom	62.2	54.1	48.6	43.6	35.5	30.8
Sheffield	United Kingdom	53.1	49.0	40.3	37.7	29.4	26.8

ANNEX II: MAPS FOR THE GLOBAL SAMPLE OF 120 CITIES, 1990-2000

This set of maps provides the results of our interpretation of the land cover data extracted from satellite images for the 120 cities in the global sample for two time periods: one circa 1990 and one circa 2000. The cities are organized in alphabetical order.

The original land cover data classification identified land use in each 30-by-30-meter pixel in the study area. Every pixel was classified as either *built-up*, *open* (that is, not built-up), or *water*. The maps presented here include the *built-up area*, the *urbanized area*, and the *city footprint.* Two maps are presented for each city, the first depicting the built-up area and urbanized area in two time periods, and the second depicting the built-up area and the city footprint for the same two time periods.

The *built-up area* corresponds to paved surfaces, rooftops, and other impervious surfaces identified in the satellite imagery. It is further classified into categories based on the spatial proximity of the built-up pixels. Each built-up pixel is classified into one of three categories by calculating the percentage of land that is built-up within a circle one-kilometer-square in area:

- *Urban*: A built-up pixel for which the area within the one-kilometer-square circle surrounding it is more than 50 percent built-up;

- *Suburban*: A built-up pixel for which the area within the one-kilometer-square circle surrounding it is 10 to 50 percent built-up; and

- *Rural*: A built-up pixel for which the area within the one-kilometer-square circle surrounding it is less than 10 percent built-up.

The *urbanized area* consists of the built-up area of the city and the open space embedded in it. We cannot distinguish between public open spaces that are likely to remain open and vacant lands that may be built upon later. The Urbanized area includes two types of open pixels:

- *Urbanized open space*: An open pixel for which the area within the one-kilometer-square circle surrounding it is more than 50 percent built-up.

- *Captured open space*: A patch less than 200 hectares in area containing open pixels that are completely surrounded by built-up area and urbanized open space pixels.

The urbanized area does not include rural open space pixels, defined as:

- *Rural open space*: An open pixel for which the area within the one-kilometer-square circle surrounding it is less than 10 percent built-up.

The urban footprint consists of the built-up area of the city and the open space that is fragmented or affected by being in close proximity to it. Open space pixels in the city footprint are classified into two categories:

- *Fringe open space*: An open pixel that is within 100 meters of an urban or suburban built-up pixel; and
- *Captured open space*: A patch less than 200 hectares in area containing open pixels that are completely surrounded by built-up area and fringe open space pixels.

The rural open space in the city footprint maps is defined as follows:

- *Rural open space*: An open pixel not classified as fringe open space or captured open space.

The reader should note that both captured open spaces and rural open spaces in the urbanized area maps and the city footprint maps are not identical. The urbanized area maps intend to capture only the open spaces embedded within the built-up area of cities. In 2000, for example, urbanized areas added, on average, 21±1 percent to the built-up areas of cities. The city footprint maps, on the other hand, intend to capture the open spaces in and around the built-up areas of cities that are fragmented or affected by their close proximity to built-up areas. In 2000, for example, city footprints added, on average, 93± 7 percent to the built-up areas of cities.

The maps are given as PDF files, as JPEG files, and as ArcGIS shapefiles, and will soon be available on Lincoln Institute's Web site (www.lincolninst.edu).

ANNEX III: DENSITY METRICS FOR THE HISTORICAL SAMPLE OF 20 U.S. CITIES, 1910-2000

City	Average Tract Density (persons per hectare)									
	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000
Baltimore	98.2		39.7	41.8	30.1	25.9	22.3	17.4	15.9	14.8
Boston	62.7		65.0	63.5	25.0	19.7	16.9	15.2	14.4	14.2
Buffalo			54.4	54.0	36.3	25.8	21.8	16.7	15.9	14.5
Chicago	64.6	63.0	72.1	71.4	35.5	26.5	22.7	19.3	17.7	17.1
Cincinnati			28.9	23.8	23.4	18.0	15.5	12.7	11.5	10.5
Cleveland	47.2	47.3	47.5	31.4	27.0	23.8	20.9	16.5	14.8	14.0
Columbus			35.3	34.5	29.8	21.4	19.5	15.8	13.5	12.8
Detroit			51.6	35.7	28.9	24.9	21.0	16.5	14.7	14.1
Indianapolis			28.2	27.1	23.8	16.9	13.7	11.3	10.9	10.1
Los Angeles			27.4	20.5	20.5	22.1	23.8	23.8	26.7	29.2
Milwaukee		59.7	57.0	52.7	32.1	22.2	19.9	17.1	16.0	14.2
Minneapolis				30.1	26.1	19.1	17.2	14.3	13.2	12.3
Nashville			26.7	29.1	15.3	13.3	10.6	9.1	8.3	8.7
New York	116.9		147.7	110.1	95.8	45.5	32.1	26.9	25.8	26.4
Philadelphia				80.7	34.4	27.3	21.9	17.7	16.4	15.3
Pittsburgh	47.5		47.9	32.5	25.1	19.5	16.2	13.8	12.6	11.7
St. Louis	52.0		52.4	29.2	30.8	22.0	17.1	13.7	12.2	11.4
St. Paul			23.5	24.9	25.0	16.6	17.8	15.3	13.4	13.4
Syracuse			39.6	36.6	25.2	18.1	15.5	14.0	11.4	11.4
Washington			34.3	41.6	42.1	22.4	19.4	15.8	15.2	16.0
Average	69.9	56.7	48.8	43.6	31.6	22.5	19.3	16.1	15.0	14.6

***Note*: Average tract density was calculated as the ratio of the total population in 'urban' tracts (tracts with more than 1,000 people per hectare) and the total area of these urban tracts.**

ANNEX IV: URBANIZED AREA DENSITIES | IN THE HISTORICAL SAMPLE OF 30 CITIES, 1800-1900

	Urbanized Area Densities (persons per hectare)										
City	1800	1810	1820	1830	1840	1850	1860	1870	1880	1890	1900
Accra											314
Algiers	1217	1146	1079	978	765	599	489	498	508	494	401
Bangkok						276	298	322	348	327	176
Beijing	250	261	272	283	295	307	320	334	285	199	139
Buenos Aires	257	234	212	193	188	205	224	238	237	207	133
Cairo	154	161	168	175	184	196	215	237	313	469	607
Chicago						19	27	37	40	42	48
Guatemala	125	109	95	82	71	62	65	68	71	74	77
Istanbul	366	374	382	390	399	405	413	420	402	379	357
Jeddah						625	672	724	750	750	750
Johannesburg											43
Kolkota		133	159	190	222	216	218	258	306	332	371
Kuwait											69
Lagos						200	179	160	143	128	115
London	265	284	305	327	289	266	256	244	233	222	211
Los Angeles								42	42	41	41
Manila	1099	1187	1282	1385	1048	993	1012	1031	1051	852	560
Mexico City	369	379	390	400	408	416	424	446	471	514	589
Moscow	140	126	114	103	102	118	137	159	184	214	246
Mumbai		294	364	451	559	684	809	858	820	772	683
Nairobi											106
Paris	497	494	491	489	430	368	329	310	292	191	125
Santiago	118	117	116	115	114	225	125	138	153	171	190
Sao Paulo									192	158	130
Shanghai		632	632	632	632	632	553	457	404	386	369
Sydney		176	185	195	274	438	698	550	445	392	227
Teheran						229	260	295	335	381	426
Tel Aviv											
Tokyo				147	137	128	124	140	158	187	269
Warsaw	551	401	292	213	215	230	245	279	368	463	497
Average	416	383	385	375	352	341	352	344	342	334	285

***Note*: Average urbanized area densities were interpolated for each decade from historical population data and from urbanized areas calculated from historical maps. The decade in which density reached its peak is highlighted.**

ANNEX IV: URBANIZED AREA DENSITIES IN THE HISTORICAL SAMPLE OF 30 CITIES (CONTINUED), 1900-2000

	Urbanized Area Densities (persons per hectare)										
City	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000
Accra	314	250	198	164	198	183	150	130	121	100	73
Algiers	401	360	339	323	337	353	280	170	152	147	127
Bangkok	176	203	240	217	184	157	111	74	57	75	78
Beijing	139	205	309	433	409	386	394	425	200	63	65
Buenos Aires	133	85	60	72	87	85	76	74	77	78	74
Cairo	607	593	549	494	566	610	575	547	381	221	197
Chicago	48	57	59	53	48	41	34	27	21	17	16
Guatemala	77	93	111	132	157	186	140	107	87	81	76
Istanbul	357	282	193	109	84	84	84	104	129	145	130
Jeddah	750	697	649	509	338	232	64	76	81	74	68
Johannesburg	43	42	35	21	15	18	20	19	19	28	35
Kolkota	371	413	349	294	269	249	231	253	283	317	224
Kuwait	69	86	108	133	151	104	63	47	40	34	31
Lagos	115	112	109	89	73	59	103	138	162	157	153
London	211	201	161	116	98	83	68	56	48	49	44
Los Angeles	41	39	34	29	26	22	23	24	26	28	28
Manila	560	305	176	156	139	150	197	260	261	256	232
Mexico City	589	675	423	270	249	230	243	258	194	148	135
Moscow	246	286	298	290	276	214	179	183	170	110	76
Mumbai	683	600	507	428	507	625	455	269	324	389	384
Nairobi	106	48	22	15	23	33	46	59	68	57	47
Paris	125	115	107	100	100	99	97	96	88	56	53
Santiago	190	184	144	112	111	111	96	83	98	113	102
Sao Paulo	130	110	97	86	84	81	76	72	77	88	88
Shanghai	369	182	172	302	531	567	469	388	246	141	103
Sydney	227	83	35	31	28	27	29	31	32	32	33
Teheran	426	430	435	368	261	261	234	166	137	131	136
Tel Aviv			430	225	140	131	149	142	118	92	63
Tokyo	269	387	300	241	251	262	206	134	128	135	135
Warsaw	497	533	494	395	260	130	68	56	49	57	49
Average	285	264	238	207	200	192	165	149	129	114	102

***Note*: Average urbanized area densities were interpolated for each decade from historical population data and from urbanized areas calculated from historical maps. The decade in which density reached its peak is highlighted.**

ANNEX V: MAPS FOR THE HISTORICAL SAMPLE OF 30 CITIES

The composite maps depicting urban expansion from 1800 to 2000, combining them with historical population data, and estimating historical population densities in a global sample of 30 cities are a product of original research carried out by the study team. The references used in creating the maps and in estimating the city population for each map year are given in the following Annex VI.

In this set of maps, the reader will find composite maps, information on population, urbanized area, and average urbanized area density for each of the 30 cities in the historical sample. The cities are organized in alphabetical order. The title of each page reports the name of the city, the country in which it is located, and the span of years during which population density was calculated. The first map date, if not immediately before or after 1800, reflects the absence of maps satisfying our requirements (poor quality maps for Bangkok, Kolkota, and Tokyo in the early nineteenth century for example) or too few people (if any) inhabiting the city (Los Angeles, Nairobi, Teheran, among others). With certain exceptions (Los Angeles, Tel Aviv, and Sao Paulo) maps were not sought for dates where the population was below 20,000.

The large centered map at the top of the page shows the expansion of the urbanized area for that city. A color continuum of reds and grays is used for different map dates. Dark reds indicate earlier years, followed by lighter reds, lighter grey, and dark grays to indicate later years. Water, in blue, including rivers, lakes, and oceans, reflects the extent of water in the year 2000. The outside border of the light green non-urban area is the administrative boundary adopted in our study as containing the built-up area of the city or metropolitan area in the year 2000. In the lower left hand corner, one sees a close-up of the composite map that shows features of the historic urban core that may not have been visible in the large centered map.

The table on the bottom right hand corner summarized the population, the urbanized area (in hectares), and urbanized area density (in persons per hectare) for each map year. Above the table is a chart that graphically displays the density information contained in the table. Years are plotted on the X-axis, density per hectare is plotted on the Y-axis. Connecting the data points are blue and red lines. Blue lines indicate the densities recorded before the density in the city reached its highest peak. Red lines show the densities recorded after density reached its peak. A best-fit exponential curve was fitted to the post-peak density data points, whose equation and R-squared value are visible in body of the chart.

The maps are given as PDF files, as JPEG files, and as ArcGIS shapefiles, and will soon be available on Lincoln Institute's Web site (www.lincolninst.edu).

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