The Fragmentation of Urban Footprints: Global Evidence of Sprawl, 1990-2000

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Abstract

Cities the world over are highly fragmented. The fragmentation of the built-up area cities by the open spaces interpenetrating them is a key attribute of urban-sprawl, and sprawl as fragmentation, as distinct from sprawl as lower-density development, is now a universal feature of cities. Using satellite images and census data for 1990 and 2000 for a global sample of 120 cities, we find that cities typically contain or disturb vast quantities of open spaces, equal in area, on average, to their built-up areas. That said, we find that fragmentation, defined at various spatial scales as the relative share of open space in the urban footprint as a whole or in parts of it, is now in decline. We use multiple regression models to explain variations in fragmentation and in its decline among cities and regional groupings. We find that larger cities are less fragmented; that high levels of car ownership tend to reduce fragmentation, possibly because they allow infill at relatively low costs; that there were parallel declines in average built-up area densities and in levels of fragmentation during the 1990s; and that cities that do not permit development in large areas around are slightly, yet significantly, less fragmented. Policies aimed at reducing fragmentation should be clearly distinguished from policies aimed at increasing the density of built-up areas. Encouraging infill in cities with little population growth is qualitatively different from encouraging infill in cities with rapidly growing populations. In the former, it can form the backbone of an effective ‘smart growth’ policy. In the latter, it is overshadowed by the urgent need to prepare vast areas for projected outward expansion.

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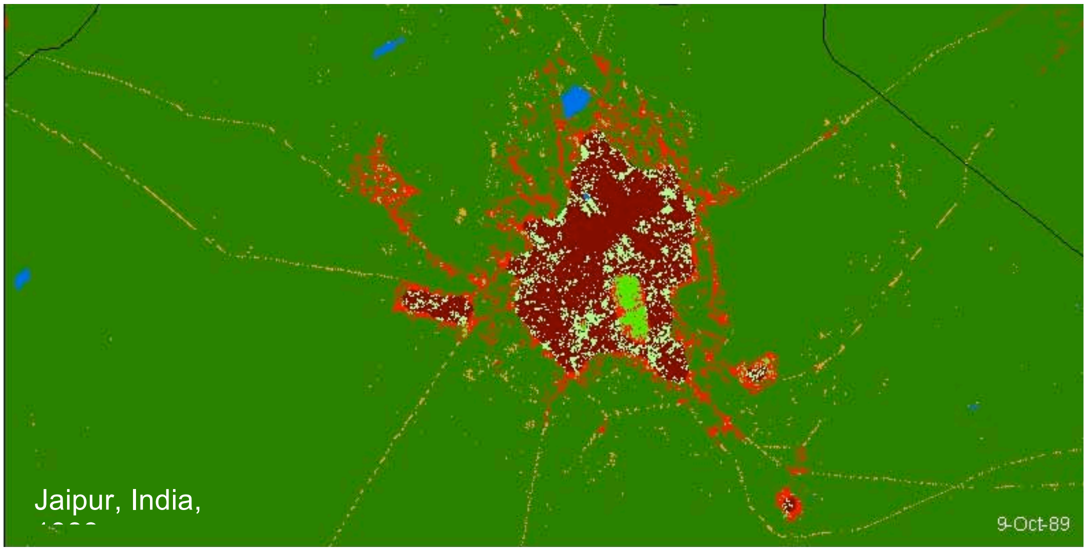
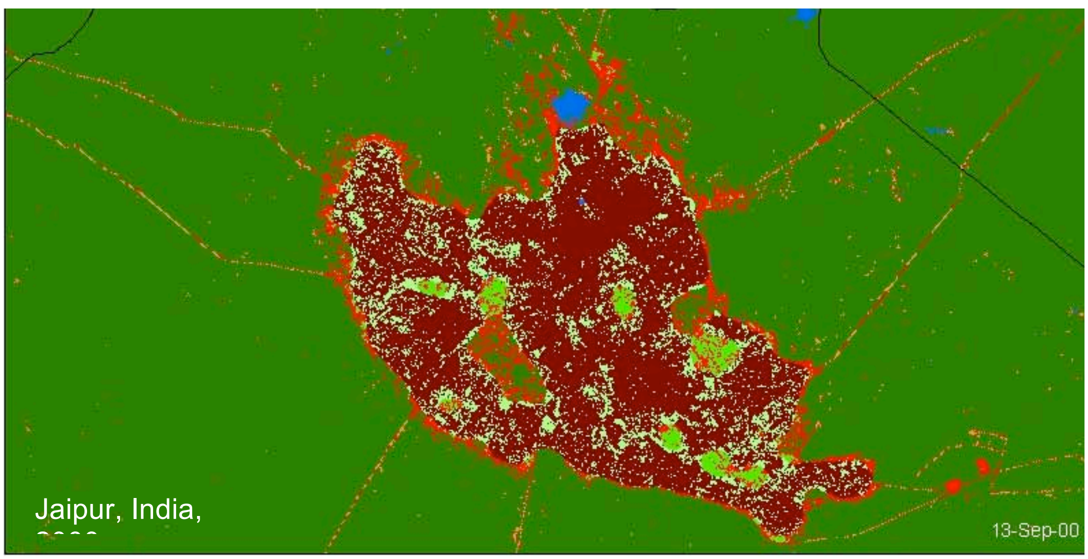




I Introduction

1. 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 and more contiguous. 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 and disturb 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 make two separate and complementary assertions: First, that the density at which urban land is built upon is too low and urgently needs to be increased; and, second, that we are being profligate about precious countryside on the urban fringe by building here and there in a scattered fashion, fragmenting and disturbing too much open space in the process. Not only are we building our cities at densities that are too low, but we are also building fragmented and disconnected cities, broken up by swaths of fragmented vacant lands.

In an earlier essay, "The persistent decline of urban densities: Global and historical evidence of sprawl", we focused on the first of these assertions, seeking to provide answers to several questions: How do densities in built-up areas 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?

In this essay we focus on the second of these assertions. We seek answers to the following questions: How is fragmentation to be defined and measured in a rigorous fashion, making it possible to compare fragmentation in cities across time and space? How can urban fragmentation be measured at different spatial scales, from the individual building, to the neighborhood, and to the metropolitan area as a whole? Can the measurement of fragmentation be effectively separated from the measurement of density? How does the fragmentation of the built-up areas of cities vary from place to place? With or without our interventions, when cities grow in population, do their built-areas become more or less fragmented? Do the rates of urban fragmentation differ among different cities and at different times? What are the factors that determine urban fragmentation and cause it to change? Is fragmentation too low in some cities, optimal in some, and excessive in others? Is urban fragmentation subject to effective policy intervention? If so, should urban fragmentation be brought under control? Is bringing it under control likely to distort land and housing markets, creating more problems that it seeks to address? Should developing-country cities pursue similar anti-fragmentation strategies to those of industrialized countries? The answers to these questions form the core of this essay.

The justifications for the multitude of urban containment policies and regulations that seek to reduce fragmentation and make cities more contiguous 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 here that the reader cannot help but be familiar with several of its specimens. The conviction that anti-sprawl strategies are the *right* strategies for our troubled times, that they are, in fact, strategies to ensure our very survival on the planet, is widespread. The evidence that urban containment strategies succeed in reducing fragmentation is anecdotal and, as we shall see later, the urban growth boundary surrounding Portland, Oregon has greatly reduced fragmentation there. Whether the societal benefits of measures designed to reduce excessive fragmentation exceed their negative side effects is still open to question, but that is almost beside the point: Political support for these measures is substantial and growing.

Urban containment strategies are also spreading to cities in developing countries where their 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 levels of fragmentation in developing-country cities, on the whole, are within reasonable bounds? How different are they from levels of fragmentation 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 and fragmentation levels 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, urban densities, and urban fragmentation? 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 industrialized 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, 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. This should not be surprising because several of the manifestations listed here are quite distinct attributes with different histories and independent causes, calling for quite different policies and strategies to address them.

Our study of urban sprawl and the literature associated with it has convinced us that its key attributes simply cannot be lumped together and measured with one simple 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 —fragmentation and its change over time—as one of these five attributes of urban expansion or sprawl and one of the most distinct among them.

Before describing these five attributes in greater detail, we must first make 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

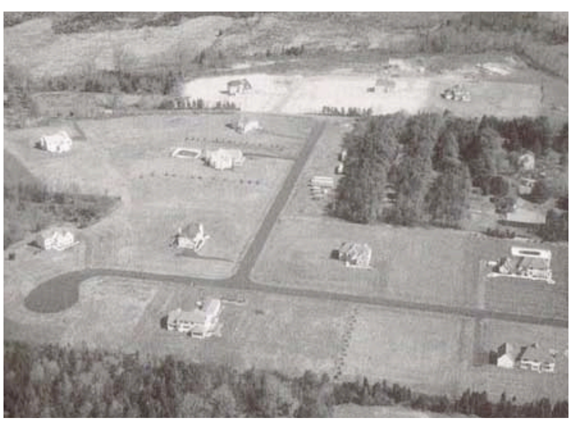
1 The terms ‘urban expansion’ and sprawl will be used interchangeably throughout this paper without necessarily attributing positive or negative attributes to these phenomena.

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 new emphasis on the latter. We then seek to explain the variation in spatial patterns 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 one particular attribute of sprawl, fragmentation, which is the focus of this essay. 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 or non-sprawling 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 least fragmented of American cities.

Figure 1.1: The 1940s Lakewood suburb of Los Angeles and the present-day Franklin Township of New Jersey[2]



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

In our study of sprawl, we focus on it both as a pattern and as a process, with a special new emphasis on the latter. After a review of the literature and a thorough examination of a wide range of metrics for measuring it in a rigorous, policy-sensitive manner, we have identified five discrete attributes of the pattern and process of sprawl that can now be measured and analyzed systematically and that together provide a relatively comprehensive[3] characterization of sprawl as both pattern and process. They are:

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.

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

[3] 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 Clawson 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).

> 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 on fragmentation. As noted earlier, a separate paper focused on decongestion (the decline of urban densities over time) and suburbanization (the moving away of the urban population from the urban core to the suburbs). A third paper in this series 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 research note on sprawl as dispersion may be appended to these papers at a later date.

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;

5. To focus interventions on specific aspects of sprawl, rather than on a muddled notion of what it is; and

6. 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. What is the relationship between sprawl as low-density development and sprawl as fragmentation?

3. Is urban fragmentation declining, stabilizing, or increasing over time?

4. 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?

5. Should developing-country cities pursue similar urban expansion policies to those now being advocated in developed countries? and

6. 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 the fragmentation of cities, one of 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 fragmentation and its decline over time is one of the attributes of sprawl most-often alluded to, and it is to fragmentation that we now turn our attention.

II Urban fragmentation and its Measurement

Fragmentation as used in the essay refers both to the way in which open spaces fragment the built-up areas of cities and the manner in which the built-up areas of cities fragment the open spaces in and around them. A fully built city surrounded by a wall and located in the open countryside does not fragment any open space and its built-up area cannot be said to be fragmented by open space. In contrast, scattered suburban homes located in partially built communities on the urban fringe can be said to be highly fragmented by open space, while the open space in and around them can be said to be highly fragmented by non-contiguous and widely-spaced residential areas.

More specifically, we seek to understand the extent to which open spaces break up built-up areas of cities and make them non-contiguous. At the same time we seek to understand the extent to which the scattered and non-contiguous built-up areas of cities fragment and disturb the open spaces in and around them. In our analysis, both urban built-up areas and urban open spaces are perceived of, in turn, as fragmented. The built-up area of a city can be seen as a figure on a background of open space, and, at the same time, urban open space can be seen as a figure on a background of built-up areas. Thus we come to understand that urban built-up areas and urban open spaces indeed fragment each other. Those of us concerned, say, with making the built-up areas of cities more connected and thus more accessible to each other (e.g. Ewing, 1997) see them as figure and their enveloping open spaces as background. Those of us concerned, say, with protecting farmland on the fringe of our cities (e.g. Brabec and Smith, 2002) see open spaces as figure and scattered built-up areas interpenetrating them as background. Our analysis seeks to address the concerns of both groups by, first, making the fragmentation of cities measurable and second, by measuring it in a comparable way in a global sample of cities.

It is important to note at the outset that we are simply concerned with fragmentation only as the spatial scatter of non-contiguous built-up areas; not in fragmentation as the division of metropolitan areas into a large number of independent jurisdictions, each with its own budget, plans, and priorities (e.g. Carruthers and Ulfaarson, 2002); not in fragmentation as segregation, or the division of urban areas into homogeneous ethnic or similar-income neighborhoods (e.g. Massey and Denton, 1988); and not in fragmentation as the breaking up of cities into distinct, single-use, residential, commercial, and industrial zones (e.g. Duany *et al*, 2001).

We also need to clearly separate our study of sprawl as fragmentation from the study of sprawl as low-density development. Unfortunately, the literature on sprawl tends to lump together low-density fully built suburban development and fragmented development. Yet a rigorous study of urban spatial structure requires that we clearly distinguish between the two. Why? First, open space in fully built neighborhoods, be it private or public, is in permanent use as open space. In contrast, most of the open spaces that fragment the built-up areas in emerging new neighborhoods on the urban fringe are vacant lands that will later be built-upon and are thus only in temporary use as open space. Second, low-density residential, commercial, and industrial development is largely the result of consumer lifestyle preferences for single-family homes, shopping malls, and low-rise workplaces, facilitated by cheap transport, the ready availability of capital and cheap land prices. In contrast, fragmented development is largely the result of the operation of land markets, with governments building inter-city roads that make distant locations on the urban fringe accessible; with developers and builders seeking to find cheaper vacant lands on the urban periphery that will maximize their returns on investment; with landowners keeping land off the market; or with informal developers and squatters seeking to find the cheapest land or the least-defensible land to start a new community.

Although both fragmentation and low-density development are key attributes of what is typically understood as sprawl, they do not necessarily go hand in hand. The fully-built suburbs of Phoenix, Arizona, for example, may contain single-family homes with small families on relatively large lots and may thus by considered sprawled in terms of low-density, but not at all sprawled in terms of fragmentation. Conversely, Rio de Janeiro, for example, with its high-density squatter settlements built on the slopes surrounding the city below, may be considered sprawled in terms of fragmentation, but not in terms of low-density. In short, low density and fragmentation are separate spatial characteristics of cities in general and of sprawl in particular, and they should be studied and considered separately as we intend to do. There is, as we noted earlier, a separate paper on density in this set of working papers.

That said, there may be good reasons for density and fragmentation to be related to each other: high densities may be found together with low levels of fragmentation and low densities with high levels of fragmentation; or, conversely, high densities may be accompanied by high levels of fragmentation and low densities by lower ones. We address this issue later.

Concerns with spatial fragmentation as a key attribute of urban sprawl have been with us for decades. Comments on the discontinuous pattern of urban expansion were already voiced in the U.S. in the 1940s and 1950s. A 1959 study of Phoenix, for example, concluded:

> The Phoenix urban area contains an unusual amount of undeveloped land, about 43,385 acres. Intermittent vacant parcels exert adverse economic effects on developed property and have disrupted the continuity of streets and utilities making public service more expensive and less efficient (Advance Planning Task Force, 1959, i).

Already in the early 1960s, Clawson characterized sprawl as 'lack of continuity in expansion' (1962, 99), and from early on the process of discontinuous development went by the pejorative name 'leapfrogging'. Leapfrogging, motivated by the search for cheap developable land in outlying areas, has been identified as a major factor in discontinuous development.

Discontinuous development has been explained by economists as the result of market forces. As Ewing, paraphrasing Lessinger (1962) and Ottensman (1977) explains:

> Expectations of land appreciation on the urban fringe cause some landowners to withhold land from the market. Expectations vary, however, from landowner to landowner, as does the suitability of land for development. The result is a discontinuous pattern of development. The higher the rate of growth of a metropolitan area, the greater the expectation of land appreciation, and the more land will be held for future development (Ewing, 1994, 2).

The decisions of landowners to place their lands on the market may also involve inertia, and some lands do appear on the market shortly after the death of their long-time owners. These decisions may also take into account alternative investments and their relative risks. Economists on their part have argued the merits and demerits of urban fragmentation for several decades, acknowledging that while it may be inefficient in the short term, it leads to more efficient development patterns in the long term (Peiser, 1989, 193):

> Urban sprawl is called inefficient because it generates low-density development that is "sprawled" over the landscape. A primary justification for interfering in the land market is a presumption that the public good is served by reducing urban sprawl through policies aimed at preventing discontinuous development. This paper argues that, contrary to conventional wisdom, a freely functioning land market with discontinuous patterns of development inherently promotes higher density development.

More recent concerns have been expressed about the fragmentation of farmlands and natural habitats by the expansion of cities:

> Without strict zoning regulations farmland often becomes parcelized as entire farms or parts of farms are sold to developers. This parcelization of farmlands leads to a checkerboard distribution of farmlands, i.e. many noncontiguous fields. Farming such scattered plots is problematic. (Pfeffer and Lapping, 1995, 85)

The argument as to whether cities should use planning instruments of one kind or another to restrain excessive fragmentation or whether to allow market forces free rein in choosing where and when to build since fragmented open space will eventually be built upon anyway has often pitted those who distrust markets with these who have faith in them. The one question that neither proponent has sought to answer is what level of fragmentation should be considered excessive? Economists point out that an urban housing market, for example, must contain a sufficient number of vacant units for housing prices to remain competitive. Indeed, the global average vacancy rate in 53 urban housing markets studied by Angel (2000, table 22.1, 299) averaged 4.8 percent. Surely, the supply of readily available land for urban development is quite different from housing vacancy levels, but do we really need an area equivalent to 100 percent of the built-up area of the city to be readily convertible to urban use? Would that not be considered excessive? What factors need to be taking into account in calculating an appropriate level of supply of land on the urban fringe?

The aim of this essay is to provide orders of magnitude of the amount of fragmented open space in cities in order to lend a measure of precision to claims that urban fragmentation is or is not excessive. We assume that all those involved in the debate understand the value of open space conservation as well as the value of efficient land and housing markets; that we could narrow down our differences on the question of how much is too much; and that we could define and quantify fragmentation with simple metrics that will allow us to inform the political decisions that will shape the urban expansion process in the years to come.

In the not so distant past, the precise measurement of fragmentation in a large number of urban areas and its change over time was a daunting task. This task has been vastly simplified in recent decades with the increased availability and affordability of satellite imagery. Using satellite imagery, it is now possible to detect and distinguish the impervious surfaces that characterize built-up areas from the non-built open spaces in and around them. Satellite images can now be coded into maps of pixels, where each pixel can be classified as built-up, open space, or water. For the present study, we used *Landsat* 5-satellite imagery with a 30-meter pixel resolution to classify images for a global sample of 120 cities for two time periods, one circa 1990 and one circa 2000. The process of classification is described in detail in Angel *et al* (2005, Chapter 3, 31-47).

Once it becomes possible to distinguish built-up pixels from open space pixels in any city in a consistent manner, it becomes possible to study urban fragmentation in a rigorous manner. It should come as no surprise to the reader that at the present time studies of urban fragmentation are rare. The most important among them, and one that has motivated the present study, is Burchfield *et al*'s "Causes of Sprawl: A Portrait from Space" (2005). The authors of that study used remote sensing data for two time periods, one circa 1976 and one circa 1992, to study sprawl as fragmentation in the United States. Indeed, they define sprawl simply as fragmentation, ignoring sprawl as low-density development. As a measure of fragmentation, they use the average amount of undeveloped land surrounding an average urban dwelling in a given city. They found that, on average, 43 percent of a 1 km^2 area around each residential location in U.S. cities was open in 1976 and that this percentage did not change by 1992. Using this metric they derived measures of average fragmentation for metropolitan areas in the U.S. and then used multiple regression models to explain the differences in these measures among these areas.

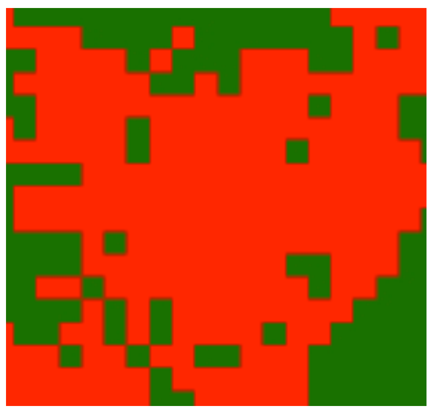
In the present study, we follow Burchfield *et al* in defining fragmentation as the relative share of the urban area that is open, as opposed to the share of the urban area which is built-up, be it with homes, businesses, roads, parking lots, airports, and all other types of impervious surface. The smaller the share of open space in the city, the less fragmented it is; the higher the share, the more fragmented it is. Admittedly, this definition does not distinguish between open space in permanent public or private use and open space that is vacant land that will eventually be built-upon. That said, there is no doubt that most open space in cities is in the second category. As we shall see later, anecdotal evidence suggests that open space in permanent use is a small fraction of the total amount of open space in and among the built-up Areas of cities. Our main concern is clearly with the level of fragmentation produced by vacant lands, but since they form the great majority of open space in cities, we can safely use the relative amount of all the open space in the city as a proxy of the relative amount of vacant lands in the city.

There is an extensive literature on the measurement of landscape fragmentation, and a host of metrics have been proposed for measuring one or another of its aspects (see, for example McGarigal and Marks, 2005, for a comprehensive set of landscape metrics). We have surveyed this literature and adopted several of its approaches to measurement and its proposed metrics in this study. All in all, however, we found that only very few of the fragmentation metrics proposed in the literature are appropriate for studying urban fragmentation in a way that addresses issues of common concern. This is not to suggest, however, that future studies of urban fragmentation may yield fruitful results by focusing on several fragmentation metrics passed over by our study.[4] Expanding on the measure used by Burchfield *et al*, we measure fragmentation in cities with four complementary measures, each corresponding to a different spatial scale.

The Edge Index

The Edge Index measures the frequency that built-up area pixels are found to be immediately adjacent to open space or water pixels (see figure 2.1). The index varies between 0 and 1, and the higher the value for this index, the larger the frequency that built-up pixels are found to be adjacent to open space pixels. Since pixels in the satellite images we used are 30-by-30 meters in size, the Edge Index is thus a good measure of the fragmentation of built-up areas at the scale of individual buildings, namely of the fragmentation of the open space in an around cities at the *micro* level.

Figure 2.1: 30-by-30 meter built-up pixels (red) and open space pixels (green)

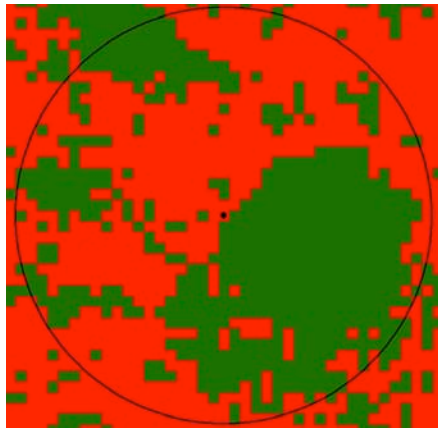


The Openness Index

The Openness Index measures the share of open space in a circle of 1 km^2 around each built-up pixel. The radius of this circle, 586 meters, corresponds to a distance covered by a leisurely 10-minute walk (see figure 2.2). The Openness Index is thus an indicator of the amount of open space within walking distance of every urban location, or the amount of open space “in the neighborhood”. In fact, it measures the average share of the area of that 1 km^2 circle that is open and not built-up. As noted earlier, the inspiration for this index came from Burchfield et al (2005, 1), who used a similar metric to measure sprawl in U.S. cities. As noted earlier, they found that, on average, 43 percent of a 1 km^2 area around each residential location in U.S. cities was open in 1976 and that this percentage did not change by 1992.

[4] Examples of such metrics include the average patch sizes of both built-up areas and open space patches; the average nearest-neighbor distances among patches; and the degree of connectivity among patches. See discussion on farmland fragmentation in Brabec and Smith, 2002.

Figure 2.2: The 'walking distance' 1 km^2 circle used to measure Openness



1. The Core Open Space Ratio

The built-up areas of cities were classified into three types: (1) urban cores, (2) suburban areas, and (3) rural areas. Urban core pixels were defined as built-up pixels surrounded by 50 percent of more built-up pixels in a 1 km^2 circle around them. Suburban pixels were defined as built-up pixels surrounded by 10 to 50 percent built-up pixels in a 1 km^2 circle around them. Rural pixels were defined as built-up pixels surrounded by less than 10 percent built-up pixels in a 1 km^2 circle around them.

It is important to keep in mind that these classifications are distinctions between urban, suburban, and rural areas based solely on their level of fragmentation and not on the respective densities in their built-up areas. It would clearly be more useful to distinguish urban and suburban areas in particular in terms of their respective built-up area densities. Unless we know the population in each and every census tract in the city, however, we cannot compute the densities of the built-up areas of these census tracts. Our calculation of built-up area density must therefore remain calculations of average density in the city as a whole, which are simply the ratio of their total population and their total built-up areas. In the future, as spatial data at the census tract level becomes readily available for cities the world over, we will be able to distinguish urban and suburban tracts by their densities.

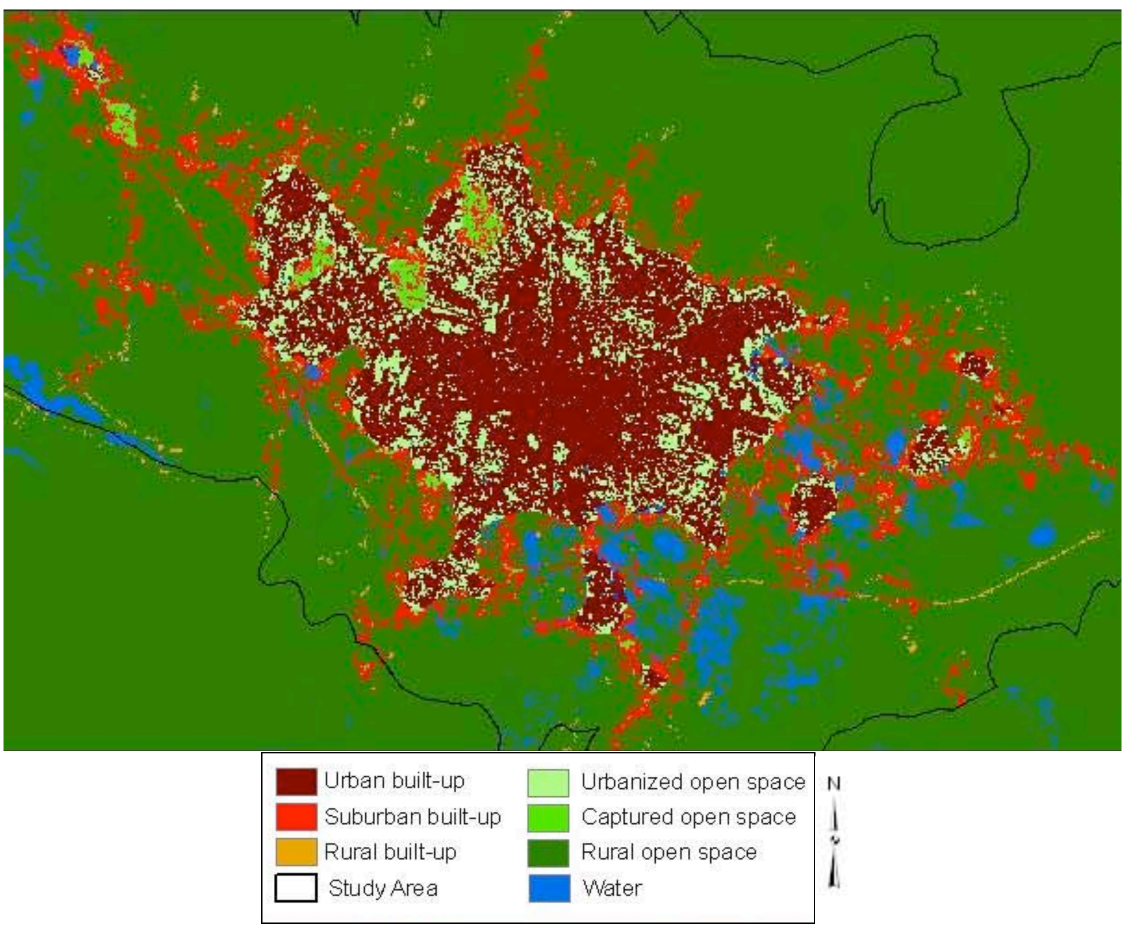
We defined a *Core Open Space pixel* in a city as an open space pixel that had a majority of built-up pixels in its immediate neighborhood, that neighborhood defined as a circle 1 km^2 in area about the center of that pixel. The totality of these pixels, plus the open spaces entirely surrounded and thus captured by core open space pixels and built-up area pixels[5] constituted the *Core Open Space* of that city.

[5] There is a 200 hectare upper bound on captured open space, introduced to eliminate large open spaces in the countryside that are entirely surrounded by wide roads and possible strip development along these roads from being included in the urbanized areas of cities.

The built-up area and the core open space in Bandung in 1991 are shown in figure 2.3. This figure shows that Core Open Space ─ consisting of the urbanized and captured open spaces in the figure ─ was intentionally defined to include only open spaces that are *fully contained within the urban core of the city*. It does not contain the open spaces surrounding sparse suburban developments on the urban fringe and is thus a conservative measure of open space fragmentation that is restricted to the urban core. In 1991, for example, core open space in Bandung added some 34 percent to the area of the city's urban core (shown in dark red).[6] In other words, the urban core of Bandung contained within it fragmented open space equivalent to 34 percent of its built-up area.

The *Core Open Space Ratio*, the ratio of core open space to the built-up area of the urban core, thus constitutes a useful third metric for measuring fragmentation. It is a distinct metric from the Edge Index and the Openness Index. It focuses attention on the *urban core* as a whole while leaving aside for the time being the fragmentation of open space in suburban areas. And it measures fragmentation at a larger scale and in a more localized area, the entire urban core of the city, than the average neighborhood level measured by the Openness Index.

Figure 2.3: The built-up area and core open space of Bandung, 1991



[6] As figure 4.1 shows, a polycentric city like Bandung can have more than one urban core.

The City Footprint Ratio

Landscape ecology studies claim that settlement development near a forest or a prairie affects vegetation and wildlife along their edges, often in a belt some 100 meters in width.[7] The City Footprint Ratio measures the relative amount of open space in and around the entire built-up area of the city that is fragmented or disturbed by it.

A *Fringe Open Space* pixel was thus defined as an open space pixel that is less than 100 meters away from an *Urban* or *Suburban* built-up pixel. An *Urban* pixel was defined earlier as a built-up pixel that had a majority of built-up pixels in its immediate neighborhood, that neighborhood defined as a circle 1 km^2 in area about the center of that pixel. A *Suburban* built-up pixel was defined earlier as a built-up pixel had more than 10 and less than 50 percent of its immediate neighborhood occupied by built-up pixels; and a rural built-up pixel was defined as a built-up pixel had less than 10 percent of its immediate neighborhood occupied by built-up pixels. All open space pixels that were more than 100 meters away from urban or suburban built-up pixels were considered to be *Rural Open Space*.

The *City Footprint* was then defined as the area including the city's built-up area, its fringe open space pixels and the open spaces entirely surrounded and thus captured by both types of pixels. These captured open space pixels were in turn included in fringe open space. The reader should note that although the City Footprint typically contains all the core open space in any given city, its definition is separate and independent from the definition of core open space.

The built-up area and the Fringe Open Space of Bandung in 1991 are shown in figure 2.4. The figure shows clearly that Fringe Open Space is intentionally defined to include all the open spaces within 100 meters of both urban and suburban development, not only the open spaces that are fully contained within the built-up area of the city. The City Footprint of Bandung includes the built-up area, its fringe open space, and the open spaces entirely captured by both. The *City Footprint Ratio* is defined as the ratio of the city footprint and the built-up area of the city. This ratio is a much more liberal measure of open space fragmentation than the Core Open Space Ratio discussed earlier. In 1991, for example, the City Footprint Ratio in Bandung was exactly 2.0: the city footprint was exactly twice the size of its built-up area. Fringe open space thus added some 100 percent to the built-up area of the city. In other words, the built-up area of Bandung affected and fragmented open space equivalent to 100 percent of its area.

The reader should note that a significant share of fringe open space is not really 'contained' within the built-up area of the city, but really engulfs it. We refer to his share

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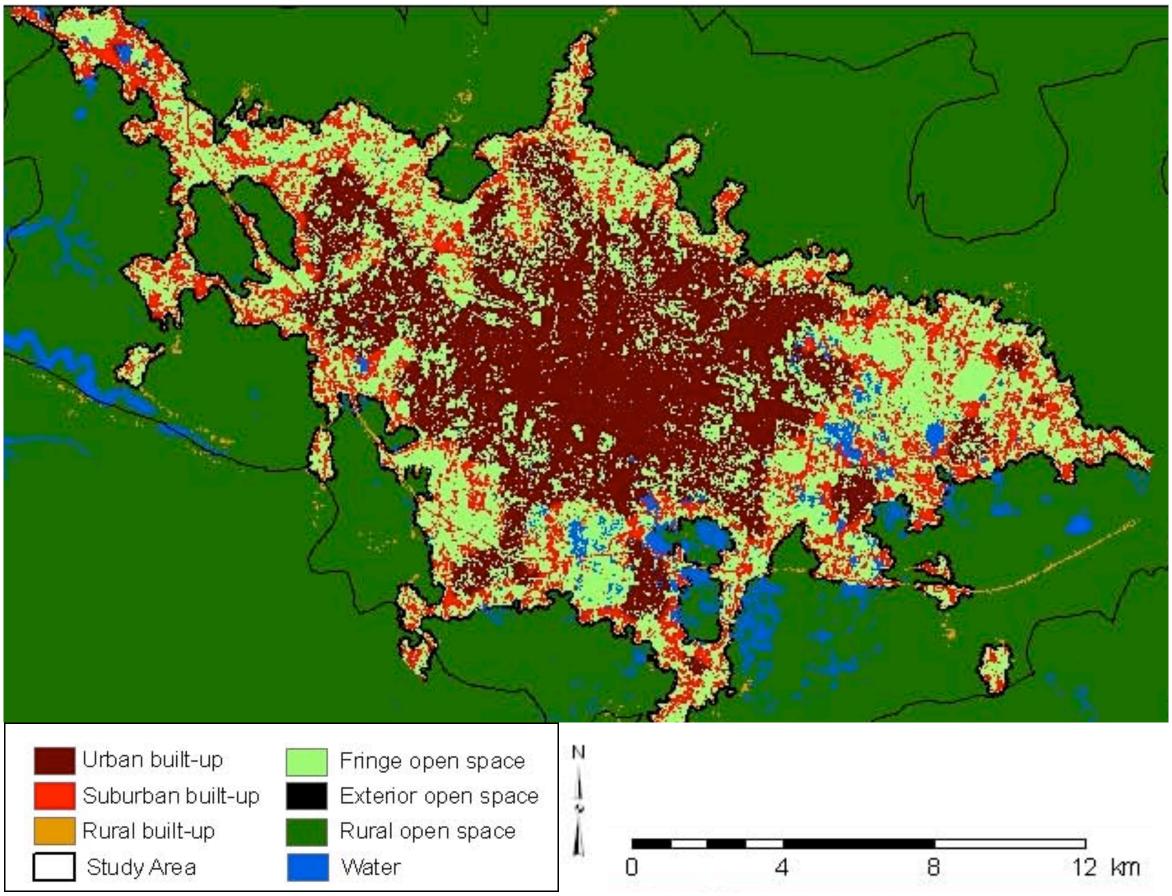
7 Studies in forest ecology identify different edge widths depending on the species being studied. Brand and George (2001) give an average edge width of 115 meters for the four bird species studied. Chen, Franklin and Spies (1992) discuss edge-widths of up to 137 meters, and one of the references in 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.

of fringe open space as *Exterior Open Space*. It consists of all fringe open space pixels that are less than 100 meters away from rural open space. Exterior open space is thus the 100-meter wide swath of open space along the outer perimeter of the built-up area of cities. It is shown in very dark green in figure 2.4. In 1991, Exterior Open Space in Bandung amounted to 14.7 percent, or one-seventh, of the city's fringe open space. The rest of the area of fringe open space was defined as *Interior Open Space*, shown in light green in figure 2.4. In 1991, interior open space constituted 85.3 percent of fringe open space in Bandung.

Figure 2.4: The built-up area the city footprint of Bandung, 1991



By definition, the 100-meter width of that swath does not vary with the size of the built-up area of the city. The reader should therefore keep in mind that the share of exterior open space in the city footprint is negatively correlated with city size, and that, other things being equal it would tend to decline with city size. In fact, the correlation between the logarithm of the built-up area of cities in 2000 and the share of exterior open space in the city footprint in that year was -0.50 and it was significantly different from 0.

The average share of the total area of this exterior swath of open space in the total area of fringe open space can be quite large: it amounted to 28.3±2.2 percent in 1990 and to

27.7±2.3 percent in 2000 in the global sample of 120 cities. In the year 2000, it varied from a minimum of 5.7 percent in Tokyo (with a built-up area of 2,540 km^2) to 69 percent in Aswan (with a built-up area of 15.7 km^2). The reason the average share of exterior open space in the city footprint is so large is that, on average, the length of these swaths of open space is some seven times longer that it would be if city footprints were perfect circles, and this multiple of seven did not vary significantly between 1990 and 2000.

Infill, extension and leapfrog

While both the academic and the popular literature on sprawl and its manifestations often distinguishes between the shares of new development that are infill, extension or leapfrog, these concepts are quite difficult to define and quantify in a rigorous manner.

Infill, for instance, assumes that we can distinguish clearly between the inside and the outside of cities. This would be entirely possible if, for example, the city was surrounded by a wall. But it is quite impossible when the outlying areas of the city are fragmented and only partially built, with buildings scattered among fragmented open spaces. Unfortunately, the contemporary metropolis is no longer set apart from the open countryside, but intermingled with it:

> One feature of postwar suburbanization has been its tendency to discontinuity—large closed settled areas intermingled haphazardly with unused areas. This intermixture of open and developed areas is largely independent of the density of the settlement within the developed areas…. The lack of continuity in expansion has been given the descriptive designation "sprawl," which well connotes its hit or miss character (Clawson, 1962, 99).

This lack of continuity creates a checkered urban periphery that makes it quite difficult to tell where the city ends and where the countryside begins in no uncertain terms.

In our study of the global sample of 120 cities, we posed the following question: We now have a detailed 30-by-30 meter pixel map of the built-up area of 120 cities circa 1990, and a similarly detailed map the built-up area of those same cities circa 2000, and we can easily identify every pixel that was built between these two dates. How do we determine unequivocally whether or not such a pixel constitutes infill rather than an outward extension of the city?

Extension should be somewhat easier to define, but it is not. Intuitively, we understand the extension of the built-up area of the city to mean the *outward* development of an area *immediately adjacent* to that built-up area. One ambiguity here is in the confusion about what constitutes outward as against inward development, for example. A second ambiguity may arise in agreeing on what we mean by immediately adjacent: do we really mean that the wall of a new building must touch the wall of an existing one, or do we still consider new buildings that are less than, say, 100 meters from existing built-up areas to be a form of direct extension of the built-up area of the city?

Leapfrogging should also somewhat easier to define, but it is not. Intuitively, we understand leapfrogging development to be development that skips out and away from the existing built-up area, leaping over swaths of open space, so to speak, to alight in the open countryside. One ambiguity may arise in the search for agreement as to how to distinguish between extension and leapfrogging. In other words, in agreeing how far a new development has to be from existing built-up areas to be considered leapfrogging development rather than a simple extension of the existing built-up area. A second ambiguity arises regarding the time frame during which the definitions of leapfrogging and extension must hold. A new leapfrogging development that was built in a given year, say in 1993, may become part of an extension a few years later, say by 1998, as the vacant area separating it from the built-up area of the city gets built-up. If we look at leapfrogging and extension data only at two points in time, say 1990 and 2000, that development will show up as extension. But if we looked at data from say, 1990 and 1995, it would have shown up as leapfrogging development.

Finally, we must remember that infill, extension and leapfrogging are but temporary designations that apply to new construction that has occurred during a specified time period. In the longer run, when we look at fully built-up areas of the city at a given point in time, we can no longer tell which part originated as infill, which as extension, and which as leapfrogging.

To distinguish clearly between infill, extension and leapfrog in the foregoing analysis, we proceeded as follows: First, we defined new development as clusters of contiguous built-up pixels that were detected in satellite images taken circa 2000 but were not detected in satellite images taken circa 1990. In our analysis, therefore, a cluster of pixels would be considered leapfrog only if it remained separated from the built-up area of the city for the entire decade.

In the foregoing analysis, we used the *City Footprint* defined earlier ─ and more specifically the city footprint in 1990 ─ as the means to distinguish between the shares of infill, extension and leapfrog in new development that occurred between 1990 and 2000. We defined the three as follows:

Infill was defined as consisting of all new development that occurred within *interior open space*, defined earlier as the set of all fringe open space pixels that were more than 100 meters away from rural open space in 1990.

Extension was defined as consisting of all new development that occurred in contiguous clusters that occupied *exterior open space* in full or in part, and were not infill. Exterior open space was defined earlier as the set of all fringe open space pixels that were less than 100 meters away from rural open space in 1990.

Leapfrog was defined as consisting of all new development that occurred entirely within *rural open space*, defined earlier as the set of all open space pixels that were more than 100 meters away from urban or suburban built-up pixels in 1990.

This definition of leapfrog development is very liberal: any new development that is more than 100 meters, typically only one city block away, from existing development is considered leapfrog. In reality, one may ask, how far from existing built-up areas does typical leapfrog development take place? We looked at leapfrog development in the 1990s in our global sample of 120 cities. The average distance of leapfrog development in the 1990s from the existing built-up areas of cities in 1990 was 1.86±0.28 kilometers (sig. 2-tailed 0.000). We also calculated that 35±3 percent of leapfrog development occurred at a distance less than one-half a kilometer from existing built-up areas (sig. 2-tailed 0.000); that 55±4 percent of leapfrog development occurred at a distance less than one kilometer from existing built-up areas (sig. 2-tailed 0.000); and that 75±4 percent of leapfrog development occurred at a distance less than two kilometers from existing built-up areas (sig. 2-tailed 0.000).

The average share of leapfrog in new development in the 1990s was 17.1±2.8 percent (sig. 2-tailed 0.000). Given the above results, we can conclude that the average share of new development more than 500 meters away from the city footprint was 12.1±2.2 percent (sig. 2-tailed 0.000); that the average share of new development more than one kilometer away from the city footprint was 8.8±2.0 percent (sig. 2-tailed 0.000); and that the average share of new development more than two kilometers away from the city footprint was 5.4±1.6 percent (sig. 2-tailed 0.000). These findings are at odds with those of Burchfield *et al* for the United States for the period 1976-1992. Burchfield *et al* (2005, 1) report that only 0.3 percent of new development in 1992 was more than one kilometer away from residential areas identified in 1976. For the ten U.S. cities in the global sample we found the average share of leapfrog in new development that was more than one kilometer away from the city footprint to be of the order of 4 percent, an order of magnitude larger than the 0.3 percent share estimated by Burchfield *et al* for the earlier period, 1976-1992. The discrepancy may be due to sampling differences or to time differences, but it is a cause for worry.

The relative shares of infill, extension, and leapfrog in new development as defined here constitute a set of dynamic fragmentation metrics. More specifically, infill development was defined in such a way that new infill development does not fragment or disturb rural open space at all. Clearly then, the greater the share of infill in new development, the less fragmented the city becomes. Extension fragments and disturbs rural open space on the urban periphery and its contribution to the level of fragmentation in the city can be both positive and negative. As for leapfrog, there is no doubt that the higher the share of leapfrog in new development the more fragmented the city becomes. Unfortunately, because we had satellite data for only two points in time, it was not possible to determine whether the relative shares of infill, extension or leapfrog development are on the increase or on the decline in our global sample of cities.

The reader should note that the definitions of the three categories of new urban development correspond to our intuitive meaning of the terms infill, extension, and leapfrog. The definition of infill is rather intuitive because it was defined as development that takes place inside interior open space, or alternatively as development that does not disturb or fragment new rural open space on the urban periphery. In fact, as figure 2.4 shows, the narrow 100-meter band of exterior open space surrounding Bandung clearly defines the interior of the city, and any new development inside this interior can only be considered infill and cannot be considered extension or leapfrog. The definition of extension is intuitive as well. Any cluster (or part of a cluster of new development net of infill) that originates within exterior open space and extends outwards from it is clearly an extension of the city. Extension thus consists of contiguous clusters of new development that are situated both in exterior open space and in rural open space, but do not occupy any interior open space. Finally, any cluster of new development that is situated entirely within rural open space is clearly in the nature of leapfrog development. It is not a direct extension of the existing built-up area, nor is it the infill of interior open space.

Fragmentation metrics are area metrics and not 'per person' metrics

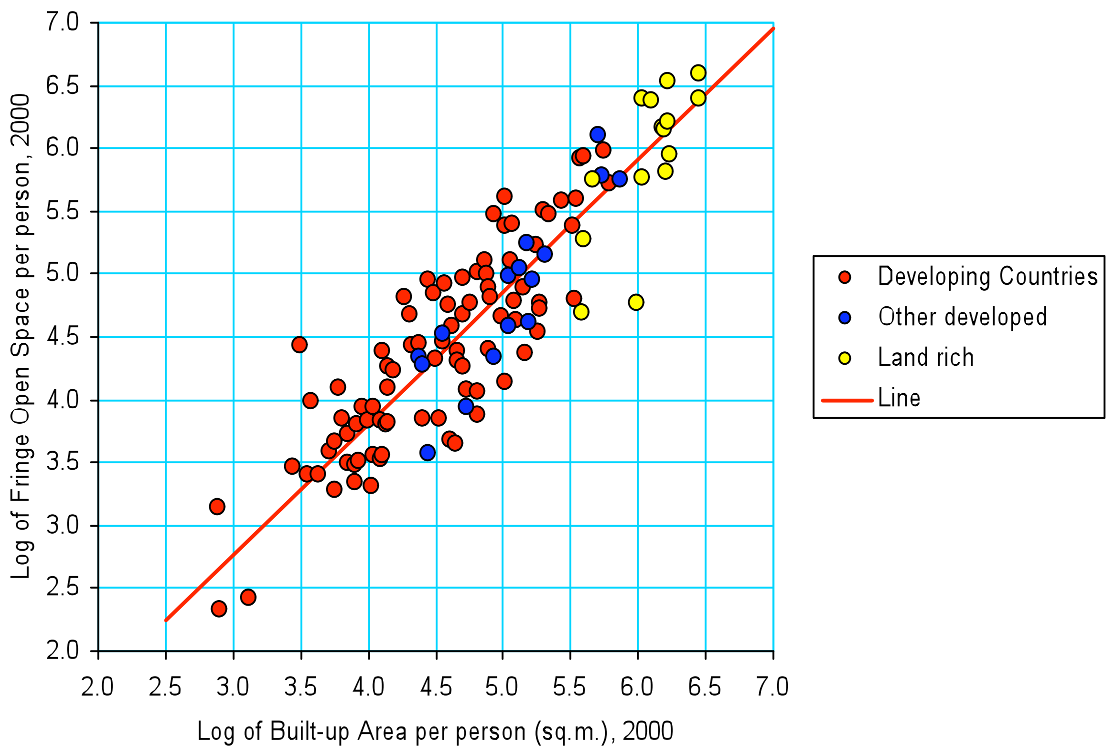
Finally, we note here that fragmentation is defined as the share of open space in relation to the built-up area of cities, and not in relation to its population. In other words, we avoid measuring fragmentation as the amount of open space per person in the city. This requires clarification, especially since the availability of *public* open space in permanent use in cities is typically measured in area per person, as the following quote demonstrates:

> The rule which is generally adopted now in the re-planning of British cities is to provide seven acres [2.83 ha] of public open space per 1,000 persons.... In the United States, the National Recreation Association advocates neighbourhood park and recreation areas on a basis of ten acres [4 ha.] per 1,000 persons (recommended) and five acres [2 ha.] per 1,000 persons (minimum), or at least 10 per cent of the neighbourhood area. (Brown and Sherrard, 1951: 149-150)

Following Burchfield *et al*, we refrain from using per person or per capita measures of fragmentation. In other words, fragmentation, as defined in this essay, is a measure of the share of open space in the spatial configuration of the city, not of the amount of open space that is fragmented, on average, by a person living in that city. This keeps the analysis of fragmentation and density separate and allows us to study each one independently of the other. Otherwise, if we did measure fragmentation as open space per person, then an increase in built-up area density will result in reducing the amount of open space per person even if the share of open space in the city footprint remained unchanged. Consider, as an example, two cities that are equally fragmented with, say, half their total area in open space. If one city had double the built-up area density of the other city, a per-person measure of fragmentation will lead us to conclude that it is half as fragmented as the other city.

This is best illustrated graphically (see figure 2.5). Each city in the global sample of 120 cities, to be introduced in the following section, is represented by a marker. Cities are divided into three regional groupings: developing countries, land-rich developed countries, and other developed countries. In figure 2.5 we graph the logarithm of fringe open space per person, measured in square meters, against the logarithm of built-up area per person also measured in square meters. The regression equation, with the former as a dependent variable and the latter as an independent variable, is: Log(Fringe open space per person) = -0.37 + 1.05·Log(Built-up area per person), with $R^2 = 0.82$.

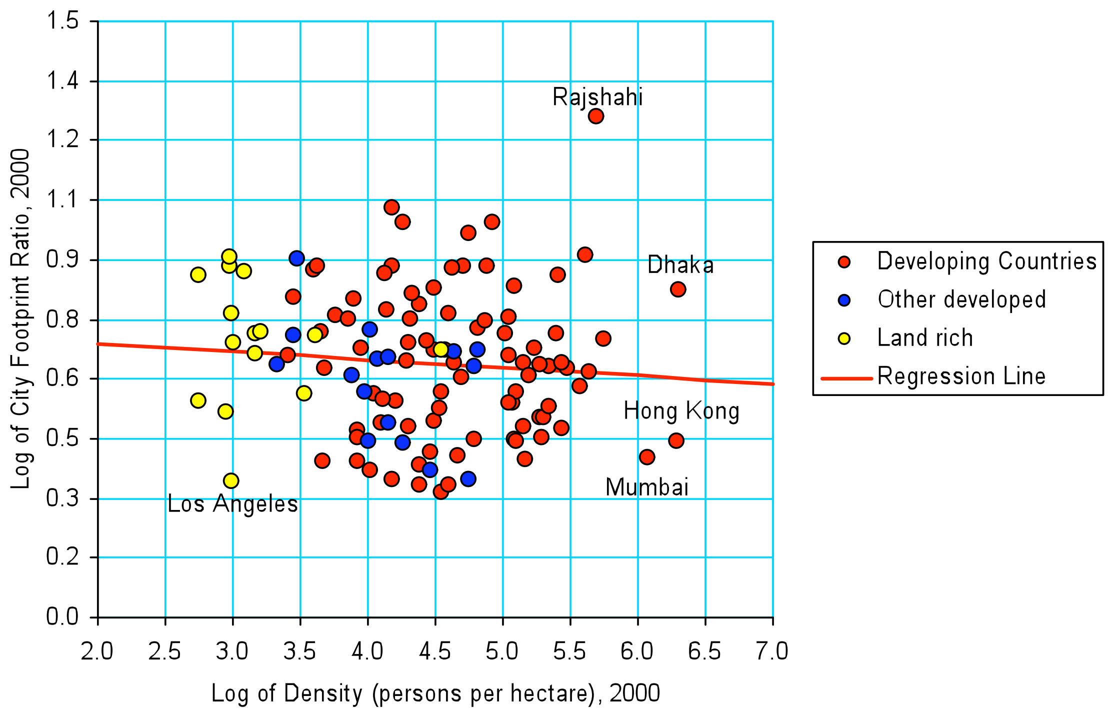
Figure 2.5: Fringe open space per person is not independent of built-up area per person



In this regression equation, the coefficient of log built-up area per person is significantly different from zero (sig. 2-tailed 0.000). The use of logarithms makes it possible to interpret the coefficients in the regression equation as *elasticities*, the sensitivities of one parameter to a change in another parameter. This equation tells us that a 10 percent increase in built-up area per person is associated with a 10.5 percent increase in fringe open space per person. Since built-up area per person is the reciprocal of density, we can also say that a 10 percent decrease in density is associated with a 10.5 percent decrease in fringe open space per person. This means that fringe area per person, as a measure of fragmentation is not independent of density in the built-up area.

In contrast, the City Footprint Ratio as we defined it earlier is a fragmentation metric that is independent of density. This is illustrated graphically in figure 2.6. In this figure we graph the logarithm of the City Footprint Ratio against the logarithm of built-up area density. The regression equation, with the former as a dependent variable and the latter as an independent variable, is: Log(City Footprint Ratio) = 0.72 - 0.02·Log(Density), with $R^2 = 0.01$.

Figure 2.6: The City Footprint Ratio is independent of built-up area density



Note: In this figure and in the figures to follow, only markers that are clear outliers are given their city names.

In this regression equation, the constant is significantly different from zero (sig. 0.000), but the coefficient of log density is not significantly different from zero. This equation can be interpreted to mean that a 10 percent increase in built-up area density is associated with an insignificant decrease of 0.02 percent in the City Footprint Ratio. This essentially means that the City Footprint Ratio as a measure of fragmentation in a given city is independent of density in the built-up area of that city. Since in this essay we are interested in focusing on fragmentation as an attribute of sprawl separate and independent of density, we shall refrain from using any 'per person' fragmentation metrics in our analysis.

To conclude, we defined fragmentation in this essay as the average share of open space in the areas of cities and measured this average share in satellite images of these cities at various scales. We then employed these metrics to study fragmentation in a global sample of 120 cities at two points in time, one circa 1990 and one circa 2000. This global sample of cities is introduced and described the next section.

III The global sample of 120 cities, 1990-2000

In an earlier study (Angel *et al*, 2005), 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 74 percent 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 Chapter II of that study. We selected cities from nine geographic regions, four population size classes and four per capita income classes. The list of cities appears in table 3.1 and their locations (as black dots) and their respective regions appear in figure 3.1.

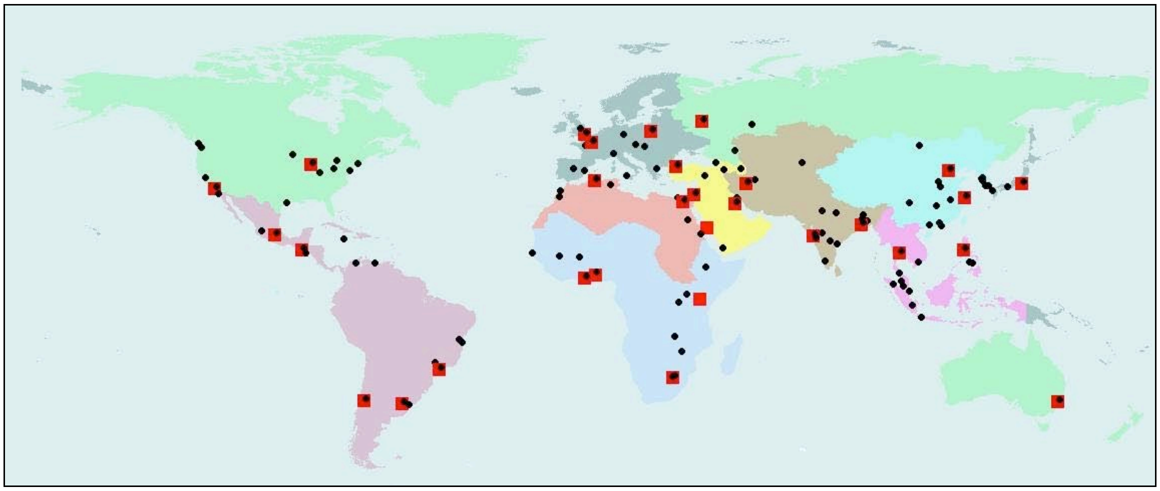
The reader should note that we sampled cities from these three these categories by population, rather than by the number of cities. That is, we divided the total population in the universe into four city size categories, for example, and selected one-quarter of the cities in the sample from each size 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 the 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, we calculated the built-up area 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 city footprint density, and the fragmentation metrics defined earlier 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)



To explain the variation in fragmentation and its decline over time 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, administered 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°.

Basic data on the global sample of cities, their division into nine regions, their population in the years 2000, and the Gross National Product per capita (in Purchasing Power Parities) is given in table 3.1 below.

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

City, Country	Population 2000	GNP/cap in PPP ($), 1995	City, Country	Population 2000	GNP/cap in PPP ($), 1995	City, Country	Population 2000	GNP/cap in PPP ($), 1995
East Asia & Pacific			**Latin America & Caribbean (cont.)+D35**			**South & Central Asia (cont.)**		
Shanghai, China	12,900,000	3,547	Tijuana, Mexico	1,167,000	8,182	Vijayawada, India	1,237,000	2,220
Beijing, China	10,800,000	3,547	Kingston, Jamaica	912,500	3,370	Rajshahi, Bangladesh	1,016,000	1,427
Seoul, Korea	9,887,779	13,958	Ribeirão Preto, Brazil	502,333	6,781	Ahvaz, Iran	997,000	5,460
Hong Kong, China	6,927,000	3,547	Valledupar, Colombia	274,300	5,618	Shimkent, Kazakhstan	360,100	4,215
Guangzhou, China	3,893,000	3,547	Guarujá, Brazil	269,104	6,781	Jalna, India	244,523	2,220
Pusan, Korea	3,830,000	13,958	Ilhéus, Brazil	161,898	6,781	Gorgan, Iran	188,710	5,460
Zhengzhou, China	2,070,000	3,547	Jequié, Brazil	130,207	6,781	Saidpur, Bangladesh	114,000	1,427
Yulin, China	1,558,000	3,547	**Northern Africa**			**Southeast Asia**		
Yiyang, China	1,343,000	3,547	Cairo, Egypt	10,600,000	3,253	Manila, Philippines	10,900,000	3,668
Leshan, China	1,137,000	3,547	Alexandria, Egypt	4,113,000	3,253	Bangkok, Thailand	7,281,000	5,846
Ulan Bator, Mongolia	738,000	1,491	Casablanca, Morocco	3,541,000	3,195	Ho Chi Minh City, Vietnam	4,615,000	1,854
Changzhi, China	593,500	3,547	Algiers, Algeria	2,760,740	4,979	Singapore, Singapore	3,567,000	21,832
Anqing, China	566,100	3,547	Marrakech, Morocco	736,500	3,195	Bandung, Indonesia	3,409,000	2,807
Ansan, Korea	549,900	13,958	Port Sudan, Sudan	384,100	1,512	Medan, Indonesia	1,879,000	2,807
Chinju, Korea	287,100	13,958	Aswan, Egypt	219,017	3,253	Palembang, Inbdonesia	1,422,000	2,807
Chonan, Korea	114,600	13,958	Tébessa, Algeria	163,279	4,979	Kuala Lumpur, Mnalaysia	1,378,000	8,217
Developed Countries			**Land-Rich Developed Countries**			Cebu, Philippines	718,821	3,668
Tokyo, Japan	26,400,000	23,828	Los Angeles, U.S.A.	16,373,645	31,338	Ipoh, Malaysia	566,211	8,217
Paris, France	9,624,000	23,225	Moscow, Russia	9,321,000	6,644	Bacolod, Philippines	429,076	3,668
London, England	8,219,226	22,652	Chicago, U.S.A.	9,157,540	31,338	Songkhla, Thailand	342,475	5,846
Milano, Italy	4,251,000	22,875	Philadelphia, U.S.A.	6,188,463	31,338	**Sub-Saharan Africa**		
Madrid, Spain	4,072,000	18,314	Houston, U.S.A.	4,669,571	31,338	Addis Ababa, Ethiopia	2,639,000	648
Warszawa, Poland	2,269,000	9,114	Sydney, Australia	3,664,000	24,013	Johannesburg, South Africa	2,335,000	8,667
Vienna, Austria	2,070,000	25,694	Minneapolis, U.S.A.	2,968,806	31,338	Accra, Ghana	1,976,000	1,804
Budapest, Hungary	1,825,000	11,301	Pittsburgh, U.S.A.	2,358,695	31,338	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			

IV Fragmentation and its decline in the global sample of 120 cities, 1990-2000

The satellite images of the 120 cities in the global sample have all been classified into three types of land use at the micro-level: every pixel of 30-by-30 meters (1/5 of an acre) was classified as either built-up, open space, or water. Given this detailed classification, we could investigate the interaction between built-up pixels and open space pixels in every city in the sample to determine the extent to which clusters of built-up pixels interpenetrated clusters of open space pixels. We could then measure this interaction in a rigorous and systematic manner to detect fragmentation.

As noted earlier, we defined five different metrics of measuring the fragmentation of cities and the open space in and around them, and each metric measured fragmentation at a different spatial scale. The edge index measured fragmentation at the scale of individual buildings. The openness index measured fragmentation at the neighborhood scale. The core open space ratio measured fragmentation in the urban core. The city footprint ratio measured fragmentation in the entire city, including its suburbs. And finally, the shares of infill, extension and leapfrog measured the shares of new construction in different parts of the urban landscape.

They key findings concerning the extent and decline in the fragmentation of cities in the 1990s are these:

1. Fragmentation at the scale of individual buildings:

    - There was an almost 50 percent chance that a built-up area as small as 1/5 of an acre (30-by-30 meters) in any city had an equivalent area of open space along one of its edges.

    - The immediate adjacency of small built-up areas to open space declined in the 1990s.

2. Fragmentation at the scale of neighborhoods:

    - A typical urban neighborhood (say, one square kilometer or 250 acres in area) contained almost as much open area as its built-up area.

    - Urban neighborhoods contained relatively less open space in 2000 than they did in 1990.

3. Fragmentation in urban cores:

    - The open space fully captured within the urban cores of cities added some 25-30 percent, on average, to their areas.

    - Cities in land-rich developed countries incorporated more open space into their urban cores than cities in other countries.

    - Urban cores contained relatively less open space in 2000 than they did in 1990.

4. Fragmentation in entire cities including their suburbs:

    - Fringe open spaces affected by the built-up areas of cities together with open space captured by them added some 100 percent, on average, to their areas.

    - Chinese cities were found to have larger City Footprint Ratios than other cities.

    - Cities affected and fragmented relatively less of the open spaces in and around them in 2000 than they did in 1990.

5. Infill, extension and leapfrog:

- Leapfrogging constituted only one-sixth of new urban development in the 1990s.

- Leapfrog development was more prevalent and infill less prevalent in developing countries than in developed countries.

In the remainder of this section, we discuss these findings one by one. We focus here on fragmentation both as a static pattern and as a process. We look at the extent of fragmentation at different spatial scales, measured along different metrics in different cities and regions at a single point in time and compare them to each other. We then look at the changes in the extent of fragmentation over time.

Fragmentation at the scale of individual buildings

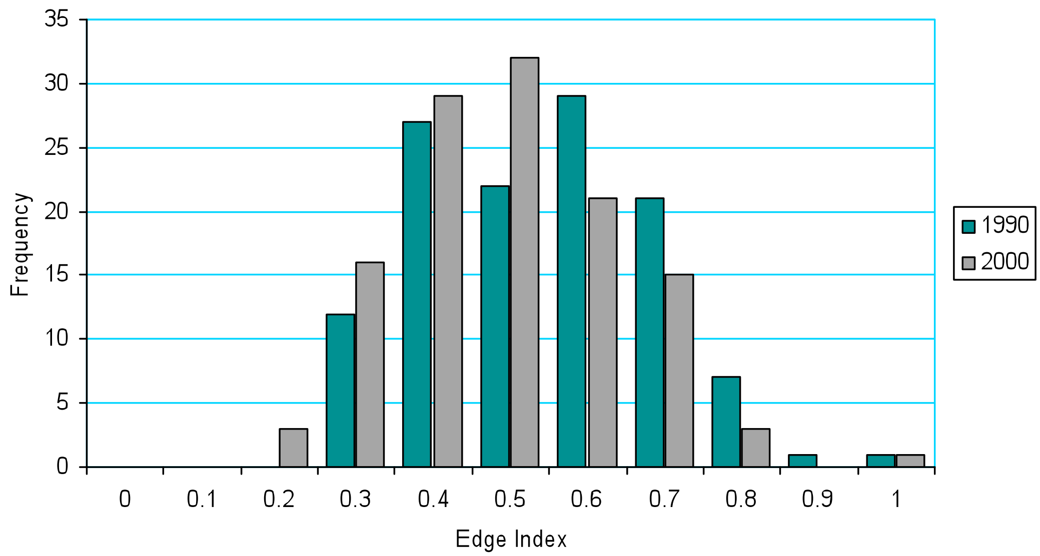
There was an almost 50 percent chance that a built-up area as small as 1/5 of an acre (30-by-30 meters) in any city had an equivalent area of open space along one of its edges

The Edge Index defined earlier measures the frequency that built-up area pixels are found to be immediately adjacent to open space or water pixels. The index varies between 0 and 1, and the higher the value for this Index, the larger the frequency that built-up pixels are found to be adjacent to open space pixels. The Edge Index is thus a good measure of the fragmentation of built-up areas at the micro level, or, alternatively, of the fragmentation of the open space in an around cities at the micro level.

We can say with a very high level of confidence that the mean value of the Edge Index in 1990 was 0.494±0.027 (sig. 2-tailed 0.000). In 2000 it was 0.445±0.025 (sig. 2-tailed 0.000). The average frequency at which built-up area pixels were found to be immediately adjacent to open space pixels was thus of the order of 50 percent. In other words, there was an almost 50 percent, or even, chance that a random built-up pixel in any city would be immediately adjacent to an open space pixel.

The frequency distribution of the values of the Edge Index for the global sample of 120 cities is shown in figure 4.1. These values appear to be normally distributed about their mean. The standard deviation from the mean was 0.15 in 1990 and 0.14 in 2000. In 1990, the minimum value of the Index was in Sao Paulo (0.24) and the maximum in Rajshahi (0.97). In 2000, the minimum value of the Index was in Sanaa (0.16) and the maximum again in Rajshahi (0.95).

Figure 4.1: The Frequency Distribution of the Edge Index, 1990-2000



Independent t-tests show that in 1990, the mean values for the Edge Index were not significantly different between cities in developing countries, cities in land-rich developed countries, and cities in other developed countries. In 2000, however, cities in developing countries and land-rich developed countries had significantly higher edge indices than cities in other developed countries (see figure 4.2). More particularly, in 1990, the Edge Index for cities in other developed countries (mostly Europe and Japan) was 0.44±0.03. In the rest of the cities in the sample it was 0.50± 0.01, but the mean difference between them was not significant at the 95 level of confidence. In 2000, however, the Edge Index for cities in other developed countries was 0.39±0.02 and in the rest of the cities in the sample it was 0.45±0.01. We can say with a very high level of confidence that the difference between them was 0.07±0.05 (sig. 2-tailed 0.008).

Figure 4.2: Variations in the Edge Index among Regional Groupings, 1990-2000

This finding demonstrates that contemporary cities are quite fragmented at the micro level, in our case at the 30-meter level, with open space pixels and built-up pixels highly interspersed. In other words, when we look at the city as a whole, we are likely to find that its built-up areas are not necessarily contiguous, nor do its impervious surfaces cover the ground in an uninterrupted manner. Surely, some areas in a typical city─most likely its older parts, its denser areas, and it central business district─are fully built, but there are large areas in that typical city which are not fully built, where there are many vacant lots, where vast stretches of land remain empty of construction, or where parks, playgrounds, playing fields, or private gardens keep the land free from development. On average, then, we are likely to find that a randomly selected small built-up area in a city is likely to have some open space along one of its edges almost half the time.

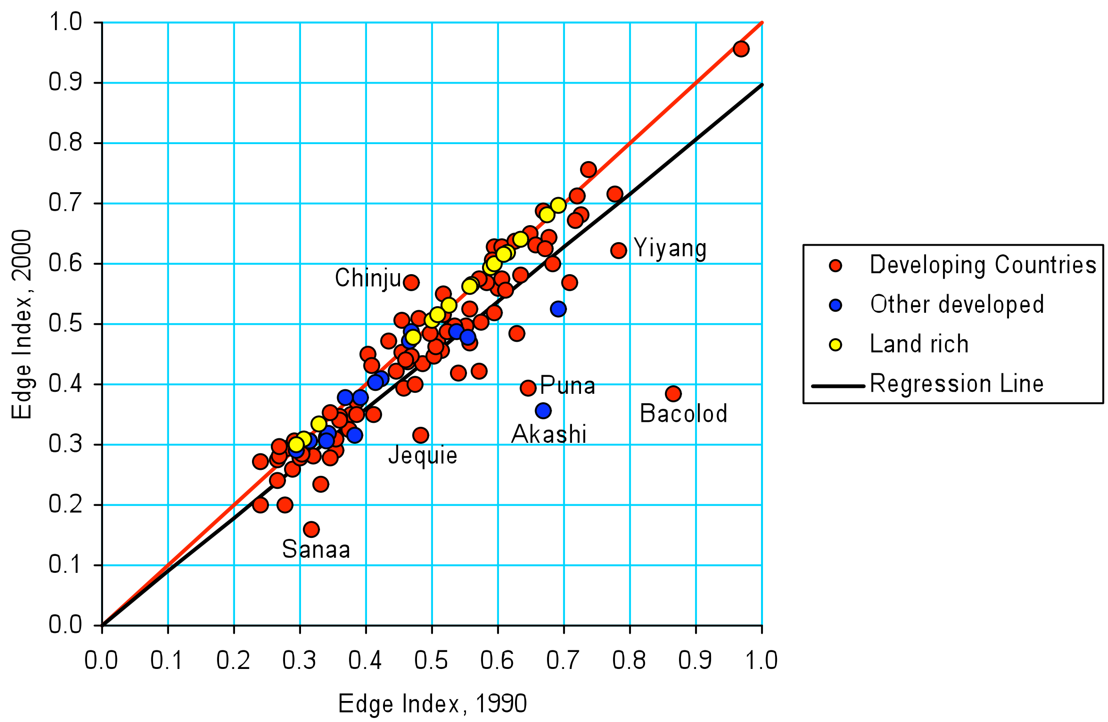
While the mean values of the Edge Index for the regional groupings were found to be significantly different from each other in 2000, there was considerable variation in the values for individual cities within each regional grouping. In cities in developing countries in 2000, the lowest values for the Index were found in Sanaa (0.16) and Ouagadougou (0.20) and the highest values in Saidpur (0.75) and Rajshahi (0.95). In cities in land-rich developed countries in 2000, the lowest values for the Index were found in Los Angeles (0.27) and Chicago (0.31) and the highest values in Astrakhan (0.64) and Oktyabrsky (0.66). In cities in other developed countries in 2000, the lowest values for the Index were found in Le Mans (0.29) and Fukuoka (0.30) and the highest values in Castellon de la Plana (0.49) and Vienna (0.52).

The immediate adjacency of small built-up areas to open space declined in the 1990s.

The Edge Index declined significantly between 1990 and 2000 in the global sample of cities. The mean Edge Index for the global sample of cities was 0.49±0.01 in 1990 and it decreased to 0.44±0.01 in 2000. We can say with a very high level of confidence that the difference between the two means was 0.048±0.013 (sig. 2-tailed 0.000). In other words, urban areas on the whole became less fragmented at the micro level of individual buildings in 2000 than they were in 1990. We can also say with a very high level of confidence that the Edge Index decreased at an average rate of 1.07±0.28 percent per annum during the 1990s (sig. 2-tailed 0.000). This would imply that the mean value of the Edge Index decreased by some 11 percent during this period.

The decline in the Edge Index is illustrated in figure 4.3 below. For a given city, the Edge Index value for 1990 is plotted on the X-axis and the value for 2000 is plotted on the Y-axis. The red line in the figure is the 45° line. If the marker for a given city is below the red line, it indicates that the value for the Edge Index decreased for that city between 1990 and 2000. As figure 4.3 shows, most city markers (94 out of 120 or 78 percent) are below the red line. The black line in figure 4.3 is the regression line through the origin and it has an R^2 value of 0.978. The slope of the regression line is 0.89, also suggesting that between 1990 and 2000 the Edge Index declined by some 11 percent.

Figure 4.3: The decline in the Edge Index, 1990-2000



Independent samples t-tests show that there was no significant difference in the rate of decline of the Edge Index between developing and developed countries. Independent samples t-tests also show that there was no significant difference in the rate of decline of the Edge Index between cities in developing countries, land-rich developed countries, and other developed countries. It declined in 78 percent of cities in the sample that were located in developing countries, 75 percent in cities in land-rich developed countries, and 77 percent in cities in other developed countries. The index was found to decrease significantly and at similar rates in all three regional groupings.

The decline in the Edge Index observed in all three regional groupings in the 1990 is an important finding. It suggests that urban development is becoming less scattered and more contiguous over time, a welcome development for those of us who prefer cities to be more contiguous and more compact. But it also suggests that a smaller share of the built-up area of cities is now found to be adjacent to open space, and to the extent that being adjacent to open space is an amenity, the value of urban structures is thereby reduced.

Fragmentation at the scale of neighborhoods

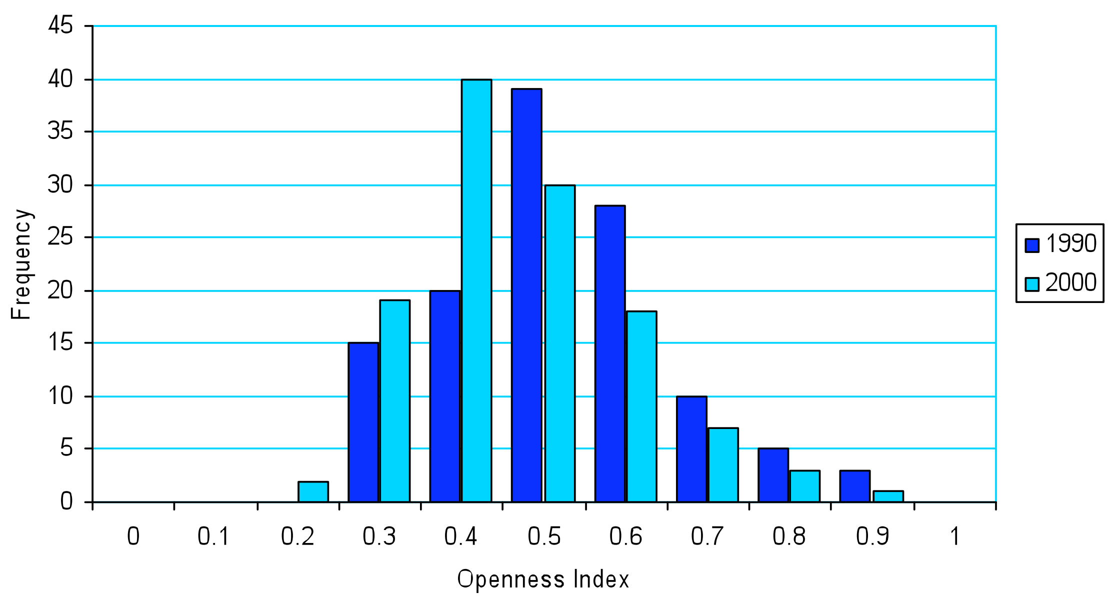
A typical urban neighborhood (say, one square kilometer or 250 acres in area) contained almost as much open area as its built-up area

As noted earlier, the Openness Index is an indicator of the amount of open space within a ten-minute walking distance of every urban location, or the amount of open space "in the neighborhood".

Single sample t-tests confirm with a very high level of confidence that the mean value of the Openness Index for a typical city was 0.47±0.02 in 1990 and 0.42±0.02 in 2000 (sig. 2-tailed 0.000). This finding for cities in the global sample in 1990 and 2000 is quite similar in value to the earlier findings of Burchfield *et al* (2005) for the United States in 1976 and 1992. It suggests that close to one half of the one-square-kilometer area in the immediate vicinity of a randomly selected built-up place in a given city is likely to consist of open space. In other words, a typical urban neighborhood consists of approximately equal areas of impervious surfaces and open fields. This gives us a sense of the fragmentation of the typical city at the neighborhood level, as against the micro-level of one or more single structures discussed in the previous section.

The frequency distribution of the values of the Openness Index for the global sample of 120 cities is shown in figure 4.4. These values appear to be normally distributed about their means. The standard deviation from the mean was 0.14 in 1990 and 0.13 in 2000. In both 1990 and 2000, the minimum value of the Index was in Sao Paulo (0.21 and 0.18 respectively) and the maximum in Rajshahi (0.89 and 0.84 respectively).

Figure 4.4: The Frequency Distribution of the Openness Index, 1990-2000

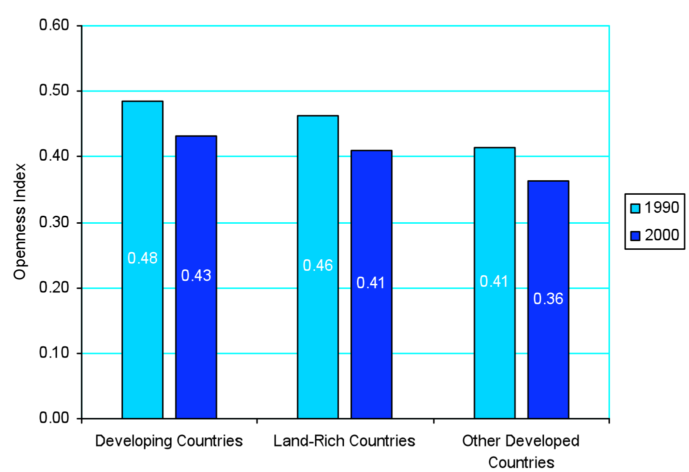


Independent sample t-tests confirm that the mean values of the Openness Index were significantly different among the three regional groupings in both 1990 and 2000 (see figure 4.5). In 1990, the Openness Index for cities in other developed countries (mostly Europe and Japan) was 0.41±0.02. In the rest of the cities in the sample it was 0.48± 0.01, and the mean difference between them, 0.068±0.055, was significantly different from zero at the very high level of confidence (sig. 2-tailed 0.018). In 2000, the Openness Index for cities in other developed countries was 0.36±0.02. In the rest of the cities in the sample it was 0.43± 0.01, and the mean difference between them, 0.066±0.048, was significantly different from zero at the very high level of confidence (sig. 2-tailed 0.009). There was no significant difference between the mean value of the Openness Index in cities of developing countries and land-rich developed countries either in 1990 or in 2000.

In 2000, the Openness Index for cities in other developed countries was 0.36±0.02 and in the rest of the cities in the sample it was 0.43±0.01. Again, we can say with a very high level of confidence that the difference between them, 0.066±0.048, was significantly different from zero (sig. 2-tailed 0.009). As in 1990, in 2000 there was no significant difference between the mean value of the index in cities of developing countries and land-rich developed countries.

We have no way to distinguish open space in permanent use from vacant land that is only temporarily free of development. That said, these findings confirm that neighborhoods in cities in other developed countries, mostly cities in Europe and Japan, contained less open space, on average, than neighborhoods in cities in land-rich developed countries and in cities in developing countries. They also confirm that fragmentation at the neighborhood level is as prevalent in developing-country cities as it is in U.S. cities, for example. Surely, densities in developing-country cities are much higher, but that said, the built-up areas in their urban neighborhoods are not more contiguous and do not fill up a larger share of their areas. In fact, as we already noted, fragmentation at the neighborhood level is found to be significantly higher in developing-country cities than in European and Japanese cities.

Figure 4.5: Variations in the Openness Index among Regional Groupings, 1990-2000



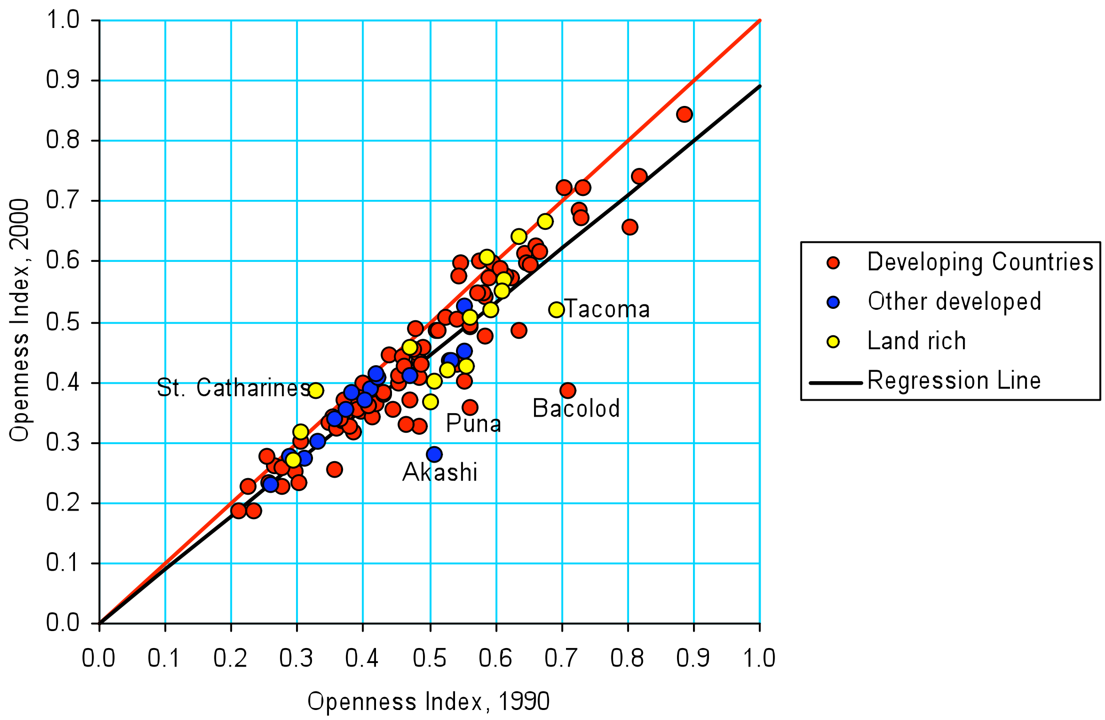
While the mean values of the Openness Index for the three regional groupings were found to be significantly different from each other, there was considerable variation in the values for individual cities within each regional grouping. In cities in developing countries in 2000, the lowest values for the Index were found in Sao Paulo (0.18) and Accra (0.19) and the highest values in Yulin (0.74) and Rajshahi (0.84). In cities in land-rich developed countries in 2000, the lowest values for the Index were found in Los Angeles (0.21) and Chicago (0.27) and the highest values in Astrakhan (0.53) and Oktyabrsky (0.60). In cities in other developed countries in 2000, the lowest values for the Index were found in Tokyo (0.23) and Paris (0.27) and the highest values in Vienna (0.45) and Castellon de la Plana (0.52). Some of the cities that had extreme values for the Openness Index also had extreme values for the Edge Index. This should not be surprising given the high correlation between the two indices: in the global sample of cities in 2000, for example, it was found to be 0.89 (sig. 2-tailed 0.000).

Urban neighborhoods contained less open space in 2000 than they did in 1990.

The average value of the Openness Index declined significantly between 1990 and 2000 in the global sample of cities. The mean Openness Index for the global sample of cities was 0.47±0.01 in 1990 and it decreased to 0.42±0.01 in 2000 (sig. 2-tailed 0.000). We can say with a very high level of confidence that the difference between the two means was 0.052±0.009 (sig. 2-tailed 0.000). In other words, urban neighborhoods on the whole became less fragmented at the neighborhood scale in 2000 than they were in 1990. We can also say with a very high level of confidence that the Openness Index decreased at an average rate of 1.02±0.2 percent per annum during the 1990s (sig. 2-tailed 0.000). This would imply that the mean value of the Openness Index decreased by some 11 percent during the 1990s.

The decline in the Openness Index is illustrated in figure 4.6 below. For a given city, the Openness Index value for 1990 is plotted on the X-axis and the value for 2000 is plotted on the Y-axis. The red line in the figure is the 45° line. If the marker for a given city is below the red line, it indicates that the value for the Edge Index decreased for that city between 1990 and 2000. As figure 4.6 shows, most city markers (113 out of 120 or 94 percent) are below the red line. The black line in figure 4.6 is the regression line through the origin and it has an R^2 value of 0.988. The slope of the regression line is 0.89, also suggesting that between 1990 and 2000 the Openness Index declined by some 11 percent.

Figure 4.6: The decline in the Openness Index, 1990-2000



Independent samples t-tests show that there was no significant difference in the rate of decline of the Openness Index between developing and developed countries. Independent samples t-tests also show that there was no significant difference in the rate of decline of the Openness Index among cities in developing countries, land-rich developed countries, and other developed countries. It declined in 92 percent of the cities in the sample that were located in developing countries, in a 100 percent of the cities in land-rich developed countries, and in 94 percent of the cities in other developed countries. The index was found to decrease significantly and at similar rates in all three regional groupings.

The decline observed in the Openness Index in all three regional groupings in the 1990s is an important finding. It does not directly refute the finding of Burchfield *et al* (2005, 1) that the openness index for U.S. cities remained the same between 1976 and 1992 because we measured it for a later time period, but it does suggest that the trends observed by Burchfield *et al* in the 1980s did not extend into the 1990s. We now know that open space in urban neighborhoods is becoming scarcer. Again, as in the case of the Edge Index, this is welcome news for those of us who would like to see a less scattered and more compact form of urban development worldwide. It is not welcome news for those of us who prefer to have ample open space within walking distance of their homes.

Fragmentation in urban cores

The open space fully captured within the urban cores of cities added some 25-30 percent, on average, to their areas.

The Core Open Space Ratio, the ratio of core open space to the built-up area of the urban core, constitutes a useful third metric for measuring fragmentation. It is a distinct metric from the Edge Index and the Openness Index discussed earlier. It focuses attention on the *urban core* as a whole while leaving aside for the time being the fragmentation of open space in suburban areas. And it measures fragmentation at a larger scale and in a more localized area─the urban core of the city─than the average neighborhood level measured by the Openness Index.

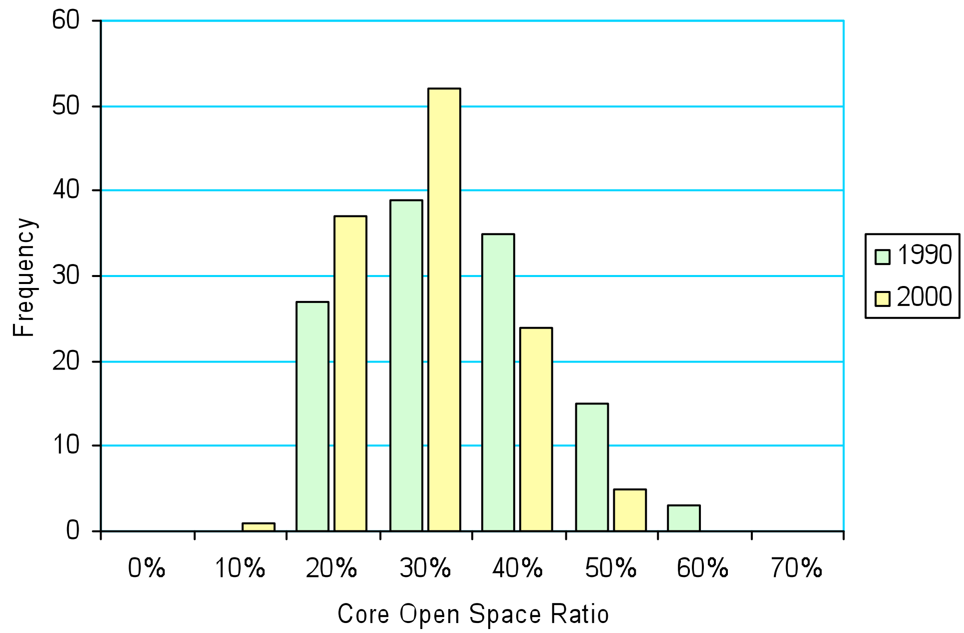
One sample t-tests confirm with a 95 level of confidence (sig. 2-tailed 0.000) that in 1990 and 2000 Core Open Space added, on average, 29.4±1.8 and 25.2±1.4 percent respectively to the *urban* built-up area of cities. We should note here that urban areas constitute a majority share of the built-up area of cities. One sample t-tests confirm with a 95 level of confidence (sig. 2-tailed 0.000) that in 1990 and 2000 *urban* areas formed, on average, 54.7±3.4 and 61.2±3.3 percent respectively of the built-up areas of cities.

This is an important finding. It confirms casual observations that cities are never fully built-up. They always contain a significant share of their areas, even of their more fully built-up areas, as open space, both as permanent open space in public and private use and as vacant land to be developed later. In the year 2000, for example, only one city in the global sample ─ Aswan ─ had an area less than 10 percent of its urban built-up area in core open space; and only five cities ─ Johannesburg, Cincinnati, Pretoria, Pittsburgh and Ndola ─ had areas equivalent to more than 40 percent of their urban built-up areas as core open space.

This finding suggests that the urban built-up areas of cities capture an area of open space that, on average, is equal to 20-30 percent of their area. As we shall see later, there are good reasons to believe that most of this core open space is not in permanent use but consists of vacant lands that are later built upon by infill development. A glance at the map of the core area of Bandung also suggests that there is very little core open space left within the inner city and that the share of core open space increases as we move away from the city's center. This is also an indication that it is open space that is not in permanent use and it likely to be filled in as the city grows. In terms of telling us something about the fragmentation of cities, this finding simply confirms that there is ample open space that is fragmented within the *urban* areas of cities, to be distinguished from the *suburban* areas of cities that surely fragment much larger quantities of open space as we shall see later. In fact, we can say with a very high level of confidence (sig. 2-tailed 0.000) that in 1990 and 2000 core open space added 22.0±1.4 and 21.4±1.2 percent to the built-up areas of cities respectively.

What concerns us here is the Core Open Space Ratio as a measure of fragmentation of the urban areas of cities. The frequency distribution of the values of this ratio for the global sample of 120 cities is shown in figure 4.7. These values appear to be normally distributed about their means. The standard deviation from the mean was 0.1 in 1990 and 0.08 in 2000. In 1990, the minimum value of the ratio was in Aswan (11 percent). In that year only three cities had values for this ratio greater than 40 percent: Ndola (52 percent), Akashi (53 percent) and Kampala (53 percent). The minimum value of this ratio in 2000 was found in Aswan (9 percent) and the maximum value in Ndola (49 percent).

Figure 4.7: The Frequency Distribution of the Core Open Space Ratio, 1990-2000

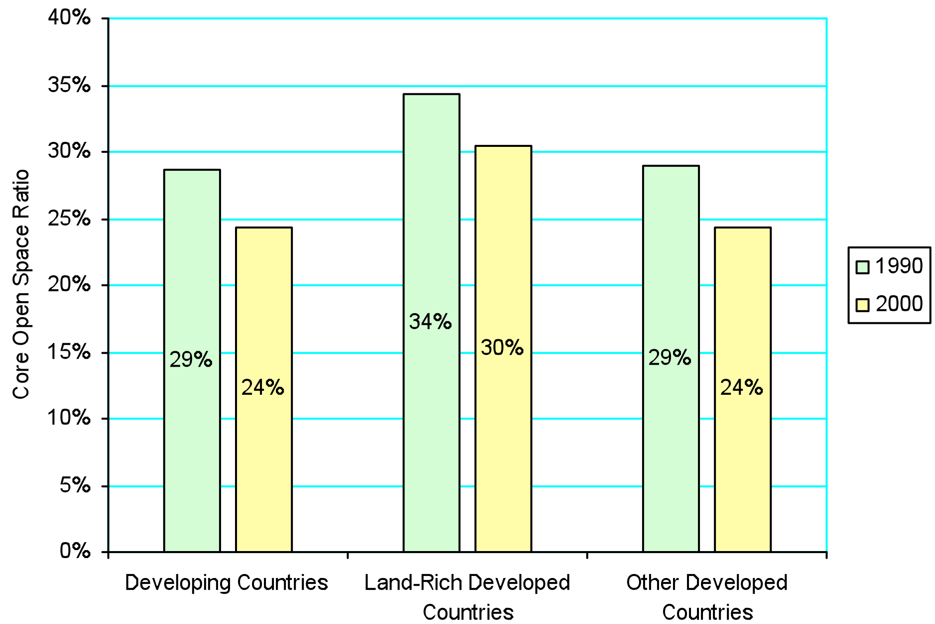


Cities in land-rich developed countries incorporated more open space into their urban cores than cities in other countries

Core open space occupied a significantly larger share of the urban built-up areas of cities in land-rich developed countries than of cities in other countries. In 1990, the core open space ratio was 34.4±2.1 percent in land-rich developed countries and 28.7±1.0 percent in other countries. We can say with a high level of confidence (sig. 2-tailed 0.022) that the difference between the two ratios was 5.7±4.8 percent. In 2000, the core open space ratio was 30.4±1.9 percent in land-rich developed countries and 24.3±0.8 percent in other countries. We can say with a high level of confidence (sig. 2-tailed 0.007) that the difference between the two ratios was 6.0±4.2 percent. Cities in land-rich developed countries were thus found to contain significantly more core open space within them than cities in other countries: Core open space added 30-35 percent to the urban built-up area of cities in land-rich developed countries, but only 24-28 percent to the built-up area of cities in other countries.

The mean core open space ratios observed in the three regional groupings in 1990 and 2000 are illustrated in figure 4.8 below.

Figure 4.8: Variations among Regional Groupings in the Core Open Space Ratio, 1990-2000

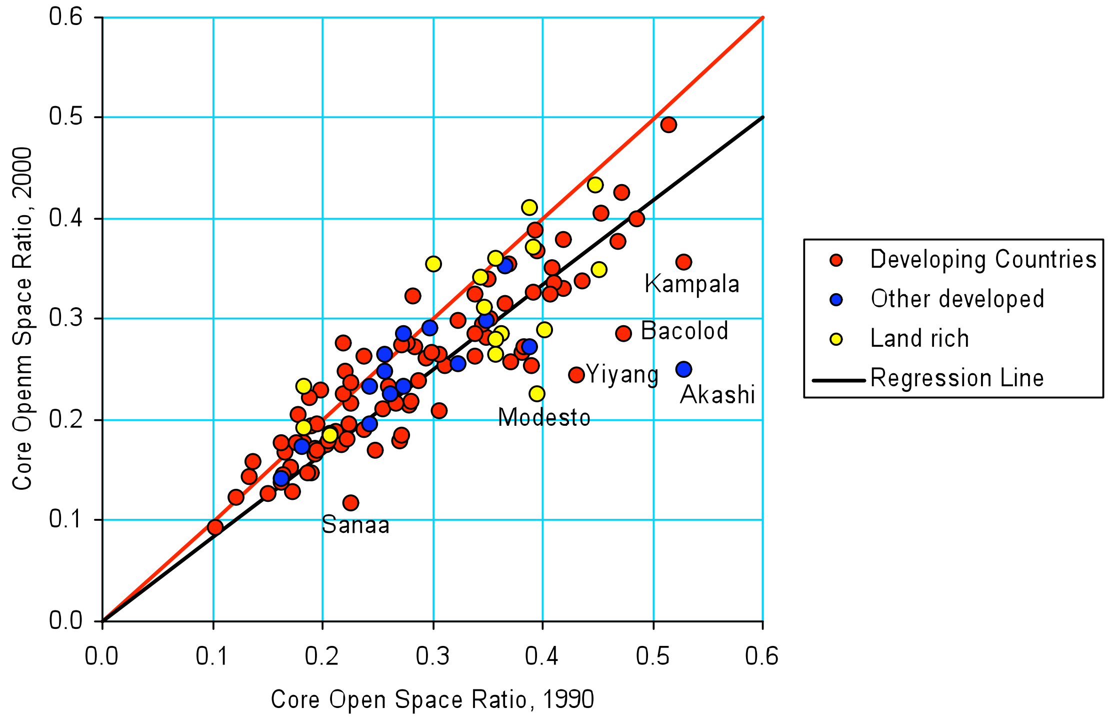


Urban cores contained relatively less open space in 2000 than they did in 1990.

The Core Open Space Ratio declined significantly between 1990 and 2000 in the global sample of cities. We can say with a very high level of confidence (sig. 2-tailed 0.000) that the mean ratio for the global sample of cities was 29.4±1.8 percent in 1990 and it decreased to 25.2±1.4 percent in 2000. We can also say with a very high level of confidence that the difference between the two means was 4.3±0.9 percent (sig. 2-tailed 0.000). In other words, in the year 2000 urban cores on the whole became less fragmented than they were in 1990. We can also say with a very high level of confidence that the Core Open Space Ratio decreased at an average rate of 1.49±0.31 percent per annum during the 1990s (sig. 2-tailed 0.000). This would imply that the mean value of the ratio decreased by some 14 percent during this period.

The decline in the Core Open Space Ratio is illustrated in figure 4.9 below. For a given city, the ratio for 1990 is plotted on the X-axis and the ratio for 2000 is plotted on the Y-axis. The red line in the figure is the 45° line. If the marker for a given city is below the red line, it indicates that the ratio decreased for that city between 1990 and 2000. As figure 4.10 shows, most city markers (99 out of 119 or 83 percent) are below the red line. The black line in figure 4.10 is the regression line through the origin and it has an R-squared of 0.971. The slope of the regression line is 0.84, also suggesting that between 1990 and 2000 the Core Open Space Ratio declined by some 16 percent.

Figure 4.9: The decline in the Core Open Space Ratio, 1990-2000



Independent samples t-tests show that there was no significant difference in the rate of decline of the Core Open Space Ratio between developing and developed countries. Independent samples t-tests also show that there was no significant difference in the rate of decline of this ratio between cities in developing countries, land-rich developed countries, and other developed countries. It declined in 85 percent of cities in the sample that were located in developing countries, 69 percent in cities in land-rich developed countries, and 88 percent in cities in other developed countries. On the whole, the index was found to decrease significantly and at similar rates in all three regional groupings.

The observed decline in the share of open space in the urban core in the 1990s is an interesting and important finding. It suggests that infill in the urban core is still taking place in cities in all three regional groupings, and that while core open space is being constantly replenished by the outward expansion of urban cores, the rate of replenishment is typically lower than the rate of infill. In fact, in ten cities in the global sample, the absolute area of core open space did not increase between 1990 and 2000: Sana'a, Modesto, Paris, Tokyo, Le Mans, Casablanca, Kingston, London, Sao Paulo, and Los Angeles. In nine of them it actually declined and in Los Angeles it stayed the same. In the rest of the 110 cities in the global sample, the absolute area of core open space increased between 1990 and 2000, but on average it formed a significantly smaller share of the expanding urban cores.

Fragmentation in entire cities including their suburbs

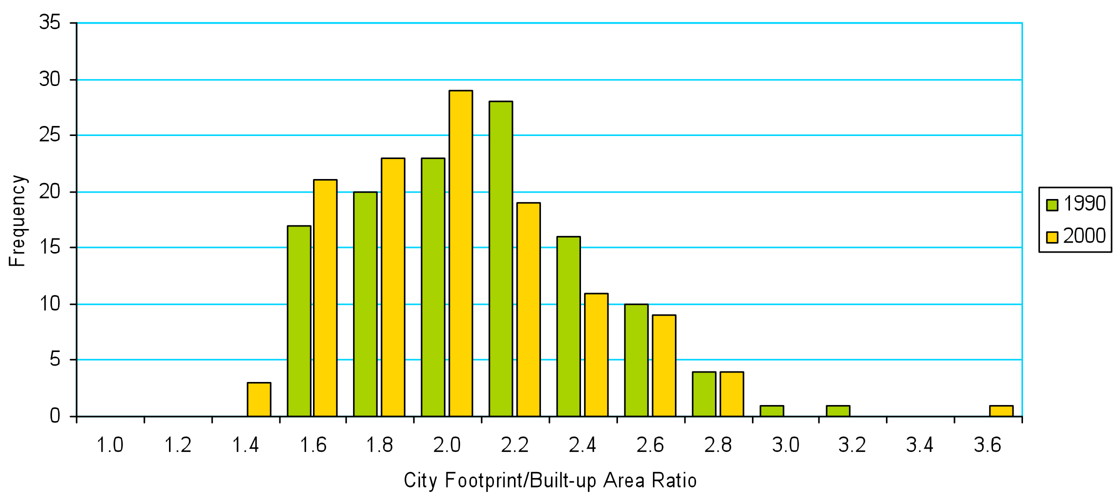
Fringe open spaces affected by the built-up areas of cities together with open space captured by them added some 100 percent, on average, to their areas

The reader may recall that Fringe Open Space was defined earlier as open space that is less than 100 meters away from Urban or Suburban built-up areas. Open spaces entirely surrounded and thus captured by both fringe open space and the built-up area that were less than 200 hectares in area were then added to fringe open space. The City Footprint was defined as the area including the city's built-up area and its fringe open space. The City Footprint Ratio was then defined as the ratio of the city footprint and the built-up area of the city. This ratio measures the relative amount of open space that is fragmented and disturbed by the entire built-up area of cities including their suburbs.

Single sample t-tests of our global sample of cities confirm with a very high level of confidence that in 1990 the mean City Footprint Ratio was 2.00±0.06 and that in 2000 it was 1.93±0.07 (sig. 2-tailed 0.000). In other words, the built-up areas of cities affected open space in and around them roughly equivalent in size to their built-up areas.

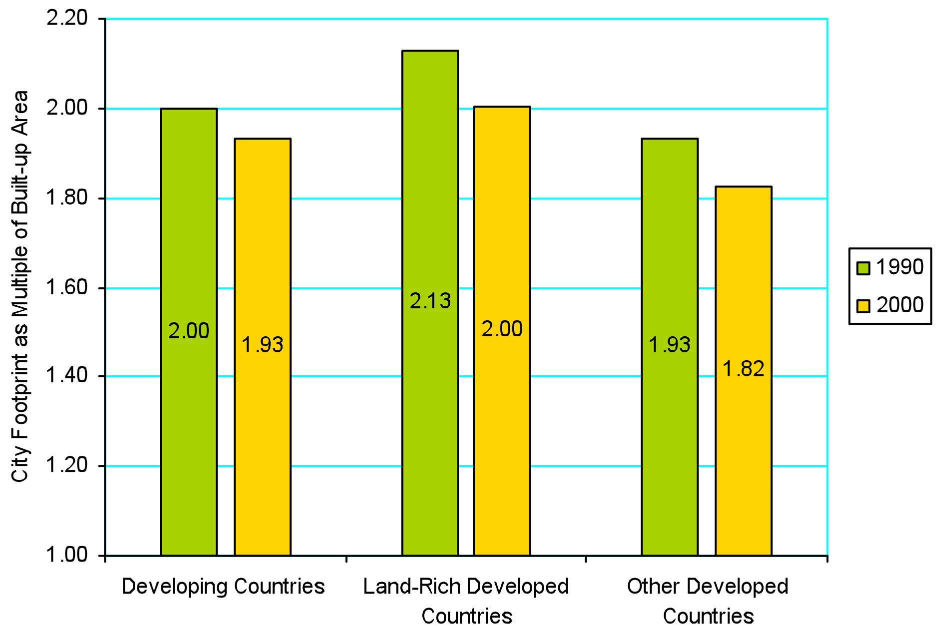
That said, there was considerable variation in this ratio among cities. While no city had a ratio less than 1.4 in 1990, only seven cities in the global sample had ratios less than 1.5: Valledupar, Sao Paulo, Mumbai, Accra, Los Angeles, Ribeirao Preto, and Tokyo. And while only one city, Bacolod, had a ratio greater than 3.0, eight more cities had ratios greater than 2.5: Rajshahi, Springfield, Zhengzhou, Kampala, Chonan, Pittsburgh, Kigali, and Bangkok. In 2000, three cities had ratios less than 1.4: Sana'a, Accra, and Sao Paulo; and only five cities had ratios greater than 2.5: Rajshahi, Zhengzhou, Yulin, Chonan, and Yiyang. The histogram showing the frequency of these ratios in 1990 and 2000 is shown in figure 4.10.

Figure 4.10: The Frequency Distribution of the City Footprint Ratio, 1990-2000



There were slight differences between the city footprint ratio among cities in the three regional groupings (see figure 4.11). Still, independent sample t-tests show that there was no significant difference in this ratio between cities in developing countries, cities in land-rich developed countries, and cities in other development countries. We can therefore say with some confidence that at the macro scale cities fragmented open space in and around them that was equivalent in size to their built-up areas, or that city footprints effectively doubled the built-up areas of cities when their built-up area was detected and measured at the micro-level (e.g. by 30-by-30 meter pixels).

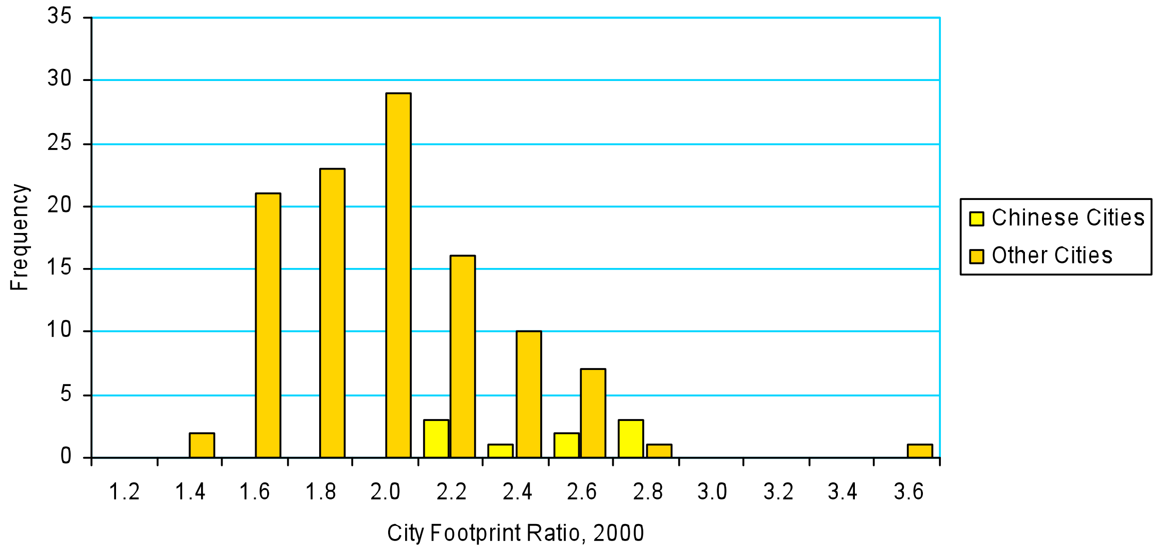
Figure 4.11: Variations among Regional Groupings in the City Footprint Ratio, 1990-2000



Chinese cities were found to have larger City Footprint Ratios than other cities

There was no clearly observable pattern in the data to distinguish differences in the city footprint ratio among cities. But it appears that the Chinese cities in our global sample (excluding Hong Kong) developed significantly larger city footprint ratios in 2000 compared to other cities (see figure 4.12). There are nine Chinese cities in the global sample and their mean city footprint ratio increased from 2.23±0.1 in 1990 to 2.40±0.09 in 2000. In the other 119 cities in the global sample, the mean city footprint ratio declined from 1.99±0.03 in 1990 to 1.89±0.03 in 2000. Independent sample t-tests confirm with a high level of confidence that while the mean difference in the city footprint ratio between Chinese cities and other cities was only 0.23±0.23 in 1990 (sig. 2-tailed 0.050), it increased 0.51±0.21 in 2000 (sig. 2-tailed 0.000).

Figure 4.12: The City Footprint/Built-up Area ratio for Chinese and other cities, 2000



Because arable land comprises less than 15% of China's land area and because the amount of arable land per person in China is one of the lowest in the world, the Chinese Government has acted, through a series of laws, to mandate strict quotas on the conversion of arable land to urban land. This has had a significant impact on the shape and character of urban expansion, resulting in fragmented development on the urban fringe, in the destruction of highly affordable rental housing in urban villages both within cities and on the fringe of cities, and in land supply bottlenecks that have led to steep increases in urban land prices in recent years.

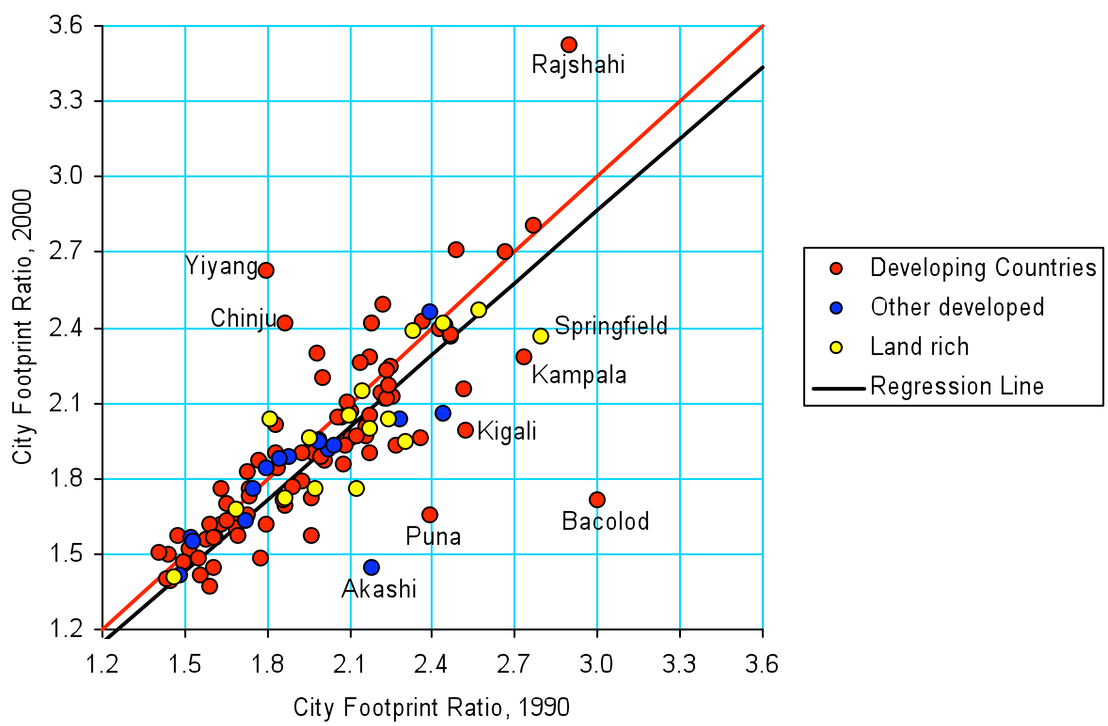
The central government in China requires that the total amount of arable land in every province remain constant over time, and that new lands be put into cultivation to compensate for any lands lost to cultivation through conversion to urban use. All urban land in China is municipally-owned, and rural land owned by communes has to be acquired by municipalities before it is converted to urban use. Because of the land conversion quotas, municipalities are restricted in their efforts to convert cultivated lands to urban use. They can, however, buy and take over the built-up areas of surrounding villages, destroy them, and redevelop them for urban use. This necessarily leads to a highly-fragmented form of urban expansion, as villages lose their residential lands but continue to cultivate the agricultural lands in and around their villages. Unfortunately, this development pattern also leads to the destruction of large quantities of highly-affordable rental housing build by villagers on the periphery of cities to house the millions who come to work in the cities without residence permits (*hokous*).

Cities affected and fragmented relatively less of the open spaces on their fringes in 2000 than they did in 1990.

The average City Footprint Ratio declined significantly between 1990 and 2000. We can say with a very high level of confidence (sig. 2-tailed 0.000) that the mean ratio for the global sample of cities was 2.01±0.05 in 1990 and it decreased to 1.93±0.07 in 2000. We can also say with a very high level of confidence that the difference between the two means was 0.080±0.043 (sig. 2-tailed 0.000). In other words, by this measure, cities and their suburbs fragmented less open space in an around them in 2000 than they did in 1990. We can also say with a very high level of confidence that the city footprint ratio decreased at an average rate of 0.42±0.20 percent per annum during the 1990s (sig. 2-tailed 0.000). This would imply that the mean City Footprint Ratio declined by some 4 percent during the 1990s.

The decline in the City Footprint Ratio is illustrated in figure 4.13 below. For a given city, the ratio for 1990 is plotted on the X-axis and the ratio for 2000 is plotted on the Y-axis. The red line in the figure is the 45° line. If the marker for a given city is below the red line, it indicates that the ratio decreased for that city between 1990 and 2000. As figure 4.13 shows, most city markers (86 out of 120 or 72 percent) are below the red line. The black line in figure 4.13 is the regression line through the origin and it has an R-squared of 0.986. The slope of the regression line is 0.96, also suggesting that between 1990 and 2000 the average City Footprint Ratio declined by some 4 percent.

Figure 4.13: The Decline in City Footprint Ratio, 1990-2000



Independent samples t-tests show that there was no significant difference in the rate of decline of the City Footprint Ratio between developing and developed countries. Independent samples t-tests also show that there was no significant difference in the rate of decline of the ratio among cities in developing countries, land-rich developed countries, and other developed countries. It declined in 70 percent of cities in the sample that were located in developing countries, in 88 percent of the cities in land-rich developed countries, and in 63 percent of the cities in other developed countries. The ratio was found to decrease significantly and at similar rates in all three regional groupings.

Those of us who are concerned with amount of open space that is being affected or fragmented by scattered urban development should be alarmed at our finding that the build up areas of cities the world over disturb and fragment an area of open space equivalent in size, on average, to their built-up areas. That said, the observed decline in the City Footprint Ratio in cities in all three regional groupings is welcome news. It suggests that cities the world over are becoming a bit more economical in their conversion of peripheral open space to urban use, and that urban development patterns are slowly becoming more contiguous and less scattered.

Infill, extension and leapfrog

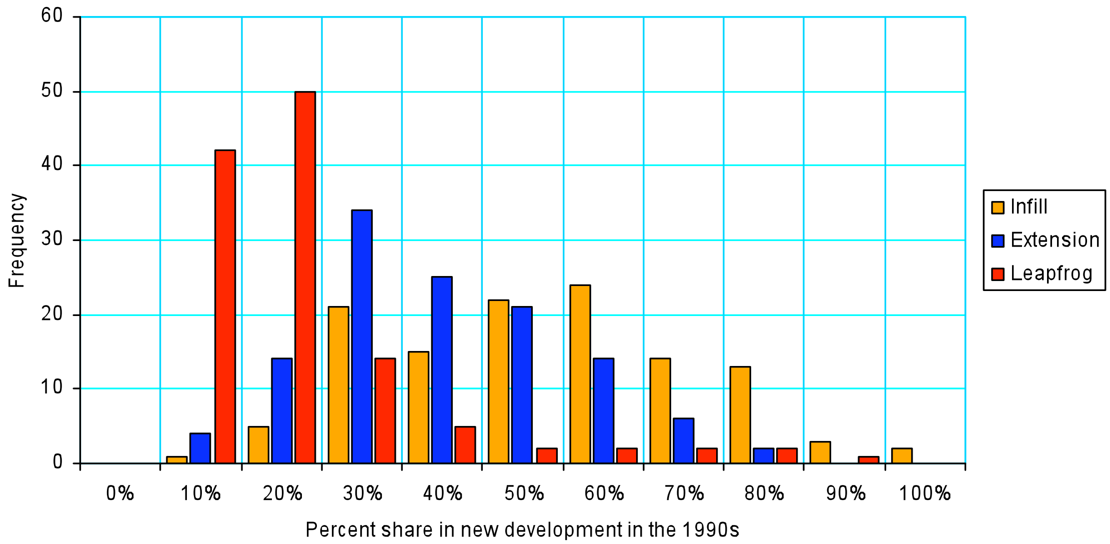
Leapfrogging constituted only one-sixth of new urban development in the 1990s

The reader may recall that infill was defined earlier as new development within interior open space; extension was defined as the set of clusters of new development that overlapped both exterior open space and rural open space; and leapfrog was defined as the set of clusters of new development that were located in rural open space.

For each city in the global sample, we calculated the percentage of new development in the 1990s that was infill, extension and leapfrog. On average, infill constituted 48.1±3.5 percent of new development, extension 34.8±2.7 percent, and leapfrog 17.1±2.8 percent (sig. 2-tailed 0.000). Thus, we can conclude that during the 1990s approximately one-half of new development occurred by infill, one-third by extension, and one-sixth by leapfrog. That said, the variation in these shares among cities in the global sample was quite wide.

The frequencies of the relative shares of infill, extension, and leapfrog in the global sample of cities in the 1990s are shown in figure 4.14. The five cities with the highest share of infill development (more than 80 percent) were Milan, Paris, Tokyo, Tacoma, and Akashi. The six cities with the lowest share of infill development (less than 20 percent) were Malatya, Harare, Tebessa, Marrakesh, Saidpur and Ahvaz. Two cities, Accra and Jaipur, had more than two-thirds of new development by extension. Four cities ─ Tokyo, Akashi, Philadelphia and Tacoma ─ had less than 10 percent of new development by extension. Finally, five cities ─ Santiago, Philadelphia, Tebessa, Harare, and Malatya ─ had more than 60 percent of new development as leapfrog. And four cities ─ Akashi, Tacoma, Jequié, and Paris ─ had less than 3 percent of new development as leapfrog.

Figure 4.14: The Frequency Distribution of the Shares of New Development in the 1990s

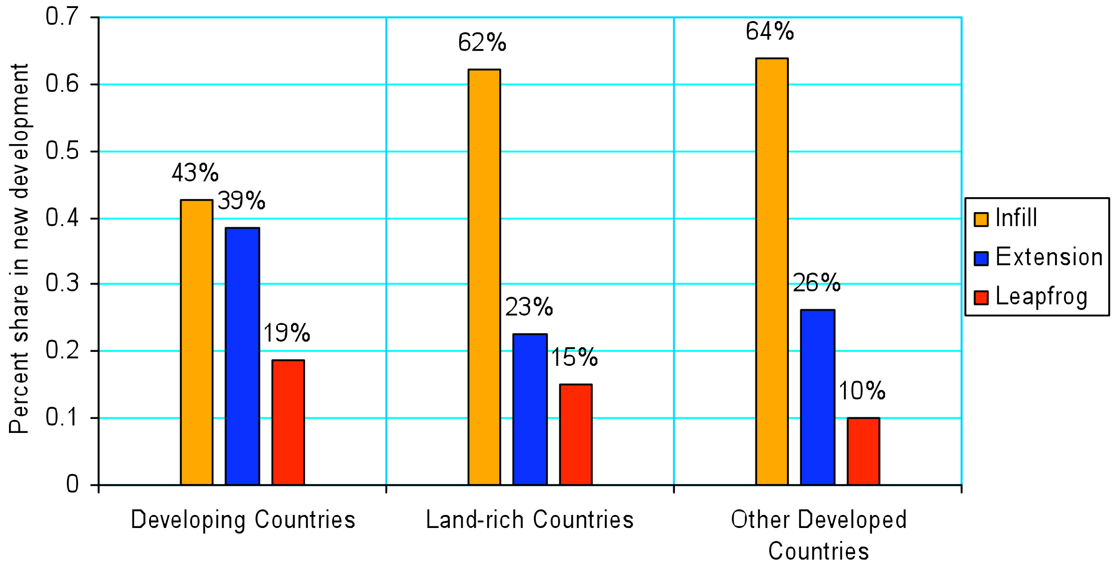


Leapfrog development was more prevalent and infill less prevalent in developing countries than in developed countries

There were significant differences in the shares of new development in the 1990s between cities in developing countries and cities in developed countries (see figure 4.15).

There was significantly less infill development in cities in developing countries in the 1990s than in cities in developed countries: the mean share of infill in new development was 42.7±1.8 percent in developing-country cities and 63.0±3.0 percent in developed-country cities, and the mean difference between them was 20.2±7.1 percent (sig. 2-tailed 0.000). In parallel, there was significantly more development by extension in cities in developing countries in the 1990s than in cities in developed countries: the mean share of extension in new development was 38.6±1.5 percent in the former and 24.4±2.2 percent in the latter, and the mean difference between them was 14.1±5.3 percent (sig. 2-tailed 0.000). There was also a small but statistically significant difference in the respective shares of development by leapfrogging in cities in these two regional groupings. This share was found to be higher in developing countries: the mean share of leapfrogging in new development was 18.7±1.7 percent in the former and 12.6±2.8 percent in the latter, and the mean difference between them was 6.1±5.8 percent (sig. 2-tailed 0.04). No significant differences were detected between the shares of infill, extension and leapfrog in new development in the 1990s between cities in land-rich developed countries and cities in other developed countries.

Figure 4.15: Shares of infill, extension and leapfrog in new development in the 1990s



To conclude this section, we review the main findings. We employed four metrics to explore the extent of fragmentation in cities and the open spaces in and around them in both 1990 and 2000, with each metric focusing on fragmentation at a different spatial scale.

The first metric, the Edge Index, focuses on fragmentation at the micro level, the adjacency of individual built-up pixels to individual open space pixels. Here we found that the probability that a small built-up area will be immediately adjacent to open space was of the order of 50 percent. We found that in 2000, Edge Index values were significantly higher in developing countries and land-rich developed countries than they were in cities in other developed countries. In the former, the frequency at which a built-up pixel was adjacent to an open space pixel was of the order of 45 percent, while in the latter it was only 39 percent. We also found that the immediate adjacency of small built-up areas to open space declined in the 1990s by some 11 percent, and that this level of decline was common to all three regional groupings.

The second metric, the Openness Index, focused on fragmentation at the neighborhood level, a circle 1 km^2 in area centered on each built-up pixel. This index measured the share of this circle that was open rather than built-up, as a measure of the amount of open space in the city available within a ten-minute walk. Here we found that close to one half of the one-square-kilometer area in the immediate vicinity of a randomly selected built-up place in a given city was likely to consist of open space. In other words, we found that a typical urban neighborhood consist of approximately equal areas of impervious surfaces and open spaces. We found that in both 1990 and 2000, Openness Index values were significantly higher in developing countries and land-rich developed countries than they were in cities in other developed countries. In 2000, for example, the mean openness of an urban neighborhood in the former two regional groupings was of the order of 43 percent, while in the latter it was of the order 36 percent. We also found that urban neighborhoods contained relatively less open space in 2000 than they did in 1990; that the average ratio of open space to the built-up area in urban neighborhoods declined by some 11 percent on average during the 1990s; and this level of decline was common to cities in all three regional groupings.

The third metric, the Core Open Space Ratio, focused on fragmentation in the urban cores of cities, as against their suburbs. The urban built-up area was defined as the set of pixels that were surrounded by a majority of built-up pixels in their immediate 1 km^2 neighborhood. This metric focused on the extent to which the closely-built urban cores of cities were fragmented by the open space in and around them, ignoring for the time being the fragmentation in suburban areas. Here we found that, on average, the urban cores of cities contained open areas that were equivalent to 25-30 percent of their built-up areas. We found that cities in land-rich developed countries had significantly higher ratios (30-35 percent) than cities in other countries (24-28 percent). We also found that urban cores contained relatively less open space in 2000 than they did in 1990. The mean share of open space in urban cores declined by 14 percent in the 1990s and this decline was common to cities in all three regional groupings.

The fourth metric, the City Footprint Ratio, focused on fragmentation at the macro level in the entire built-up area of cities, including both its urban and suburban areas. This metric focused on the open space that is affected by its proximity to urban and suburban areas, more precisely on fringe open space that is within 100 meters of urban and suburban pixels and the open space captured by fringe open space and by built-up urban and suburban areas. Here we found that, on average, the city footprint ratio was of the order of two. Namely, the built-up areas of cities disturbed or fragmented open areas that were equivalent in size to their built-up areas. As a general observation, this finding is not new, as the following quote makes clear: ”It was once estimated that there is about as much idled land in and around cities as there is land used (in any meaningful sense) for urban purposes” (Clawson, 1962, 107, quoted in Ewing, 2004, 4).

We found that there are no significant differences in the City Footprint Ratio between cities in the three regional groupings, but that cities in China have exceptionally high city footprint ratios. We also found that cities affected and fragmented relatively less of the open spaces in and around them in 2000 than they did in 1990. The mean city footprint ratio declined by four percent during the 1990s and this level of decline was common to cities in all three regional groupings.

It should come as no surprise to the reader that the extent of fragmentation and its decline measured with any of the four metrics introduced here yields similar results. As table 4.1 shows, in 2000, for example, these four metrics were highly correlated with each other. The Pearson correlations between them were all significant at the 0.01 level (2-tailed). Similar correlations were observed in 1990 (not shown). Table 4.1 shows that the correlations among the Edge Index, the Openness Index and the City Footprint are higher than their individual correlations with the Core Open Space Index. This is due, at least in part, to the fact that they all measure fragmentation in the city as a whole while the Core Open Space Ratio measures fragmentation only in the urban core.

Table 4.1: The correlations among the four fragmentation metrics in 2000

Metric	Edge Index	Openness Index	Core Open Space Ratio	City Footprint Ratio
Edge Index	1			
Openness Index	0.888	1		
Core Open Space Ratio	0.706	0.472	1	
City Footprint Ratio	0.866	0.836	0.633	1

The correlations among the four metrics and the similar results that we obtained using each individual metric confirm that there were systematic variations in fragmentation both among regional groupings and between 1990 and 2000 no matter which metric was used to measure fragmentation.

Finally, we looked at the shares of new development in the 1990s that were infill, extension or leapfrog. Here we found that on average one-half of new development occurred by infill, one-third by extension, and one-sixth by leapfrogging. We also found that infill development was more prevalent in developed countries; that development by extension was more prevalent in developing countries; and that leapfrog development was more slightly more common in developing countries than in developed countries.

Do the same levels of correlations observed in table 4.1 hold for the rates of change of the four fragmentation metrics? Are these rates of change correlated with measures of the shares of infill and leapfrog in new development? The Pearson correlation matrix in table 4.2 sheds some light on these questions. All correlations except one (-0.117) are found to be significant at the 0.01 level (2-tailed). The correlations among the rates of change in all four fragmentation levels are high and positive, suggesting that when fragmentation declines rapidly it declines rapidly at all spatial scales. The table also reveals that those cities that expanded by leapfrogging rather than by infill exhibited faster rates of fragmentation: the correlation between leapfrogging and rates of fragmentation are all positive and significant. In contrast, those cities that grew by infill rather than by leapfrogging exhibited slower rates of fragmentation: the correlation between the share of infill (as well as between the ratio of infill to leapfrog development) and rates of fragmentation are (all, except one) negative and significant.

Table 4.2: Correlations between rates of change in fragmentation levels and the share of infill and leapfrog in new development

Metric	Edge Index Rate of Change	Openness Index Rate of Change	Core Open Space Ratio Rate of Change	City Footprint Ratio Rate of Change	Log of Share of Leapfrog in New Development	Log of Share of Infill in New Development	Log of Ratio of Infill to Leapfrog
Edge Index Rate of Change	1						
Openness Index Rate of Change	0.896	1					
Core Open Space Ratio Rate of Change	0.775	0.689	1				
City Footprint Ratio Rate of Change	0.746	0.793	0.431	1			
Log of Share of Leapfrog in New Development	0.534	0.576	0.300	0.517	1		
Log of Share of Infill in New Development	-0.295	-0.268	-0.117	-0.393	-0.669	1	
Log of Ratio of Infill to Leapfrog	-0.486	-0.504	-0.254	-0.513	-0.956	0.858	1

Given these robust findings, we now turn to explaining them using multiple regression models.

V Explaining the Variation in Fragmentation among Cities

Burchfield *et al*, in their "Causes of Sprawl: A Portrait from Space", note that "a key feature that the standard monocentric city model does not explain is leapfrog development where parcels of land are left undeveloped while others further away are built up" (2005, 17). In other words, when we carefully distinguish between sprawl as low-density development and sprawl as fragmentation, then the standard economic theory is of no help in explaining fragmentation.

That said, Burchfield *et al* (2005, 1) defined a metric similar to the Openness Index to measure sprawl as fragmentation, and used this metric as a dependent variable in multiple regression models, seeking to explain the variation in the score on this metric among U.S. metropolitan areas. They found that "ground water availability, temperate climate, rugged terrain, decentralized employment, early public transport infrastructure, uncertainty about metropolitan growth, and unincorporated land in the urban fringe all increase sprawl" (2005, 1). Following them, we used scores on the Openness Index as a dependent variable and a similar set of independent variables in multiple regression models, seeking to explain variations in fragmentation in the global sample of 120 cities. We also tested models with the Edge Index, the Core Open Space Ratio, and the City Footprint Ratio and obtained similar results that for lack of space will not be reproduced here.

We tested two different sets of fragmentation models, static models and dynamic models. The static models described in this section had as their dependent variable the logarithm of the Openness Index for the year 2000. The dynamic models described in the following section had as their dependent variable the annual rate of change in the Openness Index between 1990 and 2000. The static models presented here sought to explain cross-sectional variations in levels of fragmentation among cities in the global sample at one point in time, the year 2000. The dynamic models to be presented in the following section sought to explain the variations in the rate of change in the level of fragmentation in the global sample of cities during the 1990s.

We first summarize the hypotheses that we formulated to explain variations in levels of fragmentation, and then present the results of the tests of these hypotheses with data from the global sample of cities.

Hypotheses that may explain differences in fragmentation in the universe of cities

Urban economics does not present us with anything resembling a fully-developed theory or model to explain fragmentation, especially since fragmentation at any given point in time, to the extent that it largely concerns vacant lands that will eventually be built-up, is a temporary phenomenon. Fragments of available theory may be used to formulate hypotheses that may explain differences in levels of fragmentation among cities and it is to these that we now turn our attention. They include the following:

- Fragmentation and built-up area density
- Fragmentation and city size
- Fragmentation and the private automobile
- Fragmentation, income, and income from agriculture
- Fragmentation and inflation
- Fragmentation and land availability
- Fragmentation and groundwater
- Fragmentation and the regulatory environment
- Fragmentation and informal settlements

Fragmentation and built-up area density: In principle, the density of built-up areas and their contiguity or lack thereof of these areas are not necessarily related. As we saw earlier (figure 2.5) levels of fragmentation measured, for example by the city footprint ratio, were quite independent from built-up area densities. That said, can there be a causal relationship between density and fragmentation?

We can think of cities or parts of cities, like the casbah in Algiers (see figure 5.2), with dense built-up areas that are also contiguous to each other, leaving very little open space between them. In such places, high density and a low level of fragmentation go hand in hand. Alternatively, we can think of cities or parts of cities where land is ample and cheap and where people live in large plots that are scattered across the land, leaving plots of vacant open spaces between them. In both of these types of cities, density and fragmentation pull in opposite directions: high density and low levels of fragmentation go hand in hand, and low density and high levels of fragmentation go hand in hand. We can hypothesize that in these types of cities *maturity* may be the overpowering factor: It determines both the average built-up area density and the average level of fragmentation: When cities are fully mature and have gone through many cycles of building and rebuilding, densities are high and fragmentation is low, and when cities are not yet mature, densities are low and fragmentation is high. We can also hypothesize that the *price of land* may be the overpowering factor: When land in the city is in short supply, land prices are high and therefore densities are high and fragmentation is low; when land is in ample supply, land prices are low and therefore densities are low and fragmentation is high.

Figure 5.1: The casbah in Algiers, 2006

We can also think of high density and open space as substitutes, where density and fragmentation pull in the same direction. Le Corbusier's 1925 *Plan Voisin* proposal for Paris, for example, combined high-density development in built-up areas with a high level of fragmentation of these built-up areas by open spaces. High built-up area density was thus accompanied by a high ratio of open area to built-up area. In this case, we can say that substantial amounts of open space compensated residents for high-density living.

Figure 5.2: Le Corbusier's *Plan Voisin* proposal for Paris, 1925

In parallel, we can think of families who seek larger lots in fully-built low-density suburbs as *internalizing* the open space that is missing from their neighborhoods: If they cannot ensure that the ample vacant spaces in their neighborhood will stay vacant, they want to make sure that when the neighborhood is fully built-up they will still have access to open space on their own plots. In both of these types of cities ─ the *Plan Voisin* type city and the low-density suburb ─ density and fragmentation pull in the same direction: high density and high levels of fragmentation go hand in hand, and low density and low levels of fragmentation go hand in hand. We can hypothesize that in these types of cities people's preferences for proximity to open space is the overpowering factor: When open space nearby is ample, people do not mind living at high densities. When it is in short supply, they prefer living at low densities where they can internalize open space within their private domains.

It was difficult to determine in advance which factor would be more powerful in determining whether density and fragmentation would go hand in hand or in opposite directions. As we shall see in the following section, our empirical investigation of the global sample of 120 cities provides interesting answers to these questions.

The relationship between density and fragmentation was examined by testing the null hypothesis presented below. This hypothesis, like those that follow, is presented here in its negative form, as a null hypothesis to be rejected by statistical testing. Simply put, the null hypothesis stated below must be rejected if the coefficient of Log Density 2000, (the independent variable associated with density) in the multiple regression model is significantly different from 0.

> Hypothesis 1: *Cities with higher average built-up area densities are not more or less fragmented than cities with lower average built-up area densities*.

The variable used to test this hypothesis was the **logarithm of average built-up area density** in the year 2000.

Fragmentation and city size: The more people live in a city, the higher the demand for land, and the higher the prices for that land. The higher the value of vacant lots in the city, the higher the incentive for landowners to sell them. Also, the higher the value of vacant lots, the more expensive it is for municipalities to acquire lands for parks and playgrounds. We would therefore expect that large cities will be less fragmented than smaller ones. The relationship between city size and fragmentation was examined by testing the following null hypothesis:

Hypothesis 2: *Larger cities are not more or less fragmented than smaller cities.*

The variable used to test this hypothesis was the **logarithm of the city population** in the year 2000.

Fragmentation and the private automobile: The availability of private automobiles can have two quite contradictory effects on the fragmentation of cities. On the one hand, to the extent that private automobiles make transport cheaper, they enable people to travel further and to cover greater distances on their way to work, to market, to school, and to other destinations. If the cost of covering an extra kilometer of road is relatively low, people would not mind living in more fragmented cities, where they would have to cover the extra distances involved in crossing the open spaces between their destinations. That would suggest that cities in countries with high levels of car ownership per capita would be more fragmented than cities in countries with low levels of car ownership.

On the other hand, private automobiles facilitate door-to-door travel and can move with great ease on roads narrow and wide, both paved and unpaved, in almost all weather conditions. In the absence of private automobiles, people must combine walking and public transport to get from place to place. Public transport, especially rail transport in its variety of forms, involves much higher investments per kilometer than those required for a kilometer of road, especially a narrow, unpaved one. It is more expensive, therefore, to cover an urban area on the urban fringe with a dense network of rail public transport or with wide roads on which buses can travel comfortably, than it is to cover this area with dense network of cheap, narrow, unpaved roads. And this is especially true when such fringe areas are built at low densities. This suggests that the private automobile better supports infill development than public transport, or that it is easier to infill the urban fringe with homes that rely on private automobiles than with homes that rely on an efficient system of public transport. If this were the case, then the prevalence of private automobiles would be associated with higher levels of infill and consequently with lower levels of fragmentation.

Again, it was difficult to determine in advance which factor would be more powerful in determining whether levels of automobile ownership and fragmentation would go hand in hand or in opposite directions. The relationship between automobile ownership and fragmentation was examined by testing the following null hypothesis:

> Hypothesis 3: *Cities in countries with higher levels of automobile ownership are not more or less fragmented than cities in countries with lower levels of automobile ownership.*

The variable used to test this hypothesis was the **logarithm of car ownership per capita in 1991** in the country in which the city was located.

Fragmentation, income, and income from agriculture: Other things being equal, cities with higher average incomes would consume more of everything, including land. This would suggest that densities in higher-income cities would be lower, which is indeed the case as we reported in a separate paper, but it does not necessarily suggest that richer cities would be more wasteful in their use of land and hence more fragmented than poor ones. This is especially true because fragmented land in cities is not really consumed, it is just lying vacant waiting to be developed at a later date. It is possible, however, that in rich cities more capital is available for holding land vacant. If this is true, then we can indeed expect cities in richer countries to contain more vacant lands and hence to be more fragmented than cities in poorer countries.

Similarly, we can postulate that cities in countries that derive a significant share of their national income from agriculture will have agricultural lands in and around their cities that would still be cultivated. Cities in these countries are therefore likely to be more fragmented than cities in countries with smaller shares of their GDP derived from agriculture. The relationship between income and income from agriculture and fragmentation was examined by testing the following two null hypotheses:

> Hypothesis 4a: *Richer cities are not more or less fragmented than poorer ones.*

> Hypothesis 4b: *Cities in countries with a greater share of national income derived from agriculture are not more or less fragmented than cities in countries with a lower share of national income derived from agriculture.*

The variables used to test these hypotheses were the **logarithm of the national GDP per capita in the year 2000** and the **logarithm of agricultural as a share of the country's Gross Domestic Product (GDP).**

Fragmentation and inflation: It has often been noted that in countries with high levels of inflation people tend to hold vacant land as a hedge against inflation. If that were the case, then we would expect cities in countries with high levels of inflation to be more fragmented than cities in countries with low levels of inflation. In contrast, it may be that in countries with high levels of inflation, people tend to invest in buildings, rather than in land, as a hedge against inflation. If that were the case, then we would expect cities in countries with high levels of inflation to be less fragmented than cities in countries with low levels of inflation.

It was difficult to determine in advance which factor would be more powerful in determining whether levels of inflation and fragmentation would go hand in hand or in opposite directions. The relationship between inflation and fragmentation was examined by testing the following null hypothesis:

> Hypothesis 5: *Cities in countries with higher levels of inflation are not more or less fragmented than cities in countries with lower levels of inflation.*

The variable used to test this hypothesis was the national **annual rate of change in the Consumer Price Index, 1990-2000**. The source for this data was the World Bank's *World Development Indicators* website.

Fragmentation and land availability: It stands to reason that cities surrounded by unlimited amounts of cheap, developable land would be more fragmented than cities whose outward development is constrained in one way or another. Cities with severe geographic constraints on their expansion, such as water bodies or steep slopes, are likely to be less fragmented than cities that can readily expand in all directions. Similarly, cities in countries with large amount of arable lands per capita are likely to be more fragmented than cities in countries with limited supplies of arable land. In the former, lands are more likely to be cheaper and conversion of agricultural lands to urban use easier than in the latter. The relationship between land availability and fragmentation was examined by testing the following two null hypotheses:

> Hypothesis 6a: *Geographic constraints on urban expansion that may increase transport costs do not increase or decrease fragmentation*.

> Hypothesis 6b: *Ample and cheap agricultural lands on the urban periphery do not increase or reduce fragmentation.*

The variables used to test these hypotheses were the **logarithm of buildable land** and the **logarithm of arable land**. The first was 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. The second was defined as the national **arable land and land in permanent crops per capita** in 2000. The data for the first variable was obtained from satellite data. The data for the second was obtained from the World Bank's *World Development Indicators* website.

Fragmentation and groundwater: Burchfield *et al* note that "in places where water-yielding aquifers are pervasive, developers can sink a well instead of connecting to the municipal or county water supply" (2005, 18). This makes them more footloose and less likely to develop sites that are immediately adjacent to built-up areas. Hence, we can expect cities where people can obtain water from wells to be more fragmented than cities where water can only be obtained by connecting to the municipal water supply. The relationship between the availability of well water and fragmentation was examined by testing the following null hypothesis:

Hypothesis 7: *The availability of water from wells that may free new development from dependence on municipal water supplies does not increase or decrease fragmentation.*

The variable used to test this hypothesis was **the logarithm of 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. The data for this variable was obtained from responses to a survey of the global sample of 120 cities by local consultants.

Fragmentation and the regulatory environment: Several researchers (e.g. Knapp 1985 and Nelson 1986) have noted that "urban growth boundaries are a successful tool in preventing urban incursions into agricultural areas" (paraphrased by Peiser 1989, 201-202). As we shall see later, the urban growth boundary in Portland, Oregon, for example, has significantly reduced fragmentation as measured by all indices, including the Openness Index. More generally, limits on the conversion of land from rural to urban use and zoning regulations that prevent urban development in parts of the metropolitan area restrict the possibilities for leapfrog development and thus encourage infill. To the extent that these planning policies are effective we would expect them to increase the share of infill in new development and thus to reduce fragmentation. The relationship between the regulatory environment and fragmentation was examined by testing the following null hypothesis:

Hypothesis 8a: *Cities that do not permit development in large areas around them are not more or less fragmented than cities that do.*

The variable used to test this hypothesis was the **logarithm of No Development Allowed**, defined as the percentage of the metropolitan plan area where no development was allowed in 2005. The data for this variable was obtained from a survey of local consultants in the global sample of 120 cities in 2005-2007.

Municipalities and local governments seek to regulate the urban expansion process in numerous ways, and there is good reason to believe that they can affect the level of fragmentation in one way or another. To the extent that governmental bodies can effectively regulate the conversion of lands from rural to urban use or allocate new infrastructure investments, for example, they can effectively reduce fragmentation. In short, the regulatory environment could have a substantial impact on levels of fragmentation. This impact may be compromised, however, if regulatory controls can be circumvented by moving to another jurisdiction where they do not apply or if those enforcing them are corrupt. The relationship between the effectiveness of regulatory controls and fragmentation was examined by testing the following two null hypotheses:

Hypothesis 8b: *While zoning regulations may act to limit fragmentation, cities with lax or corrupt regulatory enforcement are not more or less fragmented than cities with strict enforcement regimes.*

The variable used to test this hypothesis was the **logarithm of 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 8c: *Metropolitan areas with a large number of jurisdictions that compete with each other for growth do not have higher or lower levels of fragmentation.*

The variable used to test this hypothesis was the **logarithm of municipal fragmentation**, defined as the number of independent municipalities per 1,000,000 people in the metropolitan area in 2005. The data for all three variables were obtained from responses to a survey of the global sample of 120 cities by local consultants.

Fragmentation and informal settlements: Poor families in developing-country cities typically do not have access to the formal housing market, often resorting to the construction of houses in squatter settlements and informal land subdivisions. It has often been remarked that squatter settlements and informal land subdivisions are located on undesirable lands that are subject to flooding or mudslides, on leftover plots of land, on disputed lands with unclear titles, or on vacant public lands. This suggests that informal settlement is often infill development, taking advantage of any vacant land that is not used by the formal sector. This would suggest that cities with significant shares of their population living in informal settlements would be less fragmented than cities with small shares of their populations in informal settlements. The relationship between informal settlements and fragmentation was examined by testing the following null hypothesis:

> Hypothesis 9: *Cities with large numbers of people in informal settlements do not necessarily have higher or lower levels of fragmentation.*

The variable used to test this hypothesis was the **logarithm of informal settlements**, defined as the share of dwelling units in the city in informal settlements in 2005. The data for this variable were obtained from responses to a survey of the global sample of 120 cities by local consultants.

These hypotheses were tested in multiple regression models using data for the global sample of 120 cities. The results of these tests are presented in the following section.

Multiple regression models that explain variations in fragmentation among cities

We tested multiple regression models with each one of the fragmentation metrics discussed earlier as a dependent variable, using the same independent variables. In this essay, for lack of space, we present only the models using the Openness Index in the year 2000 as a dependent variable. The models for the other fragmentation metrics: the openness index in 1990; the edge index in 1990 and 2000; the core open space ratio in 1990 and 2000; and the city footprint ratio in 1990 and 2000 yielded quite similar, although not exactly identical, results. They did not, in our judgment, shed new light on the results for the Openness Index presented below.

The descriptive statistics for all dependent and independent variables used in estimating the models to explain variations in the Openness Index in the global sample of cities are given in table 5.1.

We used logarithmic forms for both the dependent and the independent static variables in the models, as is common in similar studies, and we did this for two reasons. First, the logarithmic forms of the Openness Index 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 Openness Index variable, for example, are shown in figure 5.1 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 fragmentation 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 fragmentation. This allows for a simple and ready interpretation of the coefficients of the different independent variables in the models.

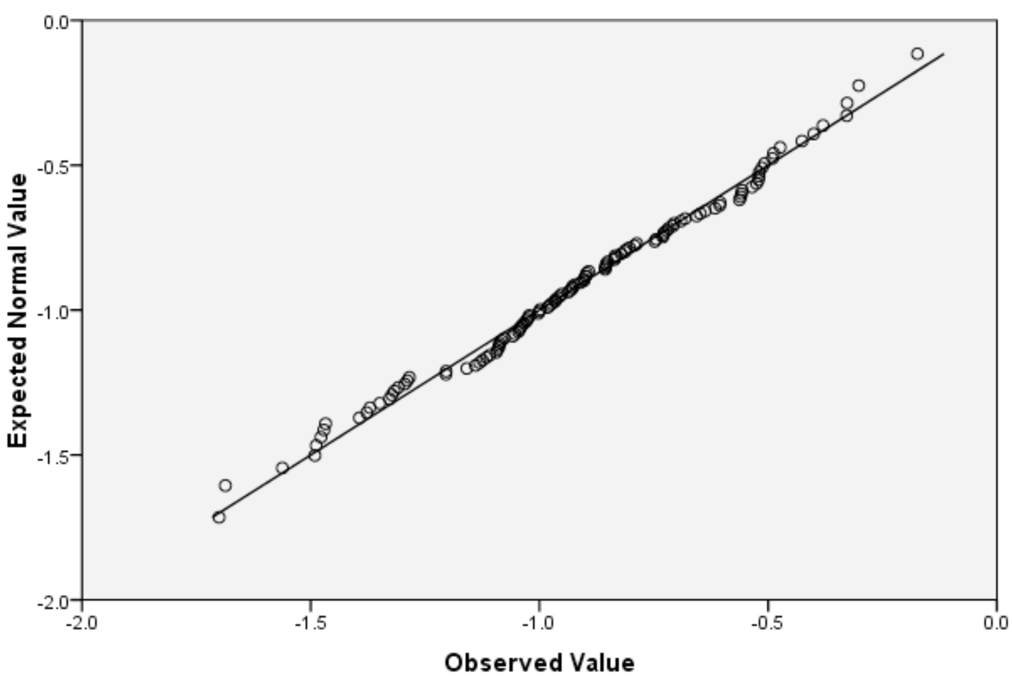
Table 5.1: Variables used in modeling fragmentation and its change over time, 1990-2000

Variable	Count	Minimum	Maximum	Mean	Std. Deviation
1st satellite image date (days)	120	13-Jun-84	19-Jan-95	26-Sep-89	829
2nd satellite image date (days)	120	1-Jul-99	26-Dec-02	28-Nov-00	312
Time elapsed between images (years)	120	5.19	16.97	11.17	2.24
Log openness index, 2000	120	-1.701	-0.174	-0.915	0.312
Openness Index Annual Growth Rate, 1990-2000	120	-0.062	0.008	-0.012	0.011
Log Core Open Space Ratio 1990	119	-2.265	-0.636	-1.283	0.355
Log of built-up area density (persons per hectare), 1990	120	2.751	6.312	4.422	0.791
Built-up Area Density Annual Growth Rate, 1990-2000	120	-0.111	0.034	-0.020	0.023
Log of population, 2000	120	11.835	17.197	14.333	1.304
City Population Annual Growth Rate, 1990-2000	120	-0.017	0.072	0.016	0.015
Log of cars per person in the country, 1991	116	-7.584	-0.531	-3.639	2.087
Log of GDP per capita, 2000 (in constant 2000 US dollars)	120	6.681	10.530	8.857	1.072
Annual rate of change of GDP per capita, 1990-2000 (in constant 2000 US$)	120	-0.082	0.062	0.020	0.025
Log of agriculture as share of GDP (percent), 1990	116	-6.908	-0.562	-2.223	1.077
Annual rate of change of the consumer	103	0.800	46.100	9.387	8.743

price index (CPI), 1990-2000					
Log of buildable land, 1990	120	-3.183	0.006	-0.363	0.430
Log of arable land + permanent crops per capita (m^2), 2000	119	2.508	10.510	7.575	1.058
Log of percent obtaining water from well, 2005	95	-4.605	0.000	-0.367	0.723
Log of percent of plan area where no development was allowed, 2005	61	-6.908	0.000	-1.785	1.213
Log of enforcement subject to corrupt practices, 2005	101	0.000	1.609	0.973	0.473
Log of independent municipalities per million people, 2005	108	0.000	5.864	0.729	1.415
Log of percent living in informal settlements, 2005	74	-4.423	-0.223	-2.131	1.157

Multiple regression models were used to test each one of the null hypotheses formulated above with the Openness Index in 2000 as the dependent variable. Simply put, the null hypothesis that states, for example, that *Richer cities are not more or less fragmented than poorer ones* (Hypothesis 4a) must be rejected if the coefficient of Log GDP per capita 2000, the independent variable associated with income, is significantly smaller or greater than zero. We reject this hypothesis with a high level of confidence if the probability that it is zero is less than 0.05. This probability denoted *Signif. (2-tailed)* in the tables below is shown in italics below the coefficients of each of the independent variables in the model.

Figure 5.3: The Normal Q-Q Plot of Log Openness Index, 2000



A large number of models, not shown, were used to test the hypotheses formulated in the previous section. To test hypothesis 1: *Cities with higher built-up area densities are not more or less fragmented than cities with lower average built-up area densities,* for example, we incorporated density in the year 2000 into several of the models we tested. In none of them was the coefficient of density found to be significantly different from zero. This hypothesis cannot therefore be rejected. Low density cities are not more or less fragmented than high density cities. Three other hypotheses were tested in several models not shown here and could not be rejected. Hypothesis 6b, a*mple and cheap agricultural lands on the urban periphery do not increase or reduce urban fragmentation,* could not be rejected. Cities in land-rich countries cannot therefore be said to be more or less fragmented than cities with limited quantities of agricultural lands. Hypothesis 8b, *cities with lax or corrupt regulatory enforcement are not less fragmented.* could not be rejected. Strict or lax regulation was not found to be associated with fragmentation. And hypothesis 8c, *metropolitan areas with a large number of jurisdictions that compete with each other for growth do not have higher levels of fragmentation,* could not be rejected. Contrary to the findings of Burchfield *et al* (2005) for the U.S., we could not confirm that municipal fragmentation led to higher levels of fragmentation of the built-up area of cities.

Four models that were tested to explain the variations in the Openness Index in the global sample of cities in the year 2000 are displayed in table 5.2 below.

Model 1, shown in the second column from the left in table 5.2, uses four independent variables to explain the variation in the logarithm of the Openness Index (Log Openness, for short) in the global sample of 120 cities. The R^2 and Adjusted R^2 of the model are 0.31 and 0.29 respectively, indicating that the model explains some 30 percent of the variation in Log Openness. We can say with 95 percent confidence that the coefficients of all four independent variables are significantly different from zero (significance shown in italics below each coefficient).

Table 5.2: Models that explain variations in the Logarithm of the Openness Index, 2000

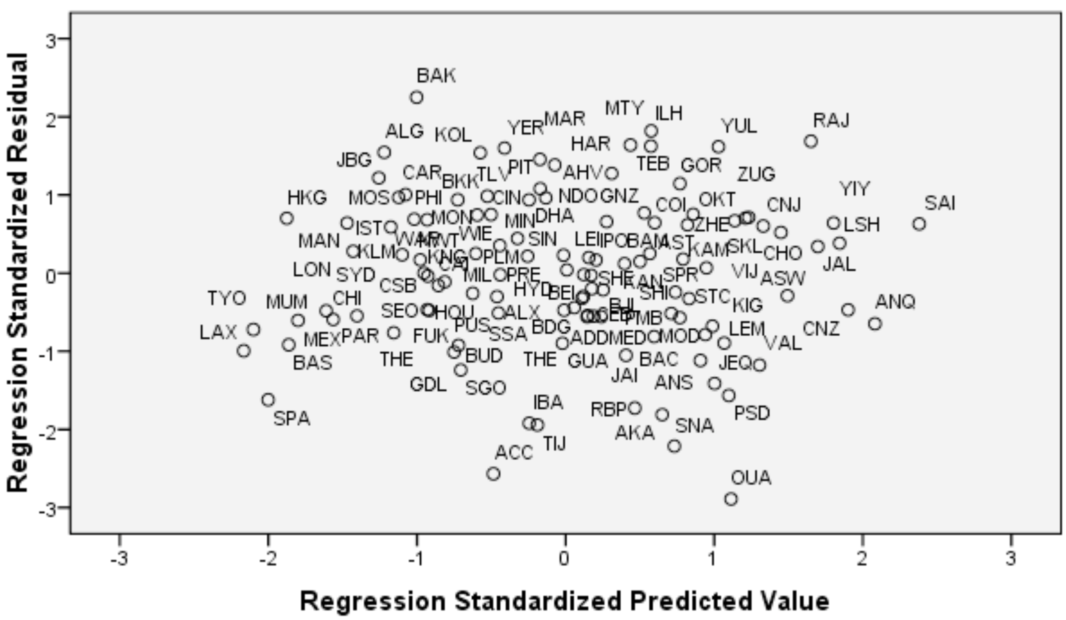
Independent Variables	Coefficients and levels of significance			
	Model 1	Model 2	Model 3	Model 4
Log city population, 2000	**-0.114**	**-0.126**	**-0.136**	**-0.078**
Signif. (2-tailed)	*0.000*	*0.000*	*0.000*	*0.005*
Log buildable land, 1990	**0.124**			
Signif. (2-tailed)	*0.036*			
Log of GDP per capita, 2000	**0.121**			
Signif. (2-tailed)	*0.014*			
Log car ownership per capita	**-0.094**	**-0.063**	**-0.081**	
Signif. (2-tailed)	*0.000*	*0.000*	*0.000*	
Log of water from well, 2005		**0.117**		
Signif. (2-tailed)		*0.006*		
Log informal settlements			**-0.078**	
Signif. (2-tailed)			*0.008*	
Annual rate of change of CPI 1990-2000		**-0.007**	**-0.010**	
Signif. (2-tailed)		*0.037*	*0.025*	
Log of agriculture as Share of GDP, 1990				**0.083**
Signif. (2-tailed)				*0.006*
Log of percent of plan area where no development allowed, 2005				**-0.056**
Signif. (2-tailed)				*0.046*
Constant	**-0.658**	**0.759**	**0.628**	**0.359**
Signif. (2-tailed)	*0.209*	*0.017*	*0.121*	*0.360*
No. of Observations	116	79	60	59
R-Squared	0.310	0.450	0.486	0.292
Adjusted R-Squared	0.286	0.421	0.449	0.253

Model 1 rejects four of the null hypotheses articulated in the previous section. Hypothesis 2 is rejected, confirming that larger cities should be expected to have lower levels of fragmentation than smaller cities, and that a 10 percent increase in city population is associated with a 1.1 percent decrease in fragmentation. Hypothesis 6a is rejected, indicating that cities with little or no physical constraints to their expansion in all directions can be expected to have higher levels of fragmentation, and that a 10 percent increase in the share of buildable land on the urban periphery is associated with a 1.2 percent increase in the Openness Index. Hypothesis 4a is rejected, indicating that cities in richer countries are more fragmented than cities in poorer countries, and that a 10 percent increase in GDP per capita is associated with a 1.2 percent increase in fragmentation. Richer countries, with their hosts of planning regulations and the means for their strict enforcement, are less able to contain urban fragmentation than poorer countries with virtually no planning tools to guide urban expansion. Finally, Hypothesis 3 is rejected, indicating that cities with higher levels of automobile ownership are less fragmented than cities with lower levels of automobile ownership, and a 10 percent increase in national car ownership in 1991 is associated with a 0.1 percent decrease in fragmentation in 2000.

It appears that the capacity of private cars to facilitate infill trumps their capacity to allow people to live further away.

It should be noted that, while significantly different from zero, none of the coefficients in this model are very high. Could it be that the model suffers from omitted variable bias? To test for omitted variable bias we plotted the standardized residuals in Model 1 against their associated standardized predicted values. The residual plot is shown in figure 5.4 below. From the concentration of points within -2 and +2 of their averages we can infer that the model does not suffer from omitted variable bias even though it explained only 30 percent of the variations in fragmentation in the year 2000 in the global sample of cities.

Figure 5.4: Residual plot for Model 1, plotting residuals against predicted values



Model 2, shown in the third column from the left in table 5.1, also uses four independent variables to explain the variation in the logarithm of the Openness Index in the global sample of 120 cities. The R^2 and Adjusted R^2 of the model are 0.45 and 0.42 respectively, indicating that the model explains some 42-45 percent of the variation in Log Openness, a higher percentage than that of Model 1. We can say with 95 percent confidence that the coefficients of all four independent variables are significantly different from zero.

Model 2, like Model 1, also confirm that larger cities are less fragmented than smaller ones, and that higher levels of car ownership are associated with lower levels of fragmentation. In addition, the model rejects two more hypotheses. Hypothesis 7 is rejected: Like Burchfield *et al* before us (2005, table 4, 22), we find that the availability of water from wells does free new development from dependence on municipal water supplies and does significantly increase fragmentation. A 10 percent increase in the share of households that obtain their water from wells is associated with a 1.2 percent increase in the openness index. Hypothesis 7 is also rejected: cities in countries with higher levels of inflation are found to be significantly less fragmented than cities with lower levels of inflation. A 10 percent increase in the annual increase in the Consumer Price Index is associated with a 0.1 percent increase in fragmentation. While significantly different from zero, this coefficient is very low. It does confirm, however, that vacant lands in the global sample of cities are not widely used as a hedge against inflation, and that it may well be that real estate holdings in the form of buildings are used as a hedge against inflation more often than vacant lands.

Model 3 contains similar variables to those in Model 2, except that it substitutes the share of households obtaining water from wells for the share of households living in informal settlements. The R^2 and Adjusted R^2 of the model are 0.49 and 0.45, indicating that the model explains almost half of the variation in Log Openness, a higher percentage than that of Models 1 and 2. We can say with 95 percent confidence that the coefficients of all four independent variables in the model are significantly different from zero. The model rejects hypothesis 9: Cities with large numbers of people living in informal settlements are significantly less fragmented than other cities. A 10 percent increase in the share of households living in informal settlements is associated with a 0.8 percent decrease in fragmentation. As expected, informal settlements tend to fill in accessible vacant lands that are in close proximity to jobs in built-up areas rather than to leapfrog to distant locations where the time and cost of travel, especially using public transport, are likely to be much higher.

Model 4 contains only three variables and their coefficients are all significantly different from zero. The R^2 and Adjusted R^2 of the model are 0.29 and 0.25 respectively, similar to those of Model 1. The model rejects two additional hypotheses. Hypothesis 4b is rejected: Cities in countries with a greater share of national income derived from agriculture are significantly more fragmented than cities in countries with a lower share of national income derived from agriculture. A 10 percent increase in the share of income from agriculture in the national GDP is associated with a 0.8 percent increase in fragmentation. This finding suggests that in countries where agriculture is a major source of income, farmers continue to till the land even when urban development starts to appear in their midst, rather than surrendering the land to speculators and moving away or abandoning farming altogether. This, in turn, leads to more fragmentation on the urban fringe. Hypothesis 8a is also rejected: Cities that do not permit development in large areas around them are significantly less fragmented than cities that do. A 10 percent increase in the share of the metropolitan plan area where no development is allowed is associated with a 0.8 percent decrease in fragmentation. This finding is an important one, although the coefficient is quite low: it appears that regulatory restrictions on urban expansion do tend to lower fragmentation.

To conclude, we review the ten key findings from the application of multiple regression models to the Openness Index in 2000 as a representative metric for fragmentation in the global sample of cities. They are:

- The density of built-up areas does not affect the spatial fragmentation of cities one way or another.
- The availability of large quantities of agricultural lands in the country does not lead to the increased fragmentation of urban areas.
- Larger cities are less fragmented than smaller ones.
- Higher levels of automobile ownership are associated with lower levels of fragmentation.
- The ready availability of well water from shallow aquifers increases fragmentation.
- There is no evidence that significant amounts of vacant lands are held off the market as a hedge against inflation.
- Informal settlements tend to act as infill and cities that have a greater share of dwellings in informal settlements are less fragmented.
- Cities in countries where larger shares of national incomes are derived from agriculture are more fragmented.
- Cities with regulatory restrictions on converting a larger share of their fringe lands from rural to urban use are less fragmented.

VI Explaining the Decline in Fragmentation

When we embarked on the study of urban expansion in the 1990 in a global sample of cities we did not expect a decline in fragmentation ─ or an increase in fragmentation, for that matter ─ during this period. The decline in fragmentation was only discovered once we defined acceptable metrics for measuring it, and only upon a rigorous examination of the results of our classifications of satellite data. Our search of the urban economics literature for clues as to why fragmentation should decline, why it should decline in some places and not in others, or while it should decline now yielded few, if any, theoretical insights. In the formulation of hypotheses that could explain these variations and shed some light on the decline in the fragmentation of urban areas in the 1990s, we have therefore had to rely in large part on anecdotal observations.

Hypotheses that may explain the decline in fragmentation

What can explain differences in the rates of change in levels of fragmentation in our sample of cities? We formulated the following seven hypotheses that may explain why this rate would be high in some cities and low in others. In testing these hypotheses, we selected the average annual rate of change in the Openness Index (Openness Change) as a dependent variable. These hypotheses postulate a causal relationship between the rate of fragmentation represented by Openness Change and:

- The rate of change in density;
- The rate of change in population;
- The rate of inflation;
- The rate of economic growth;
- The ease of movement in the city; and
- The availability of core open space for infill.

The rate of fragmentation and the rate of change in density: Several researchers (e.g. Schmid 1968, Ohls and Pines 1975, Ottensman 1977, and Peiser 1989) have suggested that infill development would take place at higher densities, because it is likely to be closer to the center of the city and be in areas with more developed infrastructure and services than, say, new development on the urban periphery. Peiser, for example, provides empirical evidence from three U.S. metropolitan areas from 1949 to 1983 that "sprawl patterns of urban growth characterized by discontinuous development lead to higher densities in areas skipped over" (Peiser, 1989, 203). This would mean that we should expect cities with large shares of infill in new development to experience lower rates of decline in average built-up area density than cities with smaller shares. Since greater shares of infill development are associated with faster rates of decline in fragmentation, we should expect that declines in fragmentation be associated with increases in density. Still, we should keep in mind that while new infill development may be at greater density than, say, new leapfrog development on the urban fringe, it may still take place at lower-than-average densities in the city, thus leading to an overall decline in average density.

In a previous paper that focused on density, we reported on the significant global decline in average built-up area densities between 1990 and 2000. We can say with a very high level of confidence that, on average, built-up area densities in the universe of cities that had populations in excess of 100,000 in 2000 declined at an annual rate of 2.01±0.40 percent during this period (Angel *et al* 2009, 49). We were also able to show that cities with fast-growing populations 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 (Angel *et al* 2009, 66).

In the present essay, we reported on the significant global decline in the fragmentation of cities between 1990 and 2000. We noted that the average rates of change in all four key fragmentation metrics during this period were negative and significantly different from zero: The average Edge Index declined at the rate of 1.07±0.28 percent per annum; The average Openness Index declined at the rate of 1.02±0.20 percent per annum; the average Core Open Space Ratio declined at the rate of 1.49±0.31 percent per annum; and the average City Footprint Ratio declined at the rate of 0.42±0.20 percent per annum. When we now look at the correlations between the rates of decline in density and the rates of decline in fragmentation, we find that many of these correlations are significant at the 0.01 level (2-tailed), as shown in table 6.1.

We can see, for example, that the rate of change of the Openness Index and the rate of change in built-up area density are positively correlated, and that this correlation is significant at the 0.01 level (2-tailed). This tells us that, contrary to what would be expected by Peiser (1989) and others, declines in fragmentation went hand-in-hand with *declines* rather than increases in average built-up area densities during the 1990s. We have shown in the previous section of this essay that variations in average built-up area density did not explain variations in average levels of the Openness Index. Dense cities were not more or less fragmented than sprawled ones. Is it possible, therefore, that the correlations shown in table 6.1, although significant, are coincidental? Or is it that loss of open space through the decline in fragmentation internalizes the need for more private open space and thus leads to lower density development? If that were the case, then more rapid declines in fragmentation will be associated with more rapid declines in density, rather than with slower declines in density.

Table 6.1: Correlations between rates of change in fragmentation and in density, 1990-2000

Metric	Built-up Area Density Annual Growth Rate	Urbanized Area Density Annual Growth Rate	Urban Footprint Density Annual Growth Rate
Edge Index Rate of Change	0.268	0.193	-0.117
Sig.(2-tailed)	*0.003*	*0.034*	*0.203*
Openness Index Rate of Change	0.383	0.320	-0.025
Sig.(2-tailed)	*0.000*	*0.000*	*0.790*
Core Open Space Ratio Rate of Change	0.185	0.083	-0.036
Sig.(2-tailed)	*0.044*	*0.368*	*0.695*
City Footprint Ratio Rate of Change	0.137	0.089	-0.346
Sig.(2-tailed)	*0.136*	*0.336*	*0.000*

The relationship between density change and openness change was examined by testing the following null hypothesis:

> Hypothesis 1: *Cities with rapid declines in built-up area density do not necessarily have lower or higher rates of Openness Change.*

The variable used to test this hypothesis was the **annual rate of change in average built-up area density, 1990-2000**, in the global sample of 120 cities.

The rate of fragmentation and population growth: Ewing, for example, suggests that "the higher the rate of growth of a metropolitan area, the greater the expectation of land appreciation, and the more land will be held for future development" (Ewing, 1994, 2). That would suggest that the faster the rate of population growth in the city, the more land will be kept off the market and we should therefore expect fragmentation to increase. It stands to reason, however, that cities that are growing rapidly in population have little time to extend infrastructure outwards to their fringe areas and beyond. In these cities, therefore, new development is more likely to take place as infill rather than as extension and leapfrog. We would thus expect fragmentation to decline more rapidly in fast-growing cities than in slow-growing ones. The relationship between the rate of population growth and the rate of change of the Openness Index was examined by testing the following null hypothesis:

> Hypothesis 2: *Cities with rapidly-growing populations do not have faster or slower rates of fragmentation of their built-up areas than cities with slower-growing populations.*

The variable used to test this hypothesis was the **average annual growth rate of the city population** between 1990 and 2000.

The rate of fragmentation and the rate of inflation: In the face of high levels of inflation, owners of vacant lands would be more reluctant to sell their lands for development because the proceeds from such sales would rapidly lose their value. If we assume that a fixed share of owners would be reluctant to part with their lands in times of high inflation, then developers searching for land would be more likely to find suitable land on the urban fringe and beyond ─ where land is more plentiful ─ that to find infill land. It stands to reason, therefore, that the decline in fragmentation would be slower in times of high inflation and more rapid in times of low inflation. The relationship between the rate of inflation and the rate of change of the Openness Index was examined by testing the following null hypothesis:

> Hypothesis 3: *Cities in countries with high rates of inflation do not have faster or slower rates of fragmentation of their built-up areas than cities in countries with slower rates of inflation.*

The variable used to test this hypothesis was the **average annual rate of change of the Consumer Price Index (CPI)** in the country between 1990 and 2000.

The rate of fragmentation and the pace of economic development: Cities in countries that that are experiencing rapid economic development are likely to have more resources for extending infrastructure into the urban periphery, be they private or public resources. In these cities, therefore, new development is more likely to take place as extension and leapfrog rather than as infill. We would thus expect fragmentation to decline more slowly in countries with higher rates of economic development. The relationship between the rate of economic growth and the rate of change of the Openness Index was examined by testing the following null hypothesis:

> Hypothesis 4: *Cities in countries with high rates of economic growth do not have faster or slower rates of fragmentation of their built-up areas than cities in countries with slower rates of economic growth.*

The variable used to test this hypothesis was the **average annual growth rate of GDP per capita growth** in the country in constant US dollars between 1990 and 2000.

The rate of fragmentation and the ease of movement in the city: As we already noted in the previous section, the availability of private automobiles can have two quite contradictory effects on the fragmentation of cities. On the one hand, to the extent that private automobiles make transport cheaper, they enable people to travel further and to cover greater distances on their way to work, to market, to school, and to other destinations. On the other hand, private automobiles facilitate door-to-door travel and can move with great ease on roads narrow and wide, both paved and unpaved, in almost all weather conditions. It was difficult to determine in advance which factor would be more powerful in determining whether higher levels of automobile ownership accelerate fragmentation or slow it down. We examined the relationship between automobile ownership and the rate of change in the Openness Index by testing the following null hypothesis:

> Hypothesis 5: *Cities in countries with higher levels of automobile ownership are not more or less likely to have higher rates of fragmentation of their built-up areas than cities in countries with lower levels of automobile ownership.*

The variable used to test this hypothesis was the **logarithm of car ownership per capita in 1991** in the country in which the city was located.

The rate of fragmentation and core open space: It stands to reason that the ample supply of core open space affects levels of infill and thus the rates of decline in fragmentation: Other things being equal, cities with large ratios of core open space to their urban built-up areas should be able to sustain more infill than cities with smaller ratios. The relationship between core open space and the rate of change in the Openness Index was examined by testing the following null hypothesis:

> Hypothesis 6: *Cities that have larger core open space ratios do not have faster or slower rates of fragmentation than cities that have smaller ratios.*

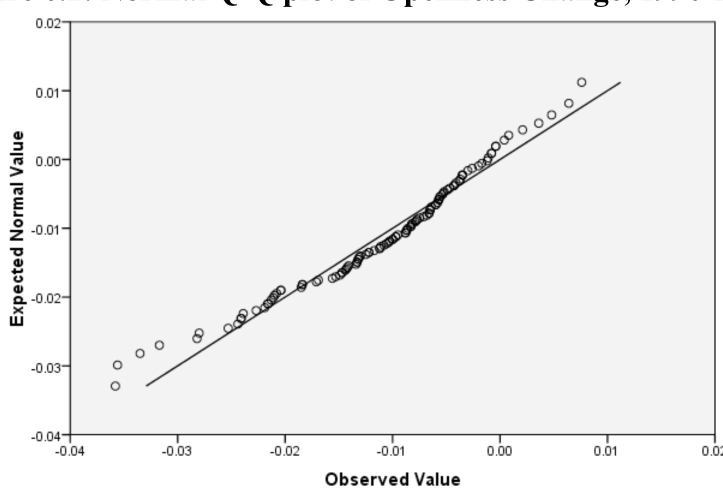
The variable used to test this hypothesis was the **logarithm of the Core Open Space Ratio** in 1990.

Multiple regression models that explain variations Openness Change

We now turn to the second set of multiple regression models. They are dynamic models, in contrast to the static models presented in Section V. These models seek to explain variations in the changes in levels of fragmentation that took place between 1990 and 2000 in the global sample of cities. They all use the annual rate of change of the Openness Index (Openness Change, for short) as the dependent variable, assuming a constant rate of change during this period. In all models, we used density change, population change, income change, and the rate of inflation 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.[8]

Multiple regression models assume that the variables used in the models are normally distributed. The results of the Q-Q test for normality of Openness Change are shown in figure 6.1 below. The fact that the observations for cities in the global sample line up along a straight line is a visual confirmation that this variable is indeed normally distributed. A histogram of Openness Change values (not shown) conforms this as well.

Figure 6.2: Normal Q-Q plot of Openness Change, 1990-2000



Note: **Four outliers have been excluded from the distribution: Akashi, Bacolod, Jaipur, and Puna. These four cities had massive declines in Openness in the 1990s, of the order of 4 percent per annum or more.**

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8 Since we calculated the Openness Index 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 density, population, income, and inflation data are available for the two periods, we opted to use the annual rate of change in the Openness Index as a dependent variable rather than the difference in Openness between the two periods. This allows us to use the initial Core Open Space Ratio, for example, as an independent variable in the models; it is independent from the rate of change in the Openness Index but not independent from the difference in the Openness Index between the two time periods.

Five multiple regression models using Openness Change as the dependent variable are summarized in table 6.2 below.

Table 6.2: Models that explain variations in the annual rate of change of the Openness Index, 1990-2000

Independent Variables	Coefficients and levels of significance				
	Model 1	Model 2	Model 3	Model 4	Model 5
Annual Change in Built-up Area Density 1990-2000	**0.194**	**0.250**	**0.214**	**0.247**	**0.288**
β-Coefficient	*0.383*	*0.493*	*0.422*	*0.473*	*0.546*
Sig.(2-tailed)	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Annual City Population Growth Rate, 1900-2000		**-0.246**	**-0.223**	**-0.286**	**-0.327**
β-Coefficient		*-0.326*	*-0.295*	*-0.379*	*-0.424*
Sig.(2-tailed)		*0.000*	*0.000*	*0.000*	*0.000*
Log of Core Open Space Ratio, 1990			**-0.010**	**-0.009**	**-0.010**
β-Coefficient			*-0.307*	*-0.266*	*-0.292*
Sig.(2-tailed)			*0.000*	*0.001*	*0.001*
Log of Car Ownership in the country, 1991				**-0.010**	**-0.001**
β-Coefficient				*-0.164*	*-0.200*
Sig.(2-tailed)				*0.060*	*0.050*
Annual GNP per capita Growth Rate in the country, 1990-2000					**0.105**
β-Coefficient					*0.165*
Sig.(2-tailed)					*0.080*
Annual Change in the Consumer Price Index in the country, 1990-2000					**-0.00014**
β-Coefficient					*-0.106*
Sig.(2-tailed)					*0.230*
Constant	**-0.008**	**-0.003**	**-0.017**	**-0.013**	**-0.019**
Sig.(2-tailed)	*0.000*	*0.087*	*0.000*	*0.007*	*0.000*
No. of Observations	120	120	119	115	100
R-Squared	0.146	0.241	0.336	0.361	0.429
Adjusted R-Squared	0.139	0.228	0.319	0.337	0.393

Model 1 includes only the rate of change of built-up area density as an independent variable and it is found to be significant at the 0.000 level (2-tailed). The R^2 and Adjusted R^2 of the model are 0.15 and 0.14 respectively, indicating that the model explains some one-seventh of the variation in Openness Change. Hypothesis 1 is rejected: cities with rapid declines in built-up area density do have rapid declines in fragmentation as well. In other words, a slower decline in fragmentation is associated with a slower decline in density, suggesting that densities increase when fragmentation increases and decrease when fragmentation decreases. This also suggests that densities in infill areas are typically lower than the average built-up area of the city as a whole, and that infill does not appear to increase the overall density in the city. The Beta coefficient of density change is given as 0.38 and it tells us that a one standard deviation change in the rate of change in density is associated with a 0.38 standard deviation in the rate of change of the Openness Index.

This is an important finding. It suggests that infill development, in and of itself, does not necessarily increase the average density of the city as a whole. Moreover, it also suggests that the faster the decline in density the faster the decline in fragmentation. This is interesting because a decline in density is typically associated with increased 'sprawl' while a decline in fragmentation is associated with decreased 'sprawl'. In the 1990s, at least, we found that sprawl as density decline had increased while sprawl as fragmentation has decreased. It may well be, as we suggested earlier, that low density and a high level of fragmentation are substitutes: both are different means of maintaining proximity to open space. This would explain why a decrease in density is associated with a decrease in fragmentation. But it may also be that they are not causally related at all, and that their statistical relationship, although significant, is accidental.

Model 2 introduces the annual rate of population growth as an independent variable. The R^2 and Adjusted R^2 of the model are 0.24 and 0.23 respectively, indicating that the model explains some one-quarter of the variation in Openness Change, a considerably higher share than Model 1. The coefficient of Population Change is negative and significantly different from zero at the 0.000 level (2-tailed). The value of the coefficient, -0.25, indicates that a 10 percent increase in the rate of city population growth is associated with a 2.5 percent decrease in the Openness Index. The Beta coefficient of Population Change is -0.33, and it tells us that Population Change is a powerful explanatory variable of Openness Change. Hypothesis 2 is therefore rejected: cities with rapidly-growing populations do have slower rates of fragmentation of their built-up areas than cities with slower-growing populations. In other words, when cities are growing rapidly in population, developers tend to build more frequently on infill sites than on leapfrog or extension sites on the urban fringe.

This is an interesting finding. It is especially relevant to those of us trying to estimate how much land will be needed for urban expansion in the rapidly-growing cities in developing countries in the coming decades. These rapidly-growing cities will extend outwards in leaps and bounds, of course, doubling and tripling their built-up areas in the process. But at the same time, they are also likely to become less fragmented. This essentially means that we do not have to assume a constant level of fragmentation when projecting the future urban areas of fast-growing cities: we can assume that the open spaces contained in their city footprints will be filled in over time, and that their Openness Indices will decline over time. This does not necessarily means that *all* the open spaces contained in their City Footprints will be filled in. This is not likely to happen even in the face of Draconian regulatory barriers to the conversion of rural to urban land. But it does mean that if trends observed in the 1990s continue the share of open space in City Footprints will decline over time.

Model 3 introduces the supply of Core Open Space as an independent variable. The R^2 and Adjusted R^2 of the model are 0.34 and 0.32 respectively, indicating that the model explains one-third of the variation in Openness Change, a still higher share than that explained by Model 2. The coefficient of Log Core Open Space Ratio is negative and significantly different from zero at the 0.000 level (2-tailed). Its value, -0.01, indicates that a 10 percent change in the Core Open Space Ratio is associated with a 0.1 percent decline in Openness. Hypothesis 6 is therefore rejected: Cities that have larger core open space ratios do experience significantly more rapid declines in Openness than cities that have smaller ratios. Still, since the coefficient is very small, this effect may be considered negligible.

Model 4 introduces the national level of car ownership as an independent variable. The coefficient of Log Car Ownership is negative and significantly different from zero at the 0.06 level (2-tailed). The value of the coefficient, -0.01, indicates that a 10 percent change in the level of car ownership in the country is associated with a 0.1 percent decrease in the Openness Index. The Beta coefficient of Log Car Ownership is -0.16, and it tells us that Log Car Ownership is a powerful explanatory variable of Openness Change. Hypothesis 5 is therefore rejected: Cities in countries with higher levels of automobile ownership do have higher shares of infill in new development and therefore slower rates of Openness Change than cities in countries with lower levels of automobile ownership.

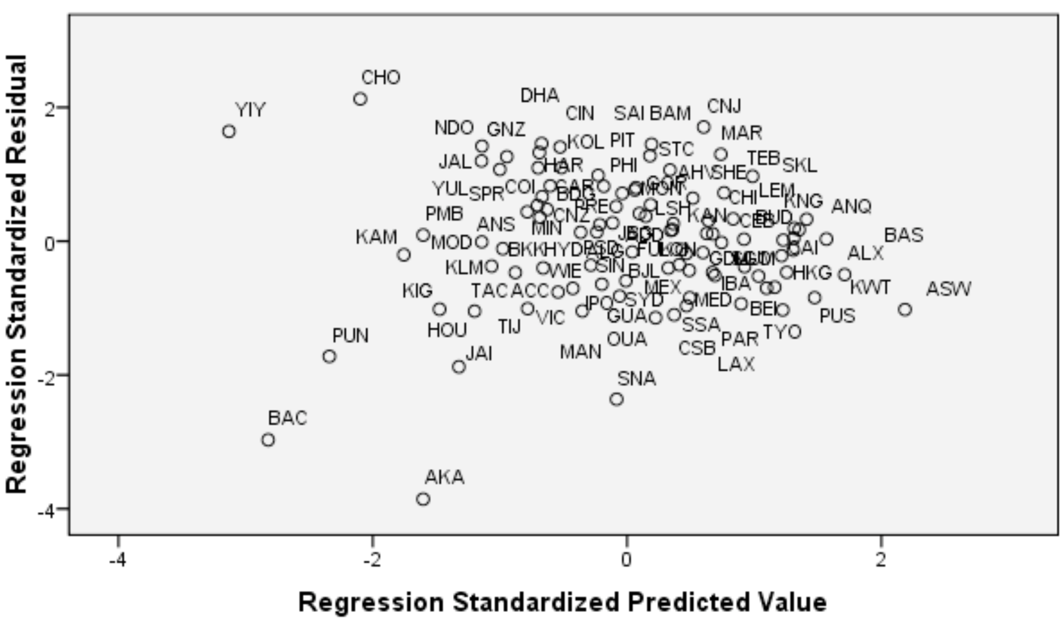
Automobile ownership thus acts to reduce fragmentation rather than to increase it. It supports infill more than it supports leapfrogging: the capacity of car-based transport systems to easily reach every available spot of land in metropolitan areas appears to outweigh its capacity to move people further away from the urban core. The area-filling capacity of car-based transport systems works to reduce fragmentation while their outreach capacity works to increase it, and when the two are pitted against each other the former capacity appears to have the upper hand. This is also an important finding. It suggests that car ownership, in and of itself, does not increase sprawl when sprawl is defined in terms of fragmentation and more specifically as leapfrogging *vis-à-vis* infill. The use of private cars encourages and supports infill, possibly because the capital costs involved in making new development areas accessible by car are considerably lower than the costs of making them accessible by public transport. That being said, we note that the coefficient of Log Car Ownership is very small and that the effects of levels of car ownership on sprawl as fragmentation, while significant, may be negligible.

Finally Model 5 introduces the average rate of economic development and the average rate of inflation during the 1990s as independent variables. The R^2 and Adjusted R^2 of the model are 0.43 and 0.39 respectively, indicating that the model explains some 40 percent of the variation in Openness Change, a still higher share than that explained by Model 4. The coefficient of the rate of GDP per capita growth is positive and significantly different from zero at the 0.08 level (2-tailed). Its value, 0.11, indicates that a 10 percent change in the city population is associated with a 1.1 percent change in the Openness Index. Even though it is not significantly different from zero at the 0.05 percent level, the relatively high value of the coefficient suggests that it is an important factor in explaining openness change. Hypothesis 4 is therefore rejected: Cities in countries with high rates of economic growth do have faster rates of fragmentation (or slower rates of decline in fragmentation) of their built-up areas than cities in countries with slower rates of economic growth.

The coefficient of the rate of inflation in model 5 is not significantly different from zero and we cannot therefore reject hypothesis 3: we are not able to determine whether cities in countries with high rates of inflation have faster or slower rates of fragmentation of their built-up areas than cities in countries with slower rates of inflation.

In conclusion we note that the five models presented here explain no more than forty percent of the variation in the rate of change in the Openness Index in the 1990s. Could it be that these models suffers from omitted variable bias? To test for omitted variable bias we plotted the standardized residuals in Model 4, as a representative model, against their associated standardized predicted values. The scatter plot is shown in figure 6.3 below. From the concentration of points within -2 and +2 of their averages (with the exception of five outliers: Chonan, Yiyang, Puna, Bacolod and Akashi) we can infer that the model does not suffer from omitted variable bias. Similar plots (not shown) were obtained for the other models presented here.

Figure 6.3: Residual plot for Model 4, plotting residuals against predicted values



We review the key findings from the application of multiple regression models to explain variations in the annual rate of change in the Openness Index, taking this metric as a representative metric for the decline in fragmentation in the global sample of cities. They are:

- Multiple regression models can explain up to 40 percent of the variation in the rate of change in the Openness Index.

- There were parallel and significant declines in average built-up area densities and in levels of fragmentation during the 1990s.

- The faster the rate of decline in built-up area density, the faster the rate of decline in the Openness Index.

- The faster the rate of population growth in the city, the faster the rate of decline in the Openness Index.

- The more open space is available in the urban core, the faster the rate of decline in the Openness Index, but the effect, while significant, is minimal.

- The higher the level of car ownership in the country, the faster the rate of decline in the Openness Index, but the effect, while significant, is minimal.

- The faster the rate of economic growth in the country, the slower the rate of decline in the Openness Index.

- The rate of inflation or restrictions on the conversion of land from rural to urban use cannot be said to affect significant changes in the Openness Index.

The declines in fragmentation in the 1990s, while clearly substantial and statistically significant, could thus only be partially explained. Paucity of data prevented us from determining whether public policies that sought to set limits on urban expansion have been successful in slowing down the fragmentation of cities. Differences in rates of fragmentation in have been explained by differences in the rate of change of built-up area density, population and income, and by the availability of cars and of open space in the urban core, variables that are not really subject to policy intervention at the city level.

VII 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 the fragmentation of the built-up areas of cities and the open spaces in and around them. Our study sought to provide this empirical foundation. We now know how the fragmentation of cities varies from place to place, how it varies over time, and what accounts for these variations. This should allow us to design and implement policies and programs that seek to restrain excessive fragmentation, policies and programs that are better targeted and better grounded in reality.

1. Review of key findings

Before discussing the policy implications of our study, we first review its key findings.

<u>On fragmentation and its decline in the global sample of cities, 1990-2000</u>

- There was an almost 50 percent chance that a city built-up area as small as 30-by-30 meters had an equivalent area of open space along one of its edges.

- The immediate adjacency of small built-up areas in cities to open space declined in the 1990s.

- A typical urban neighborhood (say, one square kilometer or 250 acres in area) contained almost as much open area as its built-up area.

- Urban neighborhoods contained relatively less open space in 2000 than they did in 1990.

- The open space fully captured within the urban cores of cities added some 25-30 percent, on average, to the areas of their urban cores.

- Cities in land-rich developed countries incorporated more open space into their urban cores than cities in other countries.

- Urban cores contained relatively less open space in 2000 than they did in 1990.

- Fringe open spaces within 100 meters of urban and suburban built-up areas (together with open space captured by them) added some 100 percent, on average, to city built-up areas.

- Chinese cities were found to have significantly more open space in and around them than other cities.

- Cities and their surrounding suburbs affected and fragmented relatively less of the open spaces in and around them in 2000 than they did in 1990.

- Leapfrogging constituted only one-sixth of new urban development in the 1990s.

- Leapfrog development was more prevalent and infill less prevalent in developing countries than in developed countries.

On explaining the variation in fragmentation among cities

- The density of built-up areas did not affect the spatial fragmentation of cities one way or another.

- Larger cities were found to be less fragmented than smaller ones.

- Higher levels of automobile ownership were associated with lower levels of fragmentation.

- The ready availability of well water from shallow aquifers increased fragmentation.

- There was no evidence that significant amounts of vacant lands were held off the market as a hedge against inflation.

- Informal settlements tended to act as infill and cities that had a greater share of dwellings in informal settlements were less fragmented.

- Cities in countries where larger shares of national incomes were derived from agriculture were more fragmented.

- Cities with planning restrictions on converting a larger share of their fringe lands from rural to urban use were less fragmented.

<u>On explaining the decline in fragmentation</u>

- There were parallel and significant declines in average built-up area densities and in levels of fragmentation during the 1990s.

- The faster the rate of decline in built-up area density, the faster the rate of decline in fragmentation.

- The faster the rate of population growth in the city, the faster the rate of decline in fragmentation.

- The more open space is available in the urban core, the faster the rate of decline in fragmentation, but the effect, while significant, is minimal.

- The higher the level of car ownership in the country, the faster the rate of decline in fragmentation, but the effect, while significant, is minimal.

- The faster the rate of economic growth in the country, the slower the rate of decline in fragmentation.

- The rate of inflation or restrictions on the conversion of land from rural to urban use cannot be said to affect significant changes in fragmentation.

What can we learn from these findings about the design, the efficacy, the targeting, and the appropriateness of urban containment and compact city strategies, the strategies aimed at limiting and reversing urban expansion or *sprawl*?

In our previous essay, "The persistent decline in urban densities: global and historical evidence of *sprawl*", we recorded our findings regarding densities in different cities, countries, and regions and their decline over time, both during the last decade of the twentieth century and during the last century. The findings of that essay yielded several policy implications:

- 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.

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

The findings in the present essay add several policy implications to those articulated in our earlier essay on densities:

- Urban areas the world over are excessively fragmented, typically containing or disturbing open space equivalent in area to their built-up areas.

- Average levels of fragmentation in cities the world over are typically much higher than those needed to sustain the healthy functioning of land markets.

- Urban fragmentation at all spatial scales is on the decline, a welcome and encouraging development.

- The private automobile should not be blamed for causing urban sprawl when sprawl is defined as discontinuous development.

- Restrictions on urban expansion may effectively reduce fragmentation, but sometimes they increase it, and sometimes fragmentation declines without them.

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

- Anti-sprawl policies that target fragmentation can be stricter in slow-growing cities in developed countries than in fast-growing cities in developing countries.

These policy implications are discussed in greater detail below.

<u>Urban areas the world over are excessively fragmented, typically containing or disturbing open space equivalent in area to their built-up areas</u>

Several of the more robust findings of this essay confirm that cities fragment and disturb open space in and around them that is roughly equivalent in area to their built-up areas. In general, only a small part of that area is occupied by open space in permanent use, be it private or public, and we can safely assume that most of the open space that is fragmented and disturbed by cities in made up of vacant lands that will be eventually developed. Typically (but not in every case), these vacant lands in and around cities are no longer owned by farmers and are no longer cultivated, but rather lying fallow waiting to be developed.

Surely, some argue, cities, including the vacant lands in and around them, take up only a small fraction of the total land area of most countries. In global terms, cities take up some one half of one percent of the total land area of the planet (Potere et al, 2009) while housing more than 50 percent of its population. That said, they do take up a much larger share of arable lands, and, in many cases, they expand into some of the best cultivated lands. Bangkok, for example, is located in the middle of Thailand's rich 'rice bowl', and any hectare of land appropriated by Bangkok reduces the land available for rice cultivation (and possible export) by one hectare. More generally, in the year 2000, for example, arable lands constituted only 11 percent of the total land area of the planet (World Bank, 2009). This means that cities may now occupy as much as five percent of the world's cultivated lands. In countries like Egypt, for example, where cultivated lands form only 3 percent of their land area, urban expansion into cultivated lands is and should be a serious concern.

It is important to understand at the outset is that there is no particular value in the excessive fragmentation of cities. Its consequences are largely negative: it increases the distance between urban locations, thus reducing overall accessibility, increasing travel times and vehicle miles traveled, increasing energy use and pollution, and increasing the cost of connecting built-up areas with roads, pipes, cables, and bus lines. It also fragments, weakens, and often destroys an inordinate quantity of farms and farmland, forests, wetlands, and other sensitive natural habitats in and around cities.

Some will argue that the fragmentation of urban areas is temporary since these vacant lands will eventually be filled in, as has happened many times before. This may have been true in the past, when the population of cities increased rapidly leading to a vast expansion of cities in the last two centuries. But, as we shall see below, it may no longer be true today, especially in cities that are not growing in population or are only growing very slowly in population and are highly unlikely to, say, double their populations or their built-up areas in the coming decades.

In short, it may not be in the public interest for cities to be as excessively fragmented as they are today. The excessive fragmentation created by *laissez-faire* discontinuous development is, in fact, a form of market failure. As Brueckner notes, "market failure arises from the failure of real estate developers to take into account all of the public infrastructure costs generated by their projects" (2000,163). To the extent that developers choose sites that increase overall fragmentation rather than reduce it, they impose additional costs on the city as a whole as well as on its surrounding countryside. This is by no means a new argument, and many cities have imposed regulations on new construction on the urban fringe that require developers to pay development impact fees to defray some of these externalities (see for example, Hart and Duerkson, 1993).

Average levels of fragmentation in cities the world over are typically much higher than those needed to sustain the healthy functioning of land markets

Economists have long argued that discontinuous development and open space fragmentation on the urban fringe increases the efficiency of land markets. Surely, if conversion to urban use was only permitted on sites that are immediately adjacent to the built-up area, then their landowners could charge monopoly prices. At any point in time, only a fraction of landlords on the metropolitan fringe are willing to sell their land and developers find only a fraction of these lands suitable for their projects: The greater the choice available to developers, so the argument goes, the more competitive, and hence the more efficient, the land market.

In the past, however, this argument was made in the absence of a quantitative dimension. Those championing the efficient land market cause cannot simply tell us that there should be plenty of land available for development. They also need to tell us 'how much land is enough'. There is no doubt that a significant percentage of vacant homes, for example, is necessary for the smooth functioning of the housing market. But the average vacancy rate in global housing markets is only of the order of 5 percent of the housing stock (Angel 2000, table 22.1, 299). By comparison, how much land should be available for immediate conversion to urban use at any time? 10 percent, 20 percent, 30 percent, 100 percent?

Metro, the regional government of the Portland metropolitan area manages its Urban Growth Boundary, adopted in 1973 with the specific aim of reducing fragmented and scattered urban development and increasing the share of infill in new development. Metro manages this boundary, moves it outwards from time to time, and forbids urban development outside it. It "is required by state law to have a 20-year supply of land for future residential development inside the boundary" (Metro, 2009). In other words, it projects land needs based on population growth and other factors affecting land needs and on that basis it determines how much land needs to be available for conversion to urban use.

Given the findings in this essay, those interesting in curtailing fragmentation now have a ready tool for estimating it and comparative norms that can be used to bring it down to acceptable levels. Given that cities are likely to remain fragmented for a long time to come, given that fragmentation can only be reduced gradually through infill, given that cities can project their land needs and plan to have a 20-year or a 30-year supply of land readily available for immediate conversion to urban use, we can now make plans for urban expansion that take existing and future fragmentation into account. We can acknowledge existing levels of fragmentation, we can formulate plans to bring it down, and we can adopt effective mechanisms for bringing it down, all the while monitoring urban land markets and ensuring that there is an adequate supply of land readily available for development.

<u>Urban fragmentation at all spatial scales is on the decline, a welcome and encouraging development</u>

The key and the rather surprising new finding in our investigation of global urban expansion is that fragmentation in cities all over the world is now in decline. The average Edge Index declined at the rate of 1.07±0.28 percent per annum; at that rate it would decline to 73 percent of its present value in 30 years. The average Openness Index declined at the rate of 1.02±0.20 percent per annum; at that rate it would decline to 74 percent of its present value in 30 years. The average Core Open Space Ratio declined at the rate of 1.49±0.31 percent per annum; at that rate it would decline to 64 percent of its present value in 30 years. And the average City Footprint Ratio declined at the rate of 0.42±0.20 percent per annum; at that rate it would decline to 88 percent of its present value in 30 years..

To wit, cities are not becoming more fragmented than before; cities do not remain as fragmented as before. On the contrary, cities are becoming significantly less fragmented than before. If, as many people do, we define sprawl as discontinuous development or as the fragmented development of the built-up areas of cities, then we can safely conclude that urban sprawl is on the decline. Similarly if, as many people do, we define sprawl as the excessive fragmentation of open space in and around cities, be it in farmlands, forests, wetlands, or sensitive natural habitats, then again we can safely conclude that urban sprawl is on the decline. In short, sprawl as fragmentation is becoming less or a problem, rather than more of a problem.

This is indeed a welcome development, and it should encourage and empower those of us who believe that there is nothing intrinsic in the functioning of cities that requires them to be excessively fragmented or to become more fragmented over time, and that political action to restrain and limit fragmentation and gradually bring it down to sustainable levels could bear fruit. Such action does not require a heroic stance in the face of inexorable centrifugal forces that push the built-up areas of cities further and further away from each other. It only requires an encouragement and active support on of a trend that is already pulling the built-up areas of cities together.

<u>The private automobile should not be blamed for causing urban sprawl when sprawl is defined as discontinuous development</u>

Popular anti-sprawl diatribes frequently lump together the animosity towards cars with the animosity towards sprawl and blame the car for causing sprawl:

> Cars are no longer just a small part of our culture they are our culture. Vehicles have taken over our lives. We convert open space, parks, and empty space into roads and wider roads…. One out of six working Americans has work related to cars, and the rest depend on them to get to work. Cars supersaturate the Los Angeles Basin and have made its air typically unfit to breathe. Cars cause sprawl (Dennen, 2008).

The academic literature on sprawl also frequently associates it with the preponderance of private cars. Glaeser and Kahn, for example, note the high correlation between car ownership and low density cities:

> The best evidence on the claim that cars made sprawl possible is the high correlation between using automobiles and living in low density edge cities. This type of correlation certainly does not prove that cars caused sprawl, but it is strong evidence suggesting at least cars and low-density living are very strong complements (Glaeser and Kahn, 2003, 23).

Glaeser and Kahn find a positive correlation between levels of car ownership and low density cities, both in the U.S. (Glaeser and Kahn, 2003, 23) and in an international sample of 70 cities (Glaeser and Kahn, 2003, 25). There is no question at all that the automobile, the bus, and the truck (and the horsecar, the streetcar, and the ferry before them) made possible the decentralization and the decongestion of cities. All cities in the world are now car, bus and truck based cities and all the cities in the world are more or less spread out, often with many sub-centers and often with decentralized employment. In this sense, the automobile, or more generally the internal combustion engine, has helped push cities further and further outwards from the ‘walking cities’ of old.

That said, we note here again that there is a difference between sprawl as low-density development and sprawl as fragmented development. And while Glaeser and Kahn lump them together, it may be useful to distinguish them from one another. Our statistical models indicate that there is a strong and significant statistical relationship between car ownership per capita and the level of fragmentation: the higher the level of car ownership, the lower the level of fragmentation and the higher the share of infill in new development.

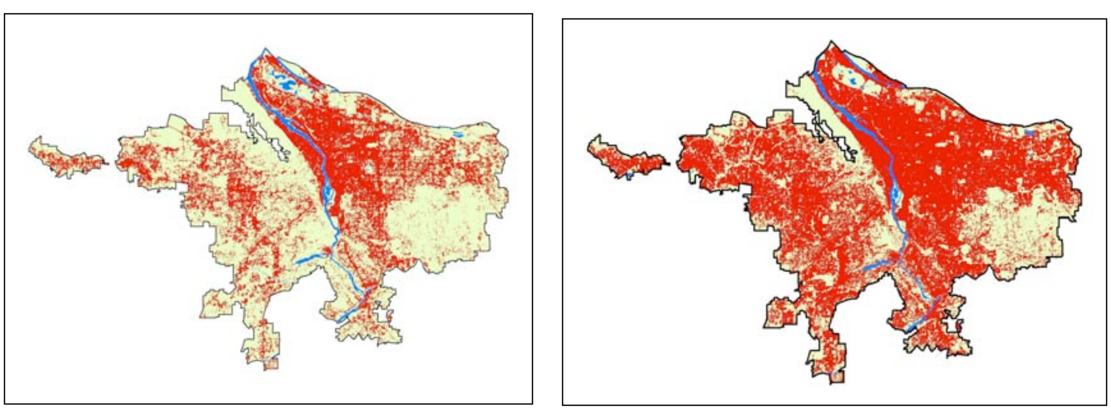
This relationship may be at least partially explained by the observation that the prevalence of private cars and, in turn, the prevalence of a road network to serve these cars, makes land more accessible. More importantly, it makes land more accessible than it would be when only public transport is available and people have to walk from their homes to a public bus station or to an informal transit stop. In other words, the car makes it possible to fill space more effectively than public transport and cities that rely more heavily on public transport at the present time have more places that are not accessible enough and therefore remain unbuilt.

Restrictions on urban expansion may effectively reduce fragmentation, but sometimes they increase it, and sometimes fragmentation declines without them

Our study has found a significant though weak relationship between planning efforts to restrain urban expansion, expressed in master plans that limit the amount of land available for conversion from rural to urban use, and levels of urban fragmentation. In our earlier study of urban densities mentioned earlier we have failed to find a significant relationship between planning efforts to restrain urban expansion and density levels.

In specific cases, there appears to be no doubt that planning intervention can clearly reduce fragmentation even though it may not have an effect on increasing built-up area densities. This becomes quite clear when we examine the effect of the Urban Growth Boundary instituted in Portland, Oregon, in 1973 on both average built-up area density and on levels of fragmentation. A cursory examination of the historical documents associated with the formation of the Urban Growth Boundary (see figure 7.2) makes clear that it was adopted with the specific objective of reducing fragmentation. There are multiple references to the protection of farmlands and natural habitats by containing sprawl and to the need to reduce leapfrogging, but no specific mention of the need to increase built-up area densities.

Figure 7.2: The expansion of the built-up area (in red) within Portland's Urban Growth Boundary (UGB), 1973-2005



It is interesting to note, therefore, 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. In other words, the restrictions on the outward expansion of the city did not affect an

increase in built-up area densities. It appears that developers continued to build at below-average densities, and to the extent than infill development entailed their buying land at higher prices, the prices of low-density development in infill areas increased beyond what they would have increased in extension and leapfrog areas.
While built-up area densities in Portland did not increase, its City Footprint Ratio declined rapidly and significantly: From 2.2 in 1973 to 1.7 in 2000 at the rate of 1.5 percent per annum; and from 1.7 in 2000 to 1.5 in 2005, at the rate of 2.5 percent per annum. Indeed, its low ratio in recent years would rank it in the second decile in the global sample of 120 cities, similar to its present rank among U.S. cities. Portland is gradually becoming one of the least fragmented cities in the world. Surely, 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, Portland has been pursuing a successful policy of accelerated infill, but that infill is taking place at relatively low built-up area densities.

To take another example of the effect of policies that restrict the conversion of rural land to urban use, we should look at Chinese cities. The Chinese government, as we noted earlier, places stiff constraints on the conversion of cultivated lands to urban use in the name of guaranteeing food security. But instead of these restrictions leading to reduced fragmentation, the Chinese cities in our sample had significantly larger City Footprint Ratios in 2000 than other cities in the sample. Chinese land conversion restrictions distort land markets, forcing municipalities to destroy large quantities of affordable rental housing in villages surrounding cities, while leaving farmers to cultivate small plots of land at low-levels of productivity in and around cities. This practice leads to an increase, rather than to a reduction, in level of fragmentation. Indeed, the average Openness Index in the Chinese cities in our sample increased significantly between 1990 and 2000.

It is also interesting to compare here how density and fragmentation in Portland compare to density and fragmentation in Los Angeles, which does not have an Urban Growth Boundary and cannot be said to be ‘planned’ in any formal sense of the word. Built-up area density in Los Angeles declined from 35.0 persons per hectares in 1989 to 34.3 persons per hectare in 2000 but its density in 2000 was still 50 percent higher than that of Portland. The City Footprint Ratio in Los Angeles declined from 1.47 in 1989 to 1.40 in 2000 and was still lower than that of Portland.

Given these examples and given our significant yet weak statistical findings, we can only conclude that future policies aimed at reducing fragmentation must be designed with special care, drawing on lessons learned in cities that have applied such policies successfully, in cities that applied such policies unsuccessfully, and in cities that have attained lower levels of fragmentation without resorting to such policies at all.

<u>Anti-sprawl policies that target fragmentation should be clearly distinguished from anti-sprawl policies that target low-density development</u>

Our parallel studies of fragmentation and built-up area densities in the global sample of cities have led us to suspect that the two may be quite distinct. Densities and levels of fragmentation may be quite independent from each other, as may be the observed declines in density and the parallel declines in fragmentation. In our view, while there may be some plausible explanations for the observed statistical relationships between density and fragmentation, there is no viable theory for linking the two together convincingly. 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. In fact, it appears that the policy instruments available for increasing built-up area densities are quite different from those that address 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 to 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; apartment house construction should be encouraged; 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 should be restrictions on conversion of land from rural to urban use; there should be impact fees for development at longer distances away from built-up areas; there should be conservation easements for keeping green areas from development; there should be exchanges of development rights to direct development into desirable areas; or there should be purchases of public open spaces, to give a few examples.

In some cases, the aim may be to increase built-up area densities and decrease fragmentation at the same time, and in those cases there would be a need to address both attribute of sprawl, each with its own appropriate set of policy instruments. In this regard, it is interesting to examine a current National Research Council report (2009) focusing on increasing urban densities so as to reduce vehicle miles traveled (VMT) and CO_2 emissions in U.S. cities.

Numerous authors have claimed that there is a relationship, or a correlation, between urban population density and transit use. Nelson/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)

These observations have led the authors of the recent report mentioned above to an investigation of the projected increase in vehicle miles traveled with a 25 percent increase and a 75-percent increase in built-up area densities. And while the authors addressed the need to increase built-up area densities in their report, they unfortunately ignored the parallel need to reduce fragmentation. But we know that U.S. cities typically contain open space equivalent in area to their built-up areas. When we speak of transit, density only matters in the sense of having enough people within walking distance of transit stations so as to make transit operation viable. The relevant density metric here is, therefore, the City Footprint Density, the one that takes into account the fragmented open space in cities, not only the density in the built-up areas; in other words, the one that measures how many people live within walking distance of transit stations. Affecting the spatial structure of cities with the aim of increasing transit use and reducing vehicle miles traveled must address both the issue of built-up area density and the issue of fragmentation. Addressing one while ignoring the other is, to say the least, unhelpful.

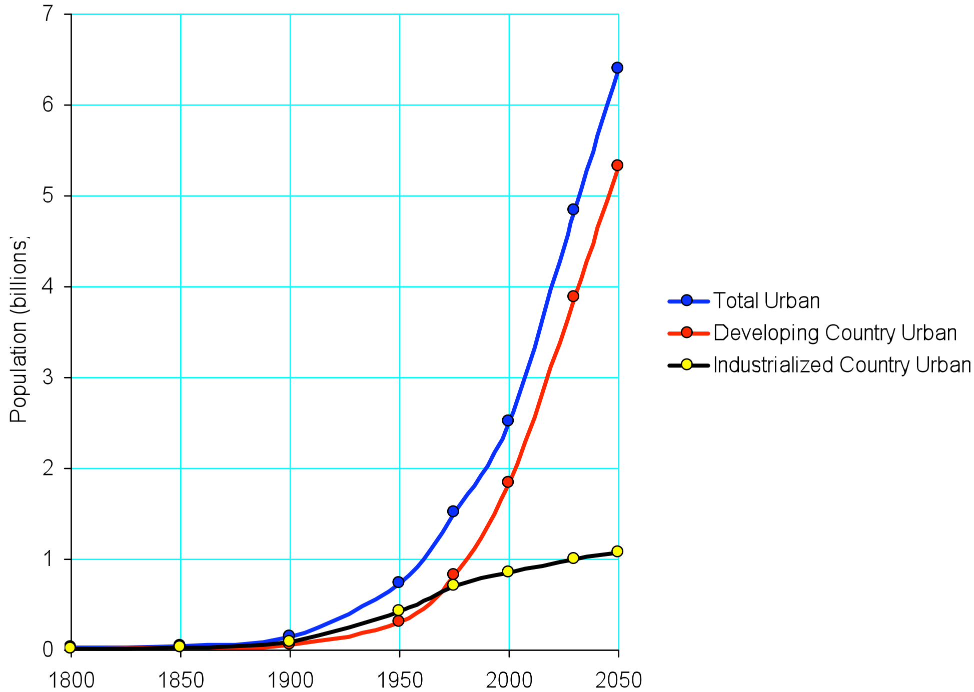
Anti-sprawl policies that target fragmentation can be stricter in slow-growing cities in developed countries than in fast-growing cities in developing countries

Urbanization in the developed countries has now reached a plateau and urban population growth there 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 rising incomes, by changing housing and commuting preferences, by transport costs, and by fiscal and financial incentives. Even if planning authorities made sure that there is a ready 30-year supply of rural land for conversion to urban use, it is hard to imagine that cities in developed countries will need to, say, double in area during the next 30 years. This means that cities in developed countries are now ripe for consolidation and for a significant reduction in fragmentation in the coming years. They already contain vast tracts of fringe land in and around them that can be filled in, and they need less land for expansion outward than ever before. Expansion outwards in developed-country cities has now become a matter of value and preference, rather than a matter of a dire need to make room to accommodate their burgeoning populations.

This is certainly not the case in the cities in developing countries. The urban population in developing countries 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 4 billion in 2030 and to 5.3 billion in 2050 (see figure 7.3). Even at existing densities, not to mention at lower densities, cities in developing countries will increase their areas 2.5-fold, on average, between 2000 and 2050. Future urban expansion in developing countries will be driven, first and foremost, by urban population growth and by rising incomes.

A 30-year supply of land for urban expansion in a typical developing-country city, a city that expects to double its population in 30 years requires roughly tripling the land area of the city. In other words, it requires the conversion of new rural land to urban use equivalent to *twice* the existing area of the city (Angel *et al*, 2009, 112-113.).

Figure 7.3: Global urban population growth, 1800-2000



In an important sense, therefore, applying policies that aim at reducing fragmentation in the slow-growing cities in developed countries to the fast-growing cities in developing countries may be misguided. Encouraging infill in cities with little population growth is qualitatively different from encouraging infill in rapidly-growing cities. In the former, it can form the backbone of an effective 'smart growth' policy. In the latter, it is overshadowed by the urgent need to prepare vast areas for outward expansion.

<u>Concluding remarks: Global comparative studies in urban spatial structure</u>

The ready availability of satellite imagery and the advanced tools for classifying images, creating maps based on these classifications, measuring these maps with relevant metrics, and analyzing these metrics using statistical measures is now breathing new life into the empirical study of urban spatial structure. Urban spatial structure is a field of study that, as Mills notes (2000,6), has been in steep decline in recent years: papers on spatial analysis accounted for 30.8 percent of all papers in the *Journal of Urban Economics* in 1978, for example, but only for 8.7 percent in 1998. Since the comparative empirical investigations centered on the urban density gradient initiated by Clark in the early 1950s there has really been little systematic progress in this field. On the whole, we have not been able to ground the study of the spatial structure of cities in a solid empirical foundation, and discussions concerning critical aspects of this important field ─ whether they be concerned with the proper approach to urban expansion, density, fragmentation, job decentralization, or open space conservation ─ are still too frequently based on flimsy assertions, unsubstantiated beliefs, ideological preferences of one kind or another, and wishful thinking.

In this study, we have tried to demonstrate 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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ANNEX I: FRAGMENTATION METRICS FOR THE GLOBAL SAMPLE OF CITIES, 1990-2000

		Edge Index		Openness Index		Core Open Space Ratio		City Footprint Ratio	
City	Country	1990	2000	1990	2000	1990	2000	1990	2000
Eastern Asia									
Anqing	China	0.406	0.447	0.482	0.486	0.199	0.229	1.985	2.295
Beijing	China	0.490	0.432	0.455	0.407	0.213	0.186	2.233	2.111
Changzhi	China	0.448	0.418	0.564	0.494	0.261	0.232	2.008	2.193
Guangzhou	China	0.521	0.548	0.586	0.540	0.220	0.275	2.182	2.410
Hong Kong	China	0.306	0.286	0.375	0.347	0.205	0.174	1.580	1.551
Leshan	China	0.587	0.566	0.669	0.614	0.179	0.204	2.452	2.404
Shanghai	China	0.387	0.368	0.410	0.360	0.189	0.221	2.111	2.061
Yiyang	China	0.785	0.618	0.806	0.653	0.432	0.243	1.799	2.622
Yulin	China	0.779	0.711	0.820	0.739	0.437	0.336	2.495	2.699
Zhengzhou	China	0.628	0.636	0.576	0.546	0.284	0.321	2.772	2.798
Ulan Bator	Mongolia	0.388	0.345	0.368	0.337	0.187	0.145	1.657	1.626
Ansan	Republic of Korea	0.294	0.305	0.398	0.349	0.280	0.212	1.734	1.820
Chinju	Republic of Korea	0.470	0.566	0.551	0.595	0.164	0.177	1.872	2.413
Chonan	Republic of Korea	0.610	0.572	0.649	0.594	0.223	0.247	2.673	2.698
Pusan	Republic of Korea	0.272	0.278	0.369	0.335	0.178	0.176	1.597	1.613
Seoul	Republic of Korea	0.271	0.294	0.308	0.300	0.191	0.193	1.659	1.693
South-East Asia									
Bandung	Indonesia	0.467	0.434	0.419	0.374	0.341	0.324	2.014	1.866
Medan	Indonesia	0.470	0.444	0.409	0.358	0.240	0.262	2.091	1.924
Palembang	Indonesia	0.561	0.466	0.544	0.427	0.368	0.315	2.366	1.954
Ipoh	Malaysia	0.477	0.397	0.533	0.434	0.412	0.335	2.276	1.927
Kuala Lumpur	Malaysia	0.414	0.347	0.448	0.351	0.340	0.284	1.963	1.716
Bacolod	Philippines	0.867	0.380	0.711	0.383	0.476	0.285	3.008	1.707
Cebu	Philippines	0.457	0.450	0.407	0.378	0.295	0.260	1.972	1.896
Manila	Philippines	0.576	0.418	0.473	0.367	0.372	0.256	2.085	1.850
Singapore	Singapore	0.527	0.483	0.490	0.426	0.420	0.377	2.178	1.892
Bangkok	Thailand	0.604	0.556	0.588	0.475	0.469	0.375	2.521	2.146
Songkhla	Thailand	0.608	0.626	0.577	0.598	0.227	0.236	2.093	2.099
Ho Chi Minh City	Vietnam	0.459	0.391	0.434	0.376	0.256	0.209	2.003	1.884
South and Central Asia									
Dhaka	Bangladesh	0.652	0.646	0.528	0.506	0.420	0.328	2.180	2.274

Rajshahi	Bangladesh	0.972	0.953	0.889	0.841			2.903	3.516
Saidpur	Bangladesh	0.740	0.754	0.706	0.720	0.354	0.299	1.834	2.009
Coimbatore	India	0.730	0.677	0.628	0.570	0.487	0.398	2.368	2.417
Hyderabad	India	0.507	0.444	0.488	0.405	0.313	0.252	2.164	1.965
Jaipur	India	0.544	0.416	0.487	0.325	0.308	0.264	1.967	1.566
Jalna	India	0.596	0.626	0.656	0.591	0.371	0.354	2.073	2.034
Kanpur	India	0.532	0.490	0.492	0.455	0.269	0.215	2.059	2.034
Kolkota	India	0.672	0.684	0.583	0.546	0.352	0.338	2.223	2.485
Mumbai	India	0.269	0.239	0.269	0.259	0.165	0.145	1.445	1.490
Puna	India	0.650	0.391	0.564	0.354	0.392	0.253	2.397	1.647
Vijayawada	India	0.463	0.437	0.514	0.482	0.308	0.207	1.841	1.836
Ahvaz	Iran	0.483	0.506	0.597	0.595	0.185	0.176	1.636	1.753
Gorgan	Iran	0.596	0.514	0.664	0.623	0.240	0.190	2.220	2.132
Teheran	Iran	0.362	0.338	0.298	0.266	0.226	0.194	1.610	1.556
Shimkent	Kazakhstan	0.410	0.428	0.402	0.395	0.197	0.194	1.774	1.865
Western Asia									
Yerevan	Armenia	0.594	0.603	0.592	0.571	0.274	0.272	2.236	2.226
Baku	Azerbaijan	0.724	0.709	0.648	0.612	0.395	0.386	2.469	2.356
Zugdidi	Georgia	0.674	0.623	0.610	0.585	0.384	0.271	2.186	2.414
Tel Aviv	Israel	0.521	0.512	0.480	0.453	0.278	0.275	2.143	2.252
Kuwait City	Kuwait	0.379	0.348	0.392	0.353	0.209	0.183	1.690	1.599
Istanbul	Turkey	0.508	0.459	0.434	0.381	0.347	0.294	1.900	1.761
Malatya	Turkey	0.681	0.641	0.730	0.684	0.411	0.350	2.469	2.369
Sana’a	Yemen	0.319	0.157	0.360	0.252	0.227	0.115	1.595	1.363
Northern Africa									
Algiers	Algeria	0.553	0.492	0.564	0.488	0.394	0.325	2.260	2.117
Tebessa	Algeria	0.684	0.597	0.731	0.670	0.274	0.183	1.740	1.725
Alexandria	Egypt	0.284	0.290	0.357	0.341	0.135	0.143	1.528	1.485
Aswan	Egypt	0.292	0.257	0.512	0.482	0.104	0.091	1.731	1.650
Cairo	Egypt	0.344	0.309	0.350	0.330	0.173	0.152	1.637	1.608
Casablanca	Morocco	0.517	0.455	0.415	0.339	0.382	0.266	1.931	1.785
Marrakech	Morocco	0.438	0.469	0.546	0.573	0.194	0.165	1.834	1.896
Port Sudan	Sudan	0.306	0.282	0.361	0.320	0.197	0.169	1.557	1.476
Sub-Saharan Africa									
Ouagadougou	Burkina Faso	0.279	0.197	0.280	0.225	0.192	0.147	1.561	1.409
Addis Ababa	Ethiopia	0.510	0.469	0.388	0.357	0.325	0.296	2.005	1.871
Banjul	Gambia	0.561	0.521	0.456	0.395	0.285	0.272	2.106	1.955
Accra	Ghana	0.322	0.278	0.236	0.185	0.175	0.126	1.455	1.389
Bamako	Mali	0.457	0.504	0.442	0.444	0.227	0.215	1.738	1.756
Ibadan	Nigeria	0.303	0.274	0.260	0.230	0.164	0.137	1.502	1.465
Kigali	Rwanda	0.630	0.482	0.556	0.398	0.409	0.324	2.529	1.988
Johannesburg	South Africa	0.614	0.553	0.483	0.445	0.454	0.404	2.240	2.113
Pretoria	South Africa	0.638	0.578	0.463	0.425	0.474	0.425	2.179	2.044

Kampala	Uganda	0.711	0.566	0.639	0.483	0.530	0.354	2.738	2.279
Ndola	Zambia	0.575	0.572	0.544	0.501	0.516	0.492	2.246	2.164
Harare	Zimbabwe	0.661	0.627	0.619	0.572	0.397	0.365	2.429	2.392
Latin America and the Caribbean									
Buenos Aires	Argentina	0.268	0.271	0.228	0.226	0.167	0.166	1.521	1.514
Guaruja	Brazil	0.334	0.232	0.420	0.360	0.219	0.174	1.800	1.610
Ilheus	Brazil	0.721	0.670	0.735	0.721	0.351	0.281	2.255	2.236
Jequie	Brazil	0.485	0.311	0.469	0.328	0.272	0.178	1.782	1.479
Ribeirao Preto	Brazil	0.244	0.270	0.257	0.274	0.138	0.156	1.477	1.568
Sao Paulo	Brazil	0.244	0.197	0.213	0.183	0.153	0.125	1.442	1.392
Santiago	Chile	0.363	0.342	0.281	0.254	0.207	0.177	1.618	1.562
Valledupar	Colombia	0.349	0.349	0.372	0.368	0.124	0.122	1.411	1.500
San Salvador	El Salvador	0.378	0.322	0.383	0.323	0.282	0.216	1.864	1.712
Guatemala City	Guatemala	0.357	0.286	0.387	0.314	0.289	0.238	1.873	1.690
Kingston	Jamaica	0.499	0.481	0.406	0.385	0.301	0.265	1.930	1.897
Guadalajara	Mexico	0.348	0.310	0.296	0.268	0.194	0.171	1.690	1.636
Mexico City	Mexico	0.358	0.307	0.298	0.248	0.223	0.179	1.696	1.564
Tijuana	Mexico	0.349	0.274	0.306	0.230	0.249	0.168	1.612	1.442
Montevideo	Uruguay	0.536	0.495	0.462	0.440	0.221	0.223	2.133	1.961
Caracas	Venezuela	0.577	0.500	0.487	0.433	0.340	0.263	2.166	1.997
Land Rich Developed Countries									
Sydney	Australia	0.529	0.416	0.405	0.337	0.359	0.278	1.872	1.717
St Catharines	Canada	0.332	0.384	0.426	0.425	0.185	0.232	1.813	2.030
Victoria	Canada	0.511	0.398	0.446	0.356	0.359	0.263	1.983	1.755
Astrakhan	Russia	0.637	0.639	0.533	0.529	0.359	0.359	2.148	2.141
Moscow	Russia	0.596	0.517	0.504	0.426	0.363	0.285	2.245	2.033
Oktyabrsky	Russia	0.677	0.665	0.625	0.602	0.349	0.310	2.337	2.383
Cincinnati	United States	0.590	0.605	0.511	0.493	0.390	0.409	2.443	2.411
Minneapolis	United States	0.563	0.504	0.465	0.407	0.393	0.370	2.176	1.991
Modesto	United States	0.560	0.424	0.488	0.394	0.397	0.224	1.958	1.952
Philadelphia	United States	0.474	0.456	0.430	0.402	0.345	0.340	2.103	2.047
Tacoma	United States	0.695	0.518	0.498	0.392	0.453	0.347	2.309	1.938
Chicago	United States	0.307	0.314	0.274	0.265	0.184	0.190	1.692	1.674
Houston	United States	0.503	0.365	0.463	0.337	0.404	0.287	2.128	1.754

Los Angeles	United States	0.296	0.269	0.237	0.210	0.209	0.183	1.468	1.403
Pittsburgh	United States	0.616	0.567	0.548	0.519	0.449	0.432	2.576	2.466
Springfield	United States	0.612	0.549	0.548	0.473	0.303	0.354	2.799	2.356
Other Developed Countries									
Wien	Austria	0.694	0.521	0.556	0.448	0.390	0.270	2.447	2.054
Le Mans	France	0.298	0.287	0.385	0.381	0.165	0.140	1.882	1.882
Paris	France	0.387	0.312	0.314	0.270	0.244	0.195	1.726	1.627
Leipzig	Germany	0.539	0.483	0.535	0.434	0.324	0.253	2.287	2.027
Thessaloniki	Greece	0.417	0.401	0.377	0.352	0.244	0.232	1.850	1.871
Budapest	Hungary	0.316	0.303	0.292	0.276	0.183	0.172	1.530	1.556
Milano	Italy	0.393	0.375	0.405	0.369	0.300	0.289	2.024	1.910
Palermo	Italy	0.426	0.406	0.424	0.406	0.258	0.246	1.990	1.942
Akashi	Japan	0.672	0.354	0.510	0.277	0.529	0.249	2.186	1.442
Fukuoka	Japan	0.318	0.302	0.334	0.300	0.209	0.186	1.536	1.546
Tokyo	Japan	0.344	0.303	0.261	0.228	0.263	0.224	1.485	1.409
Warsaw	Poland	0.556	0.474	0.472	0.408	0.351	0.298	2.046	1.922
Castellon	Spain	0.471	0.485	0.555	0.523	0.275	0.285	2.398	2.457
Madrid	Spain	0.468	0.468	0.412	0.386	0.257	0.264	1.993	1.950
London	United Kingdom	0.345	0.316	0.360	0.335	0.275	0.231	1.756	1.756
Sheffield	United Kingdom	0.373	0.374	0.422	0.410	0.367	0.351	1.804	1.834

ANNEX II: MAPS FOR THE GLOBAL SAMPLE OF 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).