Progress in Planning 75 (2011) 53–107
PROGRESS IN PLANNING
www.elsevier.com/locate/pplann

The dimensions of global urban expansion: Estimates and projections for all countries, 2000–2050

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Abstract

Our study of the expansion of a representative sample of 30 cities showed that 28 of them expanded more than 16-fold during the twentieth century. More generally, cities are now expanding at twice their population growth rates, on average, and now cover almost 0.5% of the planet's land area. We created a new dataset comprising the universe of all 3646 named metropolitan agglomerations and cities that had populations in excess of 100,000 in the year 2000, their populations in that year, and their built-up area identified in the *Mod500* map, currently the best of eight satellite-based global maps of urban land cover. Using this dataset, we estimated urban land cover in smaller cities and towns in all countries and calculated total urban land cover in every country in the year 2000. We then employed multiple regression models that could explain more than 90% of the variations in our urban land cover estimates amongst countries. Then, using U.N. urban population projections in combination with three realistic density change scenarios based on our previous global and historical study of densities, we projected urban land cover in every country and world region from 2000 to 2050. According to our medium projection, urban land cover in developing countries will increase from 300,000 km^2 in 2000 to 770,000 km^2 in 2030 and to 1,200,000 km^2 in 2050. Containing this expansion is likely to fail. Minimal preparations for accommodating it – realistic projection of urban land needs, the extension of metropolitan boundaries, acquiring the rights-of-way for an arterial road grid that can carry infrastructure and public transport, and the selective protection of open space from incursion by formal and informal land development – are now in order.

Keywords: Urban land cover; Built-up area; Sprawl; Urbanisation; Urban expansion; City growth; Satellite imagery; Urban population density

Contents

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doi:10.1016/j.progress.2011.04.001

1. Introduction and summary

1.1. Introduction

Between 1985 and 2000, the population of Accra, the capital of Ghana, increased from 1.8 to 2.7 million, a 50% increase. Its urban land cover increased from 13,000 to 33,000 ha, a 153% increase (see Fig. 1.1): urban land cover in Accra grew more than twice as fast as its population.

We examined the rate of growth of the urban population and urban land cover in a global sample of 120 cities between 1990 and 2000 (see Angel, Parent, Civco, & Blei, 2010). The former averaged 1.60% per annum and the latter averaged 3.66% per annum. The difference between them was $2.06 \pm 0.32\%$ (sig. 2-tailed = 0.000). In other words, as in Accra, urban land cover grew, on average, at *more than double* the rate of growth of the urban population. At these growth rates, the world's urban population will double in 43 years. The world's urban land cover will double in only 19 years.

Urban expansion is by no means a recent phenomenon. The historical expansion of Bangkok, the capital of Thailand, during the past 150 years is illustrated in Fig. 1.2. Bangkok increased its urbanised area from 580 ha in 1850 to 133,515 in 2002. In 1944, for example, its urbanised area comprised 8345 ha, a 14-fold increase of its 1850 area. It then doubled its area in 15 years (1944–1959), then doubled it again in nine years (1959–1968), then doubled it again in ten years

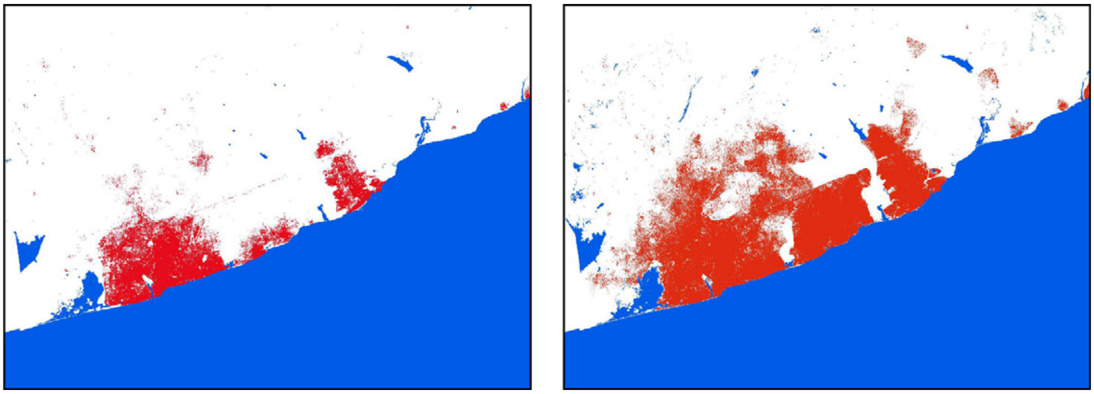


Fig. 1.1. The expansion of the built-up area of Accra, Ghana (shown in red), 1985–2000. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

(1968–1978), and then doubled it yet again in 24 years (1978–2002). In other words, the urbanised area of Bangkok increases 16-fold between 1944 and 2002.

We examined the rate of growth of urban populations and their associated urban land covers in a global historical sample of 30 cities between 1800 and 2000 (see Angel et al., 2010). The rates of urban expansion that we found in Bangkok were not atypical. Twenty-eight of the thirty cities studied increased their areas more than 16-fold during the twentieth century. The only exceptions were London and Paris, the two largest cities in the sample in 1900. These two cities increased their areas 16-fold by the year 2000 since 1874 and 1887 respectively. On average, the thirty cities in this group occupied one-half of their urbanised area circa the year 2000 some 23.5 $\pm$ 2.1 years earlier; they occupied only one-quarter of their area some 38.9 $\pm$ 3.1 years earlier; they occupied on one-eighth of their area some 54.1 $\pm$ 3.8 years earlier; and they occupied only one-sixteenth of their area some 70.2 $\pm$ 3.9 years earlier. In other words, these cities doubled their urbanised area, on average, in 16 years (1930–1946), then doubled it again in 15 years (1946–1961), then doubled it again in 15 years (1961–1976), and then doubled it yet again in 23 years (1976–2000).

The rapid growth in global urban land cover is likely to continue as long as urban populations continue to grow, as long as incomes continue to rise, and as long as urban transport remains relatively cheap and affordable. As we shall show, whilst considerable urban expansion will still occur in more-developed countries, most of the urban expansion in the coming decades will take place in the developing countries. This article therefore seeks to refocus the attention of planners, policy makers and concerned activists on urban expansion in developing countries and to begin to examine its policy implications.

In this study, we used new information from four datasets, three of them developed by the authors, to estimate the amount of urban land cover in all countries, to explain why it is larger in some countries and cities than in others, to project it into the future, to explore directions for further research, and to discuss the policy implications and the strategic options available to manage it in a realistic manner. The data used in this study is available online in our *Atlas of Urban Expansion* (Angel, Parent, Civco, & Blei, 2011). In the paragraphs below, we provide the plan of the study and a summary of its main findings before proceeding to the main body of the paper.

1.2. Global urban land cover and the universe of large cities

The first part of the paper focuses on the transformation of the *MOD500* global map of urban land cover for the year 2000, the best of the eight global urban land cover maps now available, into a more restricted map of the urban clusters associated with *named* large cities. Large cities, defined as cities that contain more than 100,000 people, are identified from two main sources, the www.citypopulation.de website (Brinkhoff, 2010) and the U.N.'s *World Urbanisation Prospects – the 2007 Revision* (U.N., 2008). The key results of this part are the first-time estimates of urban land cover and of average urban population density in the year 2000 for all large cities in all countries.

Eight global maps of 'urban' land cover in the year 2000 were examined earlier by one of the authors and his colleagues (Potere, Schneider, Angel, & Civco, 2009) and the *MOD500* map, with a pixel resolution of 463 m, was selected as the best amongst them. The *MOD500* map, like other remote-sensing maps, considers all impervious surfaces 'urban' and does not distinguish

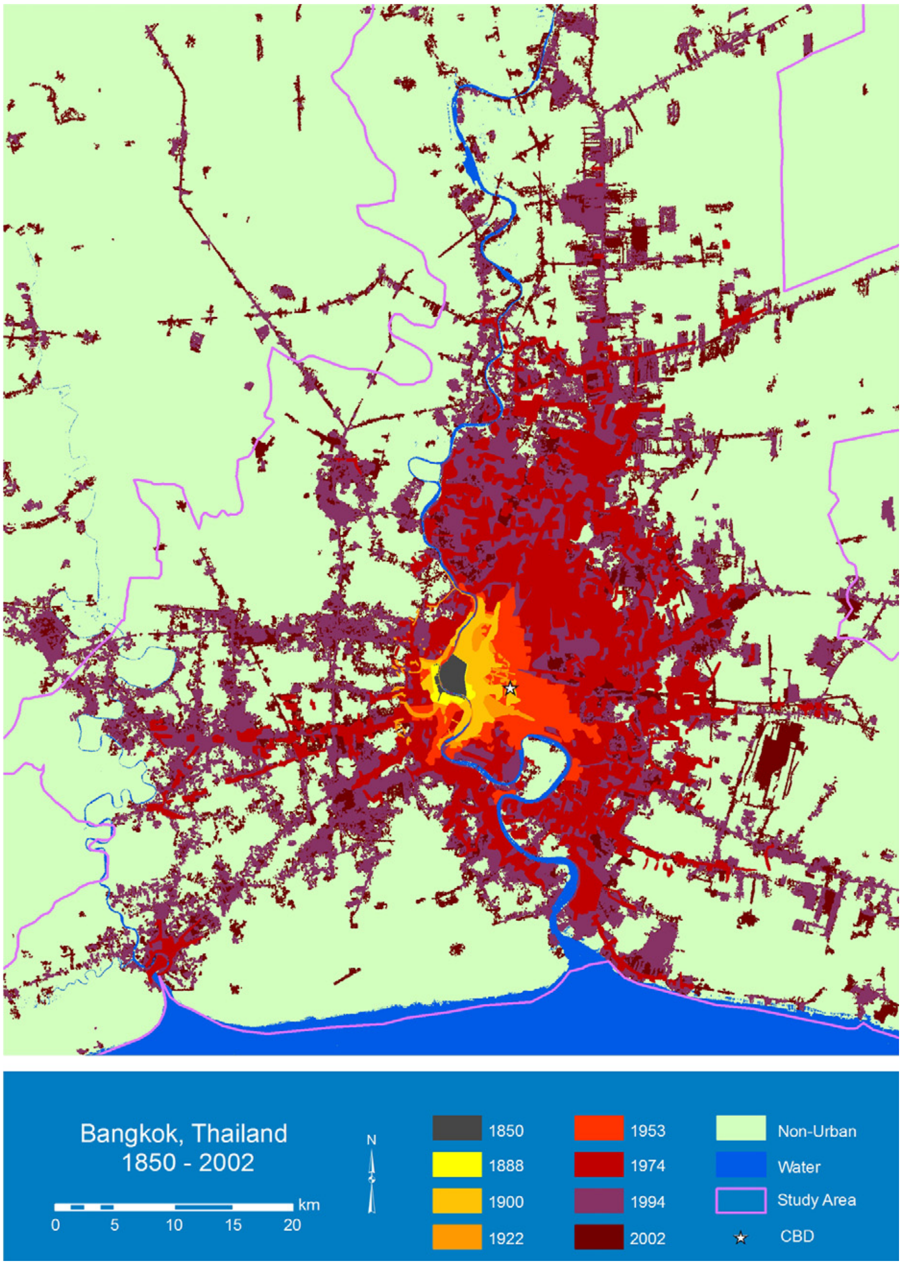


Fig. 1.2. The expansion of Bangkok, 1850–2002.

between impervious surfaces in urban and rural areas. The map therefore had to be modified to eliminate impervious surfaces in villages and small cities and towns by focusing on its identification of the land cover of *large* cities, cities that had more than 100,000 people in the year 2000. Using various sources, we created a new universe of 3646 *named* large cities. We identified the latitude and longitude of each city on *Google Earth*, its population in 2000, and the urban cluster associated with it in the MOD500 map. The total population in large cities in 2000 amounted to 2.01 billion and constituted some 71% of the total urban population in that year, 2.83 billion. Total urban land cover in large cities in 2000 amounted to some 340,000 km^2 and constituted 52% of the total 'urban' area in the *MOD500* global land cover map.

1.3. Estimates of urban land cover in small cities

The *MOD500* map could not be relied upon for calculating urban land cover in smaller cities and towns that cannot be easily distinguished from villages. In the second part of the study, we first computed the total urban population in small cities and towns in each country as the difference between the country's total urban population (estimated by the U.N.) and our calculated total population of large cities, both in the year 2000. The reader should note that because these estimates come from different data sources, subtracting them from one another is not without problems.

In the universe of large cities, a doubling of the city population is associated with a 16% increase in density. We used this density-population factor in generating our estimates. The density metric of interest in estimating urban land cover is *overall density*, defined as the ratio of the total urban population and total urban land cover in a given area. The total population in small cities in every country and every region is known. Total urban land cover in small cities is then calculated as the ratio of the total population to the overall density in small cities. In this section, we estimated the overall density in small cities in every region from information on the overall density in large cities, the median city population in large cities, the median city population in small cities, and the density-population factor introduced earlier. Our general conclusion is that overall densities in small cities are *roughly half* those in large cities. According to our calculations, urban land cover in small cities added some 266,000 km^2 to global urban land cover.

1.4. Urban land cover in all countries

We combined our estimates of urban land cover in large cities with urban land cover in small cities to calculate the total urban land cover in all countries and world regions in the year 2000. We present a table of these results as well as summary tables for world regions and global maps showing various measures of urban land cover in different countries.

According to our estimates, total urban land cover for the world as a whole in the year 2000 amounted to some 603,000 km^2. Our estimate of global urban land cover amounted to 93% of the total area identified as 'urban' in the MOD500 map. Global urban land cover in 2000 was equally divided between developing countries (49.3%) and developed countries (50.7%). There were great variations in urban land cover amongst countries: The U.S., for example, contained some 112,000 km^2 of urban land cover, 18.5% of global urban land cover and more than double the urban land cover of the next-highest country, China, 44,000 km^2. In the world as a whole, urban land cover occupied 0.47% of the total land area of countries. Urban areas occupied 0.85% of the land area of the countries of Southeast Asia but only 0.13% of the land in the countries of in Sub-Saharan Africa.

Amongst the countries that had large cities in 2000, 10 countries had more than 5% of their total land area occupied by cities: Singapore, Bahrain, Belgium, the Palestinian Territories, the Netherlands, Puerto Rico, the Czech Republic, the United Kingdom, Italy, and Germany. Twenty-two countries had 2–5% of their land areas occupied by cities, amongst them Japan, France, and the Philippines. Twenty-two additional countries had between 1 and 2% of their land area occupied by cities, amongst them the United States, Bangladesh, Turkey, and India. Twenty-eight more countries had between 0.5 and 1% of their land areas in urban use, amongst them Indonesia, Pakistan, Venezuela, and China. Twenty-seven countries had between 0.2 and 0.5% of their land in urban use, amongst them Brazil, Argentina, Mexico, and Egypt. Eighteen additional countries had between 0.1 and 0.2% of their land in urban use, amongst them the Russian Federation, Saudi Arabia, and Australia. The remaining 28 countries had less than 0.1% of their land in urban use, amongst them Canada, the Democratic Republic of Congo, Libya, and Mongolia.

1.5. Modelling urban land cover in countries and cities

The classical economic theory of urban spatial structure predicts that urban land cover will increase with population and income, as well as with a reduction in transport costs. We posited a number of hypotheses that could explain variations in urban land cover amongst countries based on this theory. We tested these hypotheses using multiple regression models with all variables in logarithmic form. In one set of models, we used total urban land cover in the country in the year 2000 as the dependent variable. The urban population in 2000, income (GDP per capita) in 1990, arable land per capita, the price of gasoline, and the share of the urban population in informal settlements were used as independent variables in the models. The coefficients of all the independent variables in this set of models were all found to be significantly different from 0 at the 95% confidence level (sig. 2-sided < 0.05).

The models were able to explain 93–95% of the variations in urban land cover amongst countries. A 10% increase in the urban population is associated with a $9.3 \pm 0.1\%$ increase in urban land cover. A 10% increase in GNP per capita is associated with a

$1.8 \pm 0.3\%$ increase in urban land cover. A 10% increase in arable land per capita is associated with a $2.0 \pm 0.0\%$ increase in urban land cover. A 10% increase in gasoline prices is associated with a $2.5 \pm 0.4\%$ decrease in urban land cover. A 10% increase in informal settlements is associated with a 0.08% decrease in urban land cover. In a second set of models, we obtained similar results in a second set of models using the total land area in large cities in the country in the year 2000 as the dependent variable.

In a third set of models, we used the year 2000 urban land cover in individual cities, rather than in entire countries, as the dependent variable in the models. These models were able to explain some 70% of the variations in urban land cover in the universe of large cities. City population, GNP per capita and arable land were found to have similar effects on urban land cover in individual cities as those identified for countries. However, the coefficient for gasoline prices was not significantly different from 0 at the 95% confidence level.

All in all, the statistical models were found to be robust and were able to explain a very large amount of the variation in urban land cover amongst cities and countries. Variations in climate, in cultural traditions, or in the policy environment in different countries may matter less than the fundamental forces giving shape to the spatial structure of cities: population, income, low-cost peripheral land, and inexpensive transport.

1.6. Projecting urban land cover in countries and regions, 2000–2050

The United Nations Population Division projects the urban population in every country from 2000 to 2050. In an earlier study (Angel et al., 2010) we found that average density in the built-up areas of a global sample of 120 cities declined at a mean annual rate of 2.0% between 1990 and 2000. It declined at 1.9% per annum in 20 U.S. cities between 1910 and 2000 and at 1.5% in a global sample of 30 cities between 1894 and 2000. We used the results of this study to estimate three realistic density scenarios for projecting urban land cover into the future: (1) a high projection, assuming a projected density decline of 2% per annum; (2) a middle projection, assuming a projected density decline of 1% per annum; and (3) a low projection, assuming that densities remain unchanged. We then projected urban land cover for all countries and regions under these three density scenarios.

Projected urban expansion between 2000 and 2050 will be a function of urban population growth and density change. The world urban population is expected to increase from 3 billion in 2000 to 5 billion in 2030 and to 6.4 billion in 2050. The rate of increase of the world urban population is expected to slow down from 2% per annum in 2000 to 1.65 in 2030 and to 1.14% in 2050. The urban population in less-developed countries will grow at a rate *five times faster* than the urban population in more-developed countries. The urban population of the more-developed countries will stabilise at around 1 billion people, whilst some countries, most of them in Eastern Europe, may lose up to 10% of their urban population by 2050. Almost all the growth in the world urban population will take place in less-developed countries: It will increase from 2 billion in 2000 to 4 billion in 2030 and to 5.5 billion in 2050. Amongst countries in the less-developed world regions, the fastest growth in the urban population will occur in Sub-Saharan Africa, followed by South and Central Asia. The projected rate of increase in urban land cover will be higher than the rates of increase of the urban population because urban population densities can be expected to decline.

At constant densities, the world's urban land cover will only double between 2000 and 2050 as the world population doubles. At a 1% annual rate of density decline it will triple. At a 2% annual rate of decline it will increase fivefold. Urban land cover in Sub-Saharan Africa will expand at the fastest rate: according to our high projection, urban land cover there will expand *more than 12-fold* between 2000 and 2050.

If densities in more-developed countries remain unchanged (low projection), urban land cover there will grow by only 21% between 2000 and 2030 and by 30% between 2000 and 2050. Urban land cover there will increase from 305,816 km^2 in 2000 to 370,390 km^2 in 2030 and to 397,566 km^2 in 2050. Assuming that densities in the more-developed countries decline, on average, by only 1% per annum (medium projection), urban land cover there will grow by 63% between 2000 and 2030, and by 114% between 2000 and 2050. Urban land cover in the more-developed countries will therefore increase from 305,816 km^2 in 2000 to 499,974 km^2 in 2030 and to 655,476 km^2 in 2050. In other words, at a 1% annual decline in average densities, urban land cover in more-developed countries will double in 50 years. If incomes continue to increase relative to gasoline prices and densities continue to decline at the 2% rate as they did in the 1990s, then urban land cover in more-developed countries will more than double between 2000 and 2030, and will triple between 2000 and 2050.

The situation is likely to be even more critical in less-developed countries, where most urban population growth will take place. Assuming that densities there decline, on average, by only 1% per annum (medium projection), urban land cover will grow by 158% between 2000 and 2030, and by 315% between 2000 and 2050. In other words, at the medium projection, urban land cover in less-developed countries will grow from 297,048 km^2 in 2000 to 767,226 km^2 in 2030 and to 1,233,461 km^2 in 2050. Assuming that densities in less-developed countries decline, on average, by 2% per annum (high projection) as they did in the 1990s, urban land cover will grow by 249% between 2000 and 2030, and by 585% between 2000 and 2050. In other words, urban land cover in less-developed countries will grow from 297,048 km^2 in 2000 to 1,035,647 km^2 in 2030 and to 2,033,633 km^2 in 2050.

1.7. Directions for future research

The availability of better estimates and projections of urban land cover in all countries and regions will make it possible to study the effects of present and future urban land cover on several important global issues: (1) the effect of urban land cover on carbon emissions; (2) the projected loss of arable land, cultivated land, and land in permanent crop production due to urban expansion; and (3) the vulnerability of low-lying coastal cities to the rise in ocean levels. We present our initial findings regarding these three issues without a detailed discussion, leaving their further analysis for future research.

1.7.1. The effect of urban land cover on carbon emissions

We tested the following hypothesis: other things being equal, the larger the amount of land in urban use in a country, the larger the total volume of its CO_2 emissions. We constructed a multiple regression model with total carbon emissions in the country in 2000 as the dependent variable and the country's GDP and total urban land cover as independent variables (all in logarithmic form). Variations in GDP amongst 148 countries in 2000 explained 89% of the variation in CO_2 emissions. A 10% increase in GDP and a 10% increase in urban land cover are associated with 5 and 6% increases in CO_2 emissions respectively. The model, although quite simplistic, does not appear to suffer from multi-collinearity problems.

1.7.2. The projected loss of arable land due to urban expansion

In the world at large, the area in urban use amounted to 3.93% of the arable land and permanent crop area in the year 2000. Cities thus occupied less than one twenty-fifth of the area occupied by arable land on the planet in 2000. The ratio of urban land to arable land was higher in more-developed countries (5.1%), than in less-developed countries (3.2%). Amongst world regions, it was highest in Latin America and the Caribbean (5.6%) and in Europe and Japan (5.6%), and lowest in Sub-Saharan Africa (1.5%).

Amongst the countries that had large cities in 2000, five countries had more land in urban use than arable land: Singapore, Bahrain, Kuwait, Djibouti, and Qatar. Urban land cover in three countries was more than half the arable land cover: Puerto Rico, Iceland, and Belgium. Urban land cover in 12 countries comprised 20–50% of arable land cover, amongst them the Netherlands, Japan, and the United Kingdom. Urban land cover in 14 more countries comprised 10–20% of arable land cover, amongst them the Republic of Korea, Venezuela and Germany. Urban land in 29 additional countries comprised 5–10% of arable land cover, amongst them Egypt, the United States and Brazil. Urban land cover in 45 more countries comprised 2–5% of arable land cover, amongst them Iran, Argentina, and China, and the Russian Federation. Urban land cover in 35 more countries comprised 1–2% of arable land cover, amongst them India and Canada. The 12 remaining countries had urban land cover that comprised less than 1% of arable land cover, amongst them Tanzania and Afghanistan.

In a future research project, we plan to use the *MOD500* land cover map for the year 2000 as our database for estimating the projected loss of arable land due to projected urban expansion. This land cover map for 2000 contains information on 16 different types of land cover, including several types of land covers associated with cultivated and permanent crop land. We plan to create equidistant buffers around every one of the 3646 urban clusters in our universe of large cities that correspond to the projected increase in urban land cover. We will then superimpose these buffers on the *MOD500* land cover map to estimate how much cultivated land will be lost to urban expansion in every country in every decade assuming the proportionate growth, i.e. identical population growth rates, of cities of all population sizes in any given country. Early tests of our projection model suggest that, on average, *half* the area of projected urban expansion will take place on cultivated land; and that the percentage loss of cultivated land in different cities is not normally distributed but almost evenly distributed amongst different percentage deciles: the number of cities where less than 10% of urban expansion is likely to take place on cultivated land is similar to the number of cities where 40–50% will take place on cultivated land and to the number of cities where 90–100% will take place on cultivated land.

1.7.3. The vulnerability of low-lying coastal cities to the rise in ocean levels

The available assessments of the amount of urban land cover in low-elevation coastal zones appear to be imprecise, probably tending to over-estimate it. Current estimates use the only global elevation model now available, an elevation model with a $\pm$16-m error, too coarse a model in our view for studying vulnerability to the expected rise in ocean levels of the order of 1 m. We conjecture that our new database, and possibly newer *Mod500* global maps for 2005 or 2010, together with more precise elevation data now expected to be available by 2014 (see, e.g. www.infoterra.de/elevation_models), can provide a better estimate of urban population and urban land cover in low-lying coastal areas than the currently available estimates. We now estimate that 10% of global urban land cover is located within 4 km from the coast, 20% within 10 km, 30% within 21 km, and 50% within 116 km. We estimate a total urban land cover of 222,000 km^2 within 40 km of the coast in the year 2000, but we cannot really tell how much of it is vulnerable to rising ocean levels without a much more precise elevation model.

Future research on these three issues may shed important light on the social, economic, and environmental consequences of the projected global urban expansion in the years to come.

1.8. Conclusion: making room for a planet of cities

In this paper, we seek to provide, for the first time, the quantitative dimension of future urban expansion, so as to present what we believe to be the minimally necessary information for an intelligent discussion of plans and policies to manage it, whether to reverse it, contain it, guide it, or let it be. The prevailing paradigm guiding urban planning in the recent past has been the 'smart growth' paradigm, whose main thrust, for a variety of reasons, has been to *contain* urban expansion in one way or another. Our contention is that this paradigm is ill-suited for countries that are still in the midst of rapid urbanisation, a process that has largely come to an end in more mature economies. Our main concern is with the developing countries, where most urban population growth (and most urban expansion) will take place in coming decades, and where most of this growth will consist of poor people. Effective containment strategies that champion sustainability and that are truly capable of constraining land supply for urban development are also likely to affect land markets in ways that will adversely affect the access of the urban poor to affordable housing. This is a cause for concern because it situates the three key goals of urban planning – efficiency, equity and sustainability – in direct conflict with each other.

The availability of reliable data regarding the amount of land that is likely to be needed to accommodate the growing population of many cities in the developing countries is clearly necessary for informed and balanced decision-making at the present time, decision-making that gives these three goals their proper weights. Our study offers an alternative urban planning paradigm that gives the equity goal its due weight without compromising sustainability. This paradigm is based on making a realistic assessment of the lands that will be needed to accommodate projected population growth in an efficient and equitable manner without compromising sustainability. Given the expected pace of projected urban expansion, it also calls for a type of planning that is minimalist in nature, focused on making the absolute minimum preparations for urban expansion now instead of spending years planning for that expansion whilst it is actually taking place.

Our recommended strategy for managing urban expansion in the coming decades is discussed at greater length in the Policy Focus Report published by the Lincoln Institute of Land Policy titled *Making Room for a Planet of Cities* (Angel, Parent, Civco, & Blei, 2011). It rejects any planning agenda for cities, especially those in developing countries that are still urbanising rapidly, that takes the need for urban containment as a given. The refusal to plan for urban expansion at realistic densities as a matter of principle, in the belief that it should not occur, in the hope that it will not occur, or in fear of the ire of those who oppose it, may be a costly mistake. That said, allowing densities in developing-country cities to decline to the very low levels now prevalent in the U.S., for example, may be a detrimental error too. Urban densities in developing-country cities – now averaging more than *four times* those of the U.S. – must remain within a range that can support public transport so as to limit carbon emissions, and that can allow cities to accommodate their expected population growth whilst keeping housing plentiful and affordable and whilst conserving land and energy.

We believe that the adoption of the urban containment paradigm in developing countries may be counterproductive at the present time. It may lead to estimates of land needs and infrastructure investments that are insufficient for, say, 20–30 years of planned expansion at realistically projected densities. Cities may thus continue to expand in an unplanned fashion, failing to guide development in more desirable directions, failing to protect even a limited selection of high-priority open spaces from development, creating land supply bottlenecks that keep the cost of land and housing out of reach for the urban poor, and failing to secure the necessary rights-of-way for the arterial roads that can eventually carry public transport and basic infrastructure into newly inhabited areas. It may indeed be more realistic and more sensible for the rapidly growing cities in developing countries to refrain from curbing their expansion, to assume instead that densities can continue to decline slowly whilst remaining sustainable, and to make adequate room for accommodating their expected populations.

2. Global urban land cover and the universe of *large* cities

2.1. Mapping urban land cover on a global scale

Despite great advances in remote sensing and satellite imagery, there is no reliable *global* map as yet that could accurately identify all land in urban use, in other words all land occupied by the built-up areas of towns, cities, and metropolitan areas. As a result, we do not yet have accurate estimates of the amount of land in urban use in different countries. Without such estimates, we cannot explain the variations in urban land cover amongst countries, nor can we project the amount of land that will be needed in the coming decades to accommodate the burgeoning urban population in many of these countries. Such estimates and projections are important, at the very least, for making the necessary legal, institutional, and infrastructural preparations for urban expansion, for assessing the effects of urban expansion on arable lands and on carbon emissions, or for evaluating the vulnerability of low-lying urban areas to rising sea levels.

That said, there has been considerable progress in the development of global urban land cover maps. In recent years various academic, governmental, and commercial groups have created no less than *eight* global maps and two related maps of the *built environment*, most of them at a reasonably high resolution of 250–1000-m pixel size. The information on these maps is summarised in Table 2.1. The eight global urban maps and two urban-related maps for Paris circa 2000 are shown in Fig. 2.1.

These maps identify impervious surfaces – namely pavements, roofs and compacted soils – that are closely associated with the built environment. The built environment identified in these maps consists of three major classes: urban areas (cities and their suburbs), rural areas (villages and farms), and inter-city transport (roads, railways and canals). Remote sensing maps with the pixel sizes mentioned above can typically detect relatively large urban areas that are many pixels in size, but are less reliable in detecting villages and small

Table 2.1
Eight global maps and two related maps of the built environment, 1992–2005.

Map and citation	Label	Source	Resolution (million)	Total area of built environment (km^2)
Vector Map Level Zero (Danko, 1992)	VMAP0	US National Geospatial-Intelligence Agency	1:1	276,000
Global Land Cover 2000 v1.1 (Bartholome & Belward, 2005)	GLC00	European Commission Joint Research Centre	988	308,000
GlobCover v2 (Arino et al., 2007; ESA, 2008)	GLOBC	European Commission Joint Research Centre	309	336,000
History Database of the Global Environment v.3 (Goldewijk, 2005)	HYDE3	Netherlands Environmental. Assessment Agency	9000	532,000
Global Impervious Surface Area (Elvidge et al., 2007)	IMPSA	US National Geophysical Data Centre (US-NOAA)	927	572,000
MODIS Urban Land Cover 500 m (Schneider, Friedl, & Potere, 2009)	MOD500	Univ. of Wisconsin, Boston Univ. (US-NASA)	463	657,000
MODIS Urban Land Cover 1 km (Schneider et al., 2003)	MOD1K	Boston University (US-NASA)	927	727,000
Global Rural–Urban Mapping Project, alpha (CIESIN, 2004)	GRUMP	Earth Institute at Columbia University	927	3,532,000
Nighttime Lights v2 (Elvidge et al., 2001)	LITES	National Geophysical Data Centre (US-NOAA)	927	NA
LandScan 2005 (Bhaduri, Bright, Coleman, & Dobson, 2002)	LSCAN	US Oak Ridge National Laboratory (US-DOE)	927	NA

Source: Adapted from Potere et al. (2009), Table 1.

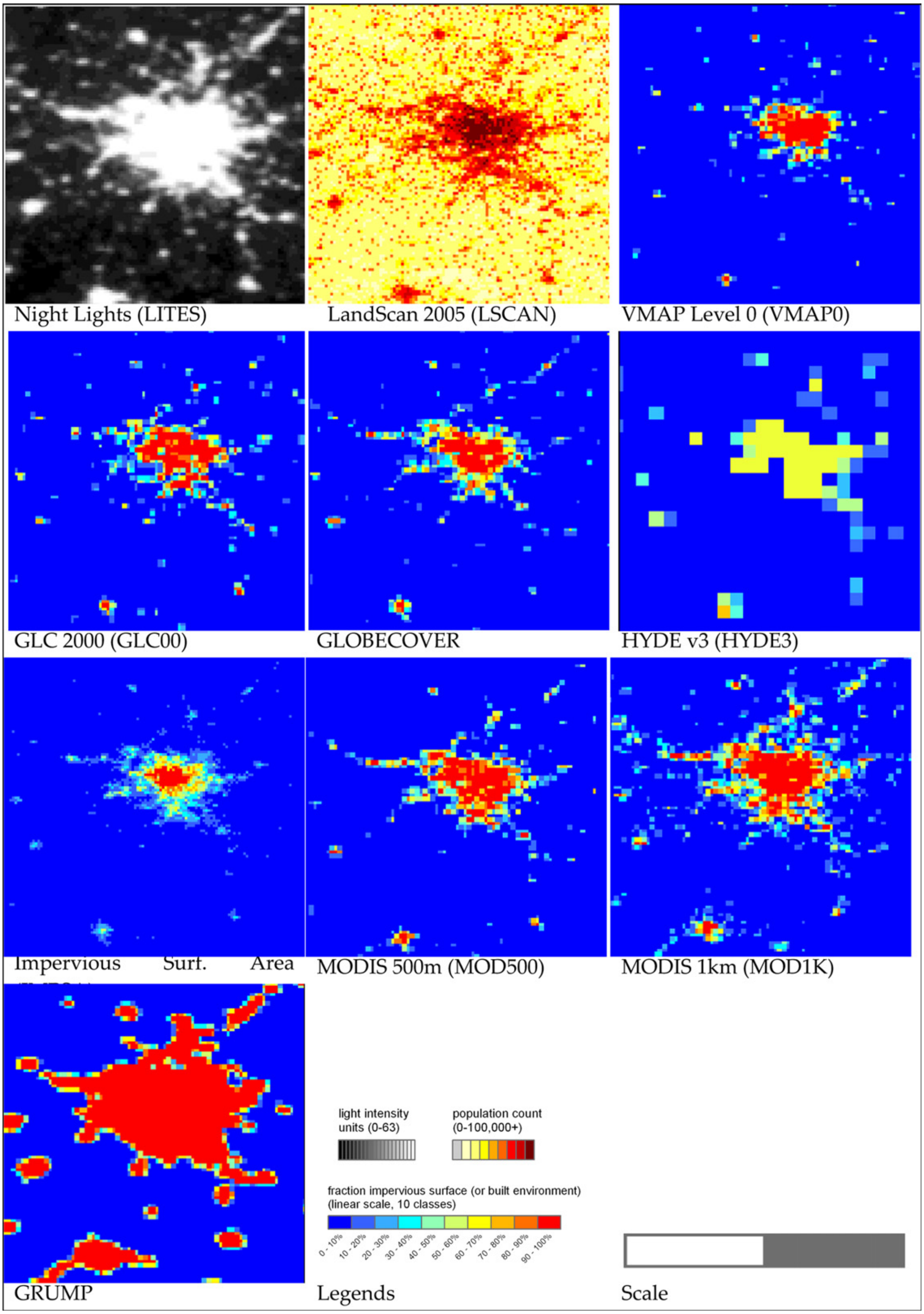


Fig. 2.1. The eight global urban maps and two urban-related maps for Paris, France, circa 2000.
Source: Adapted from Potere et al. (2009), Fig. 1.

towns, farms, or inter-city transport. This is the reason that descriptions of these maps in the remote-sensing literature commonly use the terms 'built environment' and 'urban' interchangeably, even though the maps identify as 'urban' many areas that are clearly not parts of cities by any common-sense definition of what constitutes a city.

Apart from the unfortunate confusion between 'built environment' and 'urban', it has been quite difficult to tell how accurate these eight maps are. As Table 2.1 shows, the individual map estimates of the total area of built environment in the world vary by as much as a digital order of magnitude: from 276,000 km^2 in Vector Map Level 0 (VMAP0) to 3.532 million km^2 in the Global Rural–Urban Mapping Project (GRUMP). Needless to say, these wide variations raise serious questions regarding the accuracy of these maps and render them less than useful for serious analysis.

Potere et al. (2009) set out to test the accuracy of these global maps with a two-tier assessment. The first-tier assessment compared these maps with a set of 30-m-resolution maps of cities based on *Landsat* imagery. The second-tier assessment tested the *Landsat*-based maps for accuracy with 10,000 *Google Earth* validation sites.

Two sets of *Landsat*-based city maps were used for comparison with the global urban land cover maps: A global sample of 120 cities studied by Angel et al. (2005) and a collection of 24 cities studied by Schneider and Woodcock (2008), yielding a total of 140 distinct maps of the built-up areas of cities that had populations in excess of 100,000 in the year 2000. These comparisons made it possible to determine which of the global land cover maps better approximated the *Landsat*-based maps.

Potere et al. then tested the accuracy of the detailed *Landsat*-based maps of these 140 cities by expert inspection of 10,000 validation sites using *Google Earth*. Built-up pixels in the maps were indeed built up pixels in *Google Earth* 91% of the time (user accuracy), and built-up pixels in *Google Earth* were correctly identified as built-up 89.3% of the time (producer accuracy). These maps were therefore found to be accurate enough for testing the accuracy of the global maps.

One of the accuracy tests involved checking whether the global maps omitted any of these 140 cities altogether, namely did not have a cluster of some minimum size (5 km^2) associated with them. For that test, Potere et al. increased the number of cities to 247, adding 107 cities whose contours were roughly identified in *Google Earth* and their areas were calculated. All global maps were tested for omission of any of the 247 cities on the combined list. Only two global maps, MOD500 and IMPSA, successfully mapped all the 247 cities.

A second accuracy test involved comparing the total built-up area in the *Landsat*-based maps for the 140 cities identified earlier with the area of their associated clusters in the global urban land cover maps. The results of this comparison are summarised in Figs. 2.2 and 2.3. Figs. 2.2 and 2.3 show quite clearly that the areas calculated on the MOD500 map most closely approximated the areas calculated on the *Landsat*-based maps. The GRUMP map clearly overestimated the built-up areas of cities, and the remaining maps either underestimated them or had a high degree of variability in their area calculations.

In addition to these two basic accuracy tests, Potere et al. conducted a number of tests that compared the global maps with the 140 *Landsat*-generated maps on a pixel-by-pixel basis to determine map agreement. The central conclusion of their paper is as follows: "amongst the eight maps examined for accuracy (summarised in Table 2.1), the MOD500 map was found to be the most accurate by all three accuracy measures employed: (1) it did not omit any city of a global stratified sample of 247 cities; (2) it had the highest level of agreement ($R^2 = 0.90$) with the urban extent defined by Landsat-based maps of 140 cities (previously verified by *Google Earth* imagery in tier one); and (3) it had the highest per-pixel agreement with the aggregated *Landsat*-based maps" (Potere et al., 2009, p. 6553).

The close correspondence between the MOD500 map and the higher-resolution *Landsat* maps for Paris, France, is illustrated in Fig. 2.3. The two maps cover approximately the same area, but the *MOD500* map does not identify the smaller built-up pixels that are identified on the urban fringe by the higher-resolution *Landsat* map. Still, there is no question that the *MOD500* map provides a very accurate depiction of the built-up areas of cities, especially *large cities*, defined in this article as cities that with populations of 100,000 people of more. Our estimates of urban land cover, as well as our projections, are therefore based on this *MOD500* map. To the best of our knowledge, this map provides the most reliable and the most realistic estimates of urban land cover at the present time. In the following section, we explain how the MOD500 map was used in this study in a manner that better distinguishes *urban* land cover from *non-urban* impervious surfaces in villages and farms that should not be considered 'urban'.

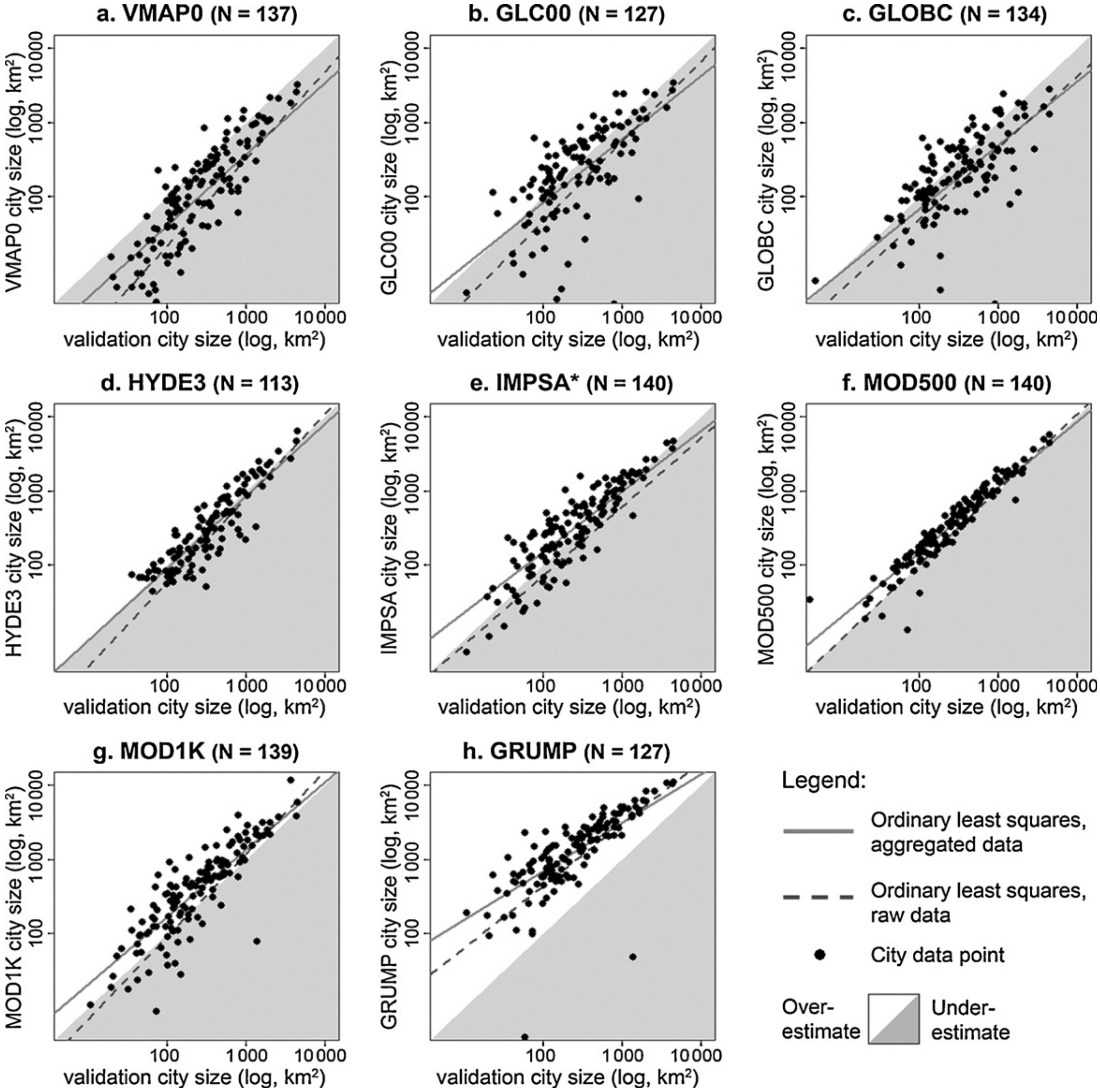


Fig. 2.2. Scatter-plots of validation of city size (in km^2) as calculated from *LandSat* imagery and as calculated by eight global urban maps (log–log scale).
Source: Potere et al., Fig. 2.

2.2. *Population and urban land cover in the universe of large cities*

As noted earlier, for purposes of this discussion we define cities with populations of 100,000 or more circa 2000 as *large cities* and cities with populations of less than 100,000 circa 2000 as *small cities*. Large cities are to be distinguished from *mega-cities*, those few metropolitan areas across the globe that may contain, say, 10 million people or more. In the year 2000, for example, there were only 16 such metropolitan areas in the world (U.N., 2008, file 11a), compared to 3646 cities that contained 100,000 people or more.

We now have a map of MOD500 contiguous urban clusters with a 463-m pixel size that are associated with a total of 3646 *named* large cities and metropolitan areas in all countries. These cities had a total population of 2.01 billion people in 2000, and these population estimates came, for the most part, from Thomas Brinkhoff's *City Population* website (Brinkhoff, 2010). The estimates are associated with the *name* of the city or metropolitan agglomeration, but are not populations within a well-defined administrative boundary. In the absence of urban population data within specific administrative districts for the world at large, as well as digital maps of these districts, we

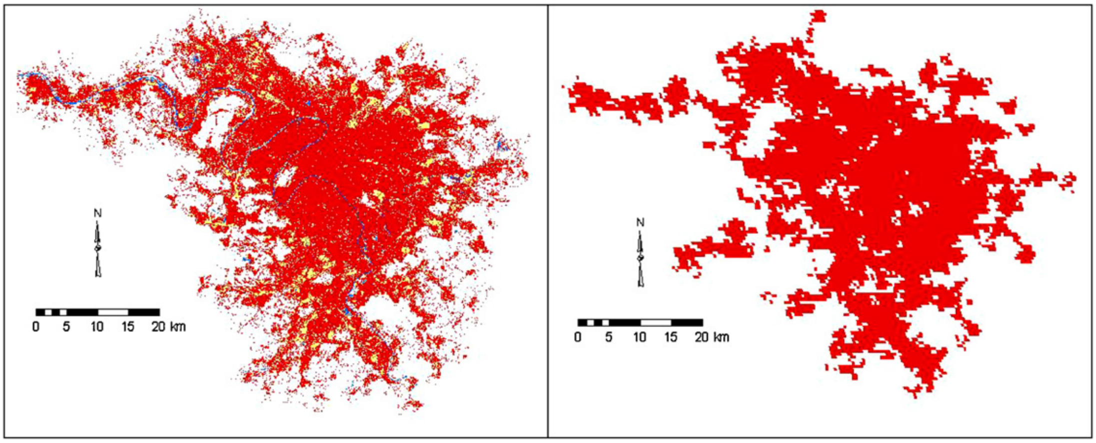


Fig. 2.3. *Landsat*-based (left) and *MOD500*-based (right) urban land cover in Paris, 2000.

assume that each population estimate for an urban agglomeration is associated with a particular MOD500 urban cluster, an assumption that may contain errors. According to our calculations, the urban clusters associated with large cities had a total built-up area of some 340,000 km^2. The number, the population, and the built-up area of large cities in different world regions are shown in Table 2.2. Their locations are shown in Fig. 2.4.

2.3. The universe of urban clusters

The built-up land cover class was extracted from the MOD500 land cover map and clusters of contiguous built-up pixels were converted into polygons. The coarse spatial resolution of urban pixels (463 m × 463 m) of the *MOD500* land cover map could not fully capture the contiguity of metropolitan areas as they were made up of groups of several disconnected, yet close, polygons. The land cover data may not discern roads linking a city to its suburbs through open spaces, for example, even though suburban polygons may belong to the same urban agglomeration. In this study, we assumed that built-up areas belonged to the same urban cluster if the distances between the centroids of their nearest-neighbour pixels were less than a maximum threshold. We assumed this threshold to be a function of the size of the built-up areas – the larger the built-up area, the farther nearby built-up areas were considered part of the same urban

Table 2.2
Regional data on the number, population and built-up areas of large cities, 2000.

Region	MOD500 estimate of total urban land cover, 2000 (km^2)	Large cities				
		Number of cities, 2000	Total population, 2000	Share of urban population, 2000 (%)	Total land cover, 2000 (km^2)	Total land cover as share of MOD500 estimate (%)
Eastern Asia and Pacific	91,010	891	458,050,151	89.2	39,858	43.8
Southeast Asia	27,564	196	107,298,112	52.2	12,883	46.7
South and Central Asia	64,876	539	287,046,836	65.9	29,705	45.8
Western Asia	26,848	157	89,553,199	73.8	12,999	48.4
Northern Africa	12,640	115	53,066,598	61.2	5342	42.3
Sub-Saharan Africa	28,228	258	131,900,462	63.5	12,820	45.4
Latin America and the Caribbean	93,541	403	258,850,267	66.3	43,279	46.3
Europe and Japan	167,162	796	400,011,554	66.4	85,710	51.3
Land rich developed countries	139,467	291	226,209,106	84.5	93,995	67.4
Developing countries	344,706	2559	1,385,765,625	70.7	156,886	45.5
Developed countries	306,630	1087	626,220,660	72.0	179,705	58.6
World	651,336	3646	2,011,986,285	71.1	336,591	51.7

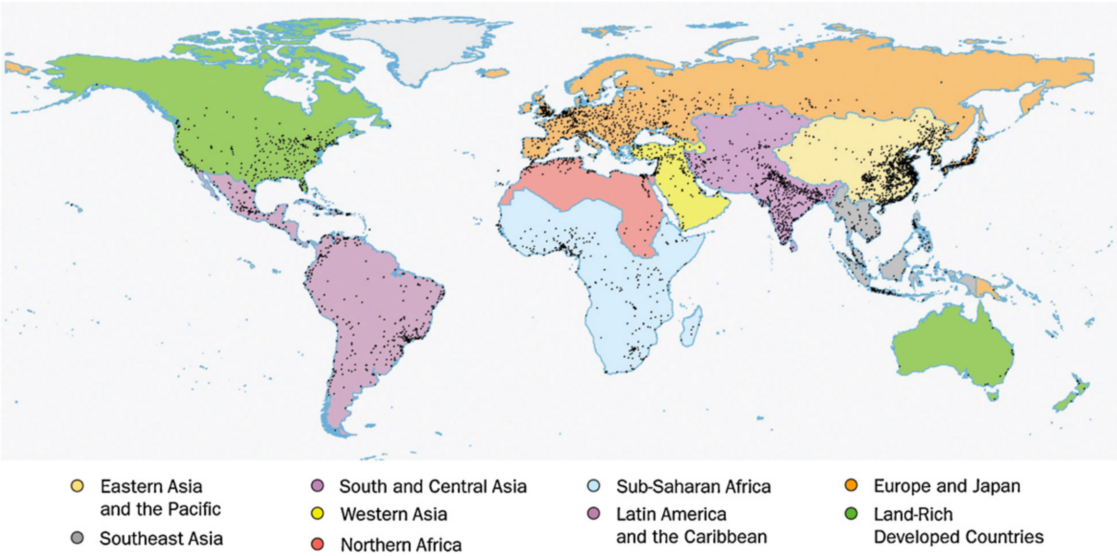


Fig. 2.4. The location of 3646 large cities in the nine world regions, 2000.

cluster. *ArcGIS* software was used to calculate distances amongst nearest-neighbour pixels and to determine which polygons belonged to the same urban cluster in the MOD500 land cover map.

The *distance of influence* of a built-up area of a given size was calculated from the figure on the right. The values used to construct Fig. 2.5 were determined using expert knowledge. An isolated built-up pixel in the MOD500 land cover map whose centroid was more than 2 km away, for example, from any large city cluster, was assumed to be a rural built-up area and was not added to any cluster smaller than 64,000 ha in area. But if the pixel was only 1 km away, for example, it was added to large cities with areas in excess of 16,000 ha but not to smaller cities with areas of less than 16,000 ha.

We created a buffer around each polygon with its width equal to the polygon's distance of influence. Built-up areas with overlapping buffers were then

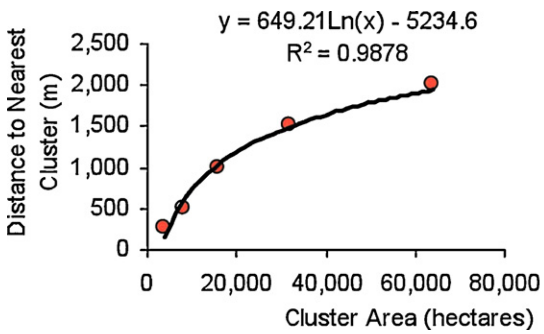


Fig. 2.5. Distance of influence as a function of cluster area.

combined into *urban clusters*. The process of creating urban clusters is illustrated in Fig. 2.6.

Whilst the MOD500 map identified built-up area clusters globally, it lacked information for the populations within cluster boundaries. The research team undertook the task of matching population figures to clusters by executing a global census of human settlements with populations over 100,000 and associating the latitude–longitude coordinates of these locations to the MOD500 map.

2.4. Constructing a universe of cities

The construction of our universe of large cities was based on three primary sources: the website www.citypopulation.de, administered by Thomas Brinkhoff and containing census figures for cities, agglomerations, and administrative divisions for 237 countries and territories; the U.N.'s *World Urbanisation Prospects–the 2007 Revision*, a United Nations publication listing the populations of urban agglomerations greater than 750,000 by country for the year 2000; and a previously assembled universe of 3943 cities with populations over 100,000 in the year 2000 (Angel et al., 2005).

Angel et al.'s (2005) universe of cities laid the foundation for a new universe of large cities. Data from Angel et al.'s list was scrutinised against a list of city names and populations developed from www.citypopulation.de. Following established practice, we employed an exponential interpolation to estimate year 2000 populations where population figures before and

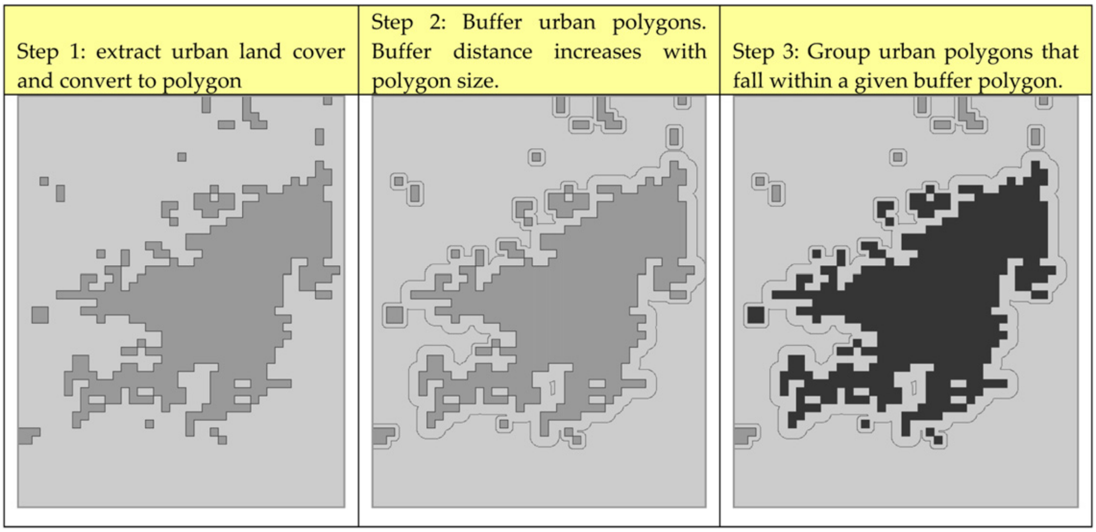


Fig. 2.6. The procedure for creating urban clusters from the MOD500 land cover map.

after year 2000 were available. Cities with populations greater than or equal to 100,000 on the www.citypopulation.de website were determined to comprise a corrected universe of large cities. Subsequently, entries on Angel et al.'s (2005) universe of cities but not on the website were eliminated in assembling the new universe, whilst entries on the website but not on Angel et al.'s (2005) list were added. Populations for entries on Angel et al.'s (2005) list were corrected to match those from the website. Rather than rely solely on the website for constructing a new large city universe, we retained Angel et al.'s (2005) list as a skeleton, primarily for the latitude–longitude data it already contained for its cities. This information was necessary for calculating cluster densities at a later stage of our research. Latitude–longitude information for new entries was obtained by creating *Google Earth* placemarks – spatial data points to which we added information on city name and population.

We assumed that Brinkhoff's city population website, replete with government census figures, provided a globally comprehensive and reliable source of information. Eleven countries lacked year 2000 population data on Brinkhoff's website (Afghanistan, Angola, Burundi, Ivory Coast, Gabon, Guinea, Libya, Myanmar, Nigeria, North Korea and Sudan), but these were countries for which comprehensive and reliable year 2000 data is very difficult to find. In general, we favoured using Brinkhoff's figure wherever possible, making our approach replicable. Figures from Angel et al.'s (2005) dataset, to our knowledge the best approximations of metropolitan populations for these countries, were used in the absence of www.citypopulation.de figures. This procedure yielded a revised universe of cities, but it also revealed vexing issues inherent to the type of population research undertaken in this study. Ultimately, we would have to modify several figures from our new universe so that they conform to the spatial extent of built-up clusters. As noted earlier, this can only be done if all population census data for all countries was associated with digital maps of census districts.

As of yet there is no reliable source for populations in urban agglomerations across the world that are made up of numerous cities. The United Nation's *World Urbanisation Prospects* lists population figures for 523 urban agglomerations with populations greater than or equal to 750,000 in the year 2000, and there is no similar list for urban agglomerations of less than 750,000 inhabitants. A number of countries report population at the metropolitan level or by agglomeration for populations between 100,000 and 750,000, yet many do not. In the context of this study, the absence of agglomeration-level or metropolitan-level population figures has proven to be problematic. A potential for error occurs when a large city is surrounded by smaller cities, towns, or villages with populations of less than 100,000. In such cases, the population associated with the cluster would underestimate the true number of inhabitants within the cluster boundaries. More precisely, a cluster would be associated with the population of the large city in the cluster, but not the population of small cities and towns also contained within the cluster. This is admittedly a source of possibly quite serious errors. Revisions to our new list, described below, attempted to address this problem.

The map of Castellón de la Plana (Castellón), Spain, is illustrative (see Fig. 2.7). This figure shows a cluster (in green) identified by the MOD500 and encompassing Castellón. A review of city populations in Spain identified Castellón as having a population 146,263 in the year 2000. Following our procedure, this became the population assigned to the MOD500 cluster. On closer inspection, however, the cluster was determined to contain at least three distinct administrative areas: Castellón de la Plana, Villarreal, Almazora, and in all likelihood, a handful of outlying villages. Strict reliance on our systematic approach to population would have underestimated the number of inhabitants represented by this particular cluster. It was later determined that approximately 60,000 people reside in Villarreal and Almazora. We resolved that a refined approach to the population of cities was necessary as these examples came to light.

Fig. 2.7. Castellón de la Plana cluster (shown in green, above). Cities within the cluster: Castellón de la Plana, Villarreal, and Almazora (below). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

2.5. Refining the universe of cities

We examined the possibility of error in our newly created universe by carefully observing population differences for cities in both Angel et al. (2005) and Brinkhoff's *City Population* data. Angel et al.'s (2005) list was a compilation and revision of two previous lists: a United Nation's Human Settlements Programme (U.N. Habitat) list of 4574 metropolitan areas in excess of 100,000 and a list of 2884 cities with populations over 100,000 for the year 2000 prepared by Professor Vernon Henderson of Brown University. The great disparity in number separating these two lists reflects the difficulties in identifying distinct metropolitan areas on a global scale. We were primarily concerned with cases where the population figures for cities in Angel et al.'s list were larger than those in Brinkhoff's list, believing that the figures from Brinkhoff's list might correspond to places with small administrative boundaries but large metropolitan areas. We posited that Angel et al.'s (2005) list may have identified agglomeration populations more accurately, making these figures better suited to our study. Using *Google Earth* to assess the spatial extent of clusters, as well as secondary research focused on populations of individual cities and metropolitan areas, we examined differences between the two lists on a case by case basis. Population figures from Angel et al. were chosen in favour of www.citypopulation.de only when clear and compelling evidence suggested that figures culled from the latter poorly reflected the true metropolitan population represented by clusters. Regrettably, perhaps, this exercise highlighted the fact that for now, in the absence of administrative area maps, a systematic effort to report urban populations at the metropolitan level on a global scale was still out of reach.

Additional revisions to our population figures were required after we matched city placemarks to clusters. Many of the larger clusters contained multiple placemarks and had to be tested for double counting. These clusters typically overlaid expansive urban areas that were reported as urban agglomerations with population greater than or equal to 750,000 in the United Nation's *World Urbanisation Prospects*. Clusters corresponding to *World Urbanisation Prospects* agglomerations were assigned the U.N. agglomeration figures and additional placemarks corresponding to city names previously within such clusters no longer contributed to the cluster population. As before, investigation into the spatial extent of urban clusters as well as secondary research for individual cities was used to ensure that the population figures matched the clusters to which they would be assigned.

2.6. Matching city locations and populations to urban clusters

Following the completion of the new list of city names, their associated population in the year 2000, and their spatial coordinates, we created a map of geographic placemarks for each city: a spatial file with latitude–longitude, city name and population data for each large city in the universe. We then plotted the MOD500 built-up area clusters on the same map. Combining the two maps resulted in one of two scenarios: (1) the placemark fell within a cluster, resulting in a positive match; or (2) the placemark fell more than 1.5 km outside a cluster, resulting in a negative match. Random testing showed that positive matches were accurate, namely that they correctly linked placemark names to clusters associated with an identifiable urban area with that name in *Google Earth*.

The inspection of each negative match showed that two types of error could explain all cases. In the first type, MOD500 failed to detect the built-up area associated with a particular city, and therefore did not associate any cluster with it. Whilst MOD500 is indeed the most accurate global land cover map to-date, it still contains errors of omission. The absence of built-up area clusters in the combined map meant that city placemarks could not be matched. We sought to address this problem by creating additional built-up area clusters for large cities by drawing contours around identifiable urban areas in *Google Earth*. Using historical *Google Earth* imagery circa 2000, we traced polygons of the built-up area for each large city that had no corresponding cluster in the MOD500 map. 311 such polygons, or 8.5% of the total number of large cities in the universe, were created in this fashion by the research team.

Errors of the second type, where the locations of placemarks fell outside clusters' 1.5-km buffer, could be remedied without major interventions. The existence of a MOD500 cluster associated with a city name was the main difference between the first and second type of errors. In these cases, corrected latitude–longitude coordinates were assigned to placemarks in the second group and they were positively matched to clusters in an iterative process.

Placemark names and their associated populations determined the names and populations ascribed to clusters. Several clusters contained more than one placemark, however, and these clusters assumed the name of the city with the largest population. The populations of clusters with multiple placemarks were the summation of all placemark populations within the cluster. Every cluster with multiple placemarks was inspected by the research team for double-counting, and efforts were made to prevent double-counting wherever possible.

Correcting for these two types of errors and ensuring that all positive matches were indeed accurate resulted in a matched universe of cities. All city names and their associated populations were now associated with an urban cluster. Using *ArcGIS* software, we then calculated the areas of matched clusters, assigned country names to city clusters, and computed cluster densities based on their populations. We now had the necessary information for analysing the amount of land in urban use and the population density in large cities in all countries that had large cities.

It is important to note in closing that the MOD500 urban land cover map also contains serious errors of commission: In addition to identifying a large number of the rural built environment as urban, it often creates urban clusters that are much larger than the urban land cover seen in *Google Earth*, for example. Checking all MOD500 clusters against urban land cover in Google Earth proved to be too time consuming. We intentionally refrained from correcting commission errors selectively, especially in cities with very low densities, as that will have biased the MOD500 map by eliminating all, or most, of the very low densities in the map. As a result, the calculated built-up area densities of some cities are unreasonably low. In the future, more accurate urban land cover maps coupled with accurate urban population counts associated with mapped administrative districts would certainly yield better results.

3. Urban land cover in small cities

We already noted earlier that we cannot assume that *all* land identified in the MOD500 land cover map is, in fact, in cities and towns. Since the map designates all land with impervious surfaces as 'urban', it must necessarily include considerable amounts of village and farmland as 'urban', since one half of the world's population still lives in villages and farms. The MOD500 map must therefore contain clusters that correspond to non-urban areas, namely to dense clusters of villages. This is particular evident in the case of China, for example, where many village clusters are identified by MOD 500 as 'urban' (see Fig. 3.1).

In this section of the paper, we focus on calculating the amount of land cover in small cities that are not villages. We have already identified all the MOD500 clusters that correspond to named large cities. Since we cannot identify all the tens of thousands of small cities by name, we must limit ourselves to estimating the *total amount of land in urban use in small cities* in each country rather than identifying them individually and calculating their land area.

The method we have chosen to arrive at these estimates for each country proceeds as follows: (a) we calculate the total population in small cities as the difference between the total urban population and the total population of large cities in the country; (b) we estimate the population density in small cities in the country; and (c) we arrive at an estimate of the total urban land cover in small cities and towns as the ratio of their total population and their population density.

3.1. Estimating the total population in small cities in every country

We first discuss our method for estimating the total population of small cities in each country and region. We can see in Table 3.1 presented earlier that the shares of the total urban population in large cities in different

Fig. 3.1. A dense cluster of villages near Beijing, China (left), identified as 'urban' in the MOD500 map (right).

Table 3.1
Observed and estimated numbers of cities and average city populations in different city population size ranges for the world as a whole and for two world regions, 2000.

City population size range		World		Eastern Asia and Pacific		Latin America and Caribbean	
From	To	Number of cities	Average city size	Number of cities	Average city size	Number of cities	Average city size
Observed							
100,000	200,000	1744	137,785	395	137,777	183	139,312
200,000	400,000	913	275,588	213	271,831	102	269,219
400,000	800,000	497	555,391	161	556,188	54	564,229
800,000	1,600,000	279	1,123,943	75	1,159,605	33	1,108,813
1,600,000	3,200,000	125	2,207,454	35	2,174,378	19	2,214,397
3,200,000	6,400,000	51	4,302,991	6	4,566,812	6	3,942,717
6,400,000	12,800,000	25	8,901,438	4	8,809,738	4	9,402,750
12,800,000+		12	17,712,296	2	15,234,370	2	17,747,839
Estimated							
12,500	25,000	17,261	17,260	7459	16,676	1462	16,676
25,000	50,000	8399	34,519	3238	33,352	761	33,352
50,000	100,000	4086	69,038	1406	66,704	396	66,704
100,000	200,000	1993	137,791	588	137,619	198	139,313

regions range from 45 to 90% with an average of 69 ± 4%. For the world at large, large cities account for 71% of the urban population. We should expect the respective shares of the urban population in small and large cities in all regions to be quite similar, but this is apparently not the case, a fact that cannot be easily explained. There is no *a priori* theoretical explanation of why the share of large cities in the total urban population should vary amongst different regions, and in the absence of such an explanation, we should expect it to be the same. Empirical observations, such as those associated with *Zipf's Law* (Zipf, 1949), for example, do suggest that they should be the same or, at the very least, similar.

In fact, when we divide the entire universe of large cities into city population size ranges, so that the upper limit of the size range is simply double the lower limit, we observe two empirical regularities, better known as 'power laws' (see, e.g. Clauset, Shalizi, & Newman, 2009): (1) the observed average city population in a given range is roughly double that of the range below it; and (2) the observed number of cities in the range is roughly half that of the range below it. These regularities are shown in Table 3.1 and Fig. 3.2 for the world at large, for Eastern Asia and the Pacific, and for Latin America and the Caribbean. They are similar for all other regions.

The above table and figure show that the observed average population in consecutive size ranges roughly doubles whilst the observed number of cities is halved. Assuming that the log–log relationship between the number of cities and the average city population in every range is linear – namely, that the power law holds in the lower ranges as well – we estimated the number of cities and the average city populations for three lower ranges as shown. It is possible, however, that this relationship is not linear: it may well be that the expected number of cities in the lower ranges in Eastern Asia and the Pacific, for example, does not double as average city population declines. In other words, it may be that, as observed with other phenomena, the power law holds in the middle ranges but fails at both edges of the distribution.

Still, why the share of the total urban population in large cities varies so much amongst regions and countries remains a mystery. It may have to do with the assignment of different benchmarks to distinguish 'urban' from 'rural' in different countries; it may have to do with unreliable census reporting in different countries; it may have to do with errors in the calculation of the total urban populations in every country by the U.N. Population Division; and, as noted above, it may have to do with the failure of the power law at the lower ranges. Finally, it is also possible that there are inherent structural differences between hierarchies of cities in different countries and regions, differences that cannot be explained yet but cannot be ignored either. This problem is left unsolved and open for further investigation by interested researchers.

For now, we have chosen to accept both the U.N. and the www.citypopulation.de figures without questioning them. The total population in small cities in

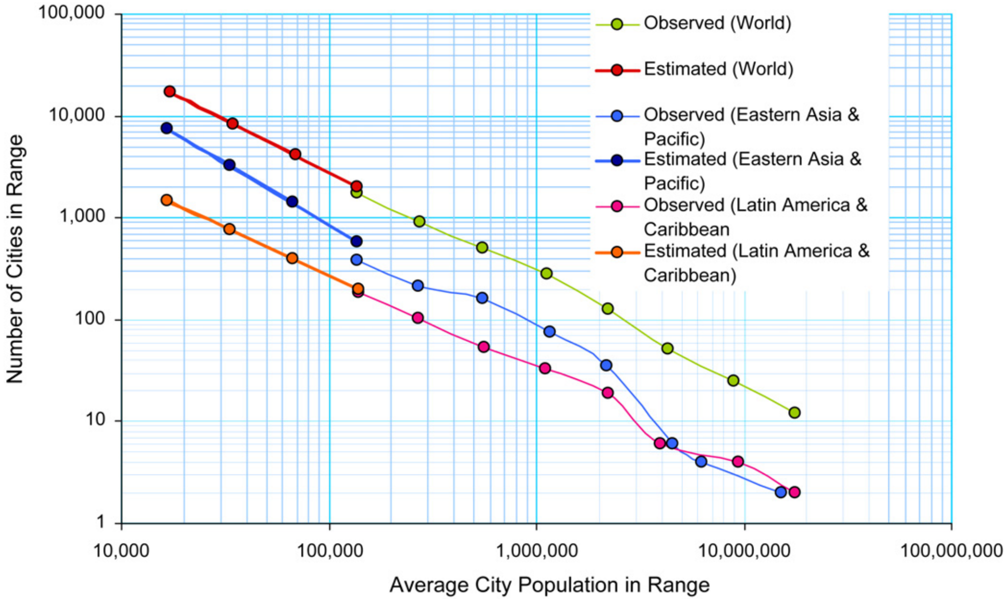


Fig. 3.2. Observed and estimated numbers of cities and average city populations in different city population size ranges for the world as a whole and for two world regions, 2000.

every country is then taken to be the difference between the total urban population estimated by the U.N. and the total population in large cities estimated by www.citypopulation.de. In the cases of two countries, this difference yields a negative number: In Libya, the population in large cities is 4.67 million and the total urban population is 4.08 million. In Japan, the population in large cities is 84.5 million and the total urban population is 82.7 million. In two additional countries, Singapore and New Caledonia, the difference is small and negative and probably due to different estimates of the total population in single large cities. In all four cases we have equated the total urban population to the total population in large cities, therefore taking the population in small cities to be equal to 0. In all other countries, the difference is positive. The total urban population and the population in large and small cities for all world regions are shown in Table 3.2.

3.2. Estimating urban population densities in small cities

The relationship between density and city population size was already established in Angel et al. (2010) in their study of a global sample of 120 cities. They found

Table 3.2
The total urban population and the population in large and small cities for all world regions, 2000.

Region	Urban population, 2000	Total population in large cities, 2000	Share of urban population in large cities, 2000 (%)	Total population in small cities, 2000	Share of urban population in small cities, 2000 (%)
Eastern Asia and Pacific	513,609,025	458,050,151	89.2	55,558,874	10.8
Southeast Asia	205,501,689	107,298,112	52.2	98,203,577	47.8
South and Central Asia	435,376,204	287,046,836	65.9	148,329,368	34.1
Western Asia	121,319,801	89,553,199	73.8	31,766,602	26.2
Northern Africa	86,642,957	53,066,598	61.2	33,576,359	38.8
Sub-Saharan Africa	207,570,819	131,900,462	63.5	75,670,357	36.5
Latin America and the Caribbean	390,328,849	258,850,267	66.3	131,478,582	33.7
Europe and Japan	602,418,651	400,011,554	66.4	202,407,097	33.6
Land rich developed countries	267,667,515	226,209,106	84.5	41,458,409	15.5
Developing countries	1,960,349,344	1,385,765,625	70.7	574,583,719	29.3
Developed countries	870,086,166	626,220,660	72.0	243,865,506	28.0
World	2,830,435,510	2,011,986,285	71.1	818,449,225	28.9

that, other things being equal, a doubling of the city population is associated with a 19 ± 1% increase in density. We repeated their modelling of densities with the new universe of 3646 cities dataset. We found that in the entire universe of large cities, on average, a doubling of the city population is associated with a 16.0% increase in density (see Table 5.9). We used this newer density-population factor in generating our estimates.

The density metric of interest in estimating urban land cover is *overall density*, defined as the ratio of the total urban population and total urban land cover in a given area. The total population in small cities in every country and every region is known. Total urban land cover in small cities is then calculated as the ratio of the total population to the overall density in small cities. In this section, we estimate the overall density in small cities in every region from information on the overall density in large cities, the median city population in large cities, the median city population in small cities, and the density-population factor introduced in the previous paragraph. Our general conclusion, as we shall show below, is that overall densities in small cities are *roughly half* those in large cities.

Fig. 3.3 shows the average density, the median density, and the overall density in large cities for all world regions. As the figure shows, the average densities in every region were found to be higher than median and overall densities, yet median and overall densities were found to be quite similar, suggesting that median density is a better measure of the central tendency of densities than average density.

We associate the overall density in large cities in each region with a typical city in the region with a population equal to the median population in large cities in the region. To determine the overall regional density in small cities, we need to decide on the median population size of small cities in the region. From the data on medians calculated during the construction of Table 3.1 (not shown), we found that the median population size in each range is 0.89 ± 0.01 of the mid-range population. Namely, for the city population range 200–400,000, for example, the mid-range is 300,000 and the median city population size is 0.89 × 300,000 = 267,000. We used that factor to calculate the median population of small cities. We assumed that small cities have populations ranging from 10,000 to 100,000. The mid-range population in small cities is therefore 55,000, and the median population is 0.89 × 55,000 = 48,940. Using this figure, we could now calculate the overall density in small cities in all regions. For the world at large in the year 2000, for example, the median city population N_L and the overall density (in persons per hectare, or p/ha) Δ_L in large cities in 2000 were 201,329 and 59 p/ha respectively. Given that the median

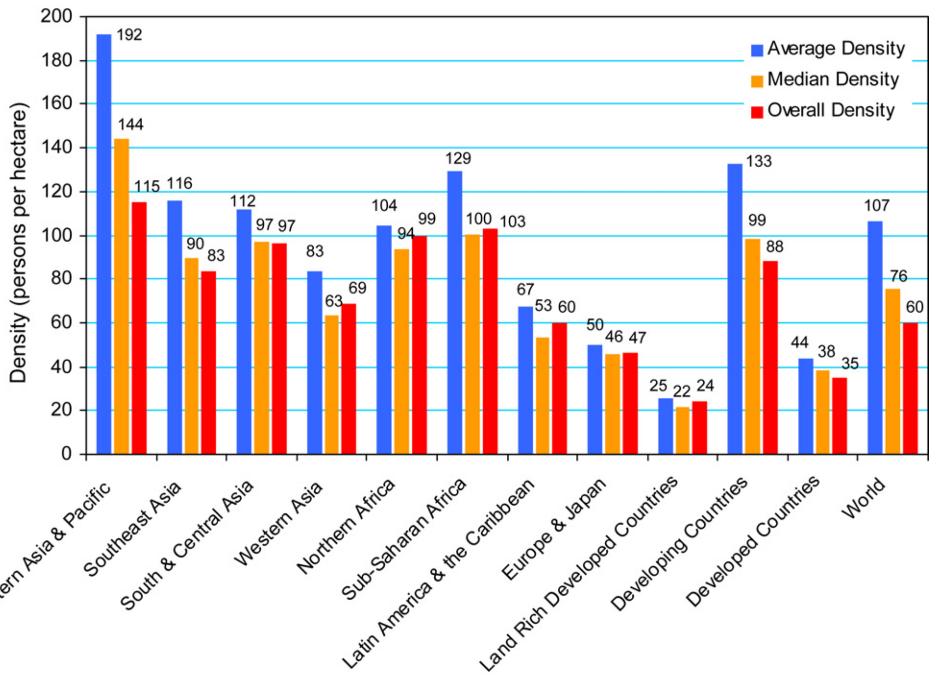


Fig. 3.3. A comparison of average density, median density, and overall density in large cities in all world regions.

Table 3.3
Density metrics for large cities and estimated overall density in small cities for world regions.

Region	Average density in large cities	Median density in large cities	Overall density in large cities	Median population in large cities	Overall density in small cities	Regional L–S overall density ratio
Eastern Asia and Pacific	192	144	115	225,723	55	0.48
Southeast Asia	116	90	83	175,821	47	0.56
South and Central Asia	112	97	97	193,725	51	0.53
Western Asia	83	63	69	232,744	32	0.47
Northern Africa	104	94	99	165,059	58	0.58
Sub-Saharan Africa	129	100	103	209,950	52	0.50
Latin America and the Caribbean	67	53	60	223,492	29	0.48
Europe and Japan	50	46	47	200,578	24	0.52
Land rich developed countries	25	22	24	243,667	11	0.45
Developing countries	133	99	88	208,895	45	0.51
Developed countries	44	38	35	211,034	17	0.50
World	107	76	60	209,468	30	0.50

population in small cities N_L is equal to 48,940, we can calculate the overall density in small cities Δ_S as follows:

$$\Delta_S = \Delta_L \cdot e^{-0.16 N_L/N_S} = 60 \cdot e^{-0.16\times 209468/48940} = 30\,\text{p/ha}. \quad (1)$$

Given the median population and the overall density in large cities in all regions, we used this formula to calculate the overall density in small cities in all regions. The results are shown in Table 3.3, together with the data on average and median regional densities used to construct Fig. 3.3.

The reader should note that we can only apply the formula in (1) for regions or countries with full city hierarchies, namely with a substantial number of cities in every city population range. In countries with one single primate city, for example, the formula fails to generate realistic overall densities for small cities. Ulan Bator, with a population of 764,000 people and an overall density of 71 persons per hectare is the only large city in Mongolia. Formula (1) yields a density of 7 persons per hectare for small cities there, clearly an unrealistic figure. We have thus opted to use the formula for regions only, and then to apply the regional density ratios (the regional overall density in small cities divided by the regional overall density in large cities) to calculate the overall density in small cities in individual countries. Generally, therefore, as the last column in Table 3.2 shows, we estimated that overall densities in small cities are *roughly half* those observed in large cities.

We used the estimated total population in small cities and the estimated overall densities in small cities to calculate the total amount of urban land cover in small cities in each region: it is simply the ratio of the two. The results of this calculation for all world regions are shown in Table 4.1 in the following section.

4. Urban land cover in all countries, 2000

We added our estimates of urban land cover in small cities to our earlier estimates of urban land cover in large cities to obtain estimates of total urban land cover for all countries and regions for the year 2000. This led to the creation of an important new database. This database makes it possible, for the first time, to obtain a clear picture of the actual amount of land in urban use in different countries, to examine urban land cover as a share of the total land area or of the arable land area in different countries, to explain variations in urban land cover amongst countries (and amongst large cities), to project urban land cover in different countries into the future, and to begin to examine whether variations in, say, carbon emissions, could be explained by variations in urban land cover. In addition, this new database can now be used by others to study various issues of interest that have so far evaded rigorous research because of the lack of reliable comparative data.

Table 4.1 summarises our estimates for total urban land cover in each region, where total urban land cover is shown as the sum of urban land cover in large and small cities. It is useful to compare our estimates of urban land cover in each region with the estimates obtained from the MOD500 ‘urban’ land cover map. This comparison is given in the last three columns of Table 4.1 and in Fig. 4.1.

All in all, our estimate of the urban land cover for the world as a whole amounts to 93% of the MOD500 map

Table 4.1
Estimated urban land cover in all regions, 2000.

Region	Urban land cover in large cities, 2000 ('000 km^2)	Urban land cover in small cities, 2000 ('000 km^2)	Total urban land cover, 2000 ('000 km^2)	MOD500 estimate of total urban land cover ('000 km^2)	Estimate as percent of MOD500 estimate (%)
Eastern Asia and Pacific	39.9	10.2	50.0	91.0	55.0
Southeast Asia	12.9	21.6	34.4	27.6	125.0
South and Central Asia	29.7	30.2	59.9	64.9	92.3
Western Asia	13.0	9.7	22.7	26.8	84.6
Northern Africa	5.3	6.8	12.1	12.6	95.9
Sub-Saharan Africa	12.8	13.8	26.6	28.2	94.1
Latin America and the Caribbean	43.3	48.0	91.2	93.5	97.5
Europe and Japan	85.7	89.0	174.7	167.2	104.5
Land rich developed countries	94.0	37.2	131.2	139.5	94.1
Developing countries	156.9	140.1	297.0	344.7	86.2
Developed countries	179.7	126.2	305.9	306.6	99.8
World	336.6	266.3	602.9	651.3	92.6

estimate, but there are substantial differences between the two estimates in individual regions. Our estimate of urban land cover for Eastern Asia and the Pacific, for example, is only 55% of the MOD500 estimate possibly because of the inclusion of closely packed villages as part of the 'urban' land cover in the latter, as noted earlier. In contrast, our estimate for Southeast Asia is 25% higher than the MOD500 estimate. In this region, the MOD500 map may have failed to identify a large number of small cities. We believe that there is no question of not having identified a large number of large cities: to the best of our knowledge, we identified practically *all* large cities by name and location in the MOD500 map, and where a MOD500 cluster was not associated with them we created a new cluster and added it to the map.

We find that the two datasets – the U.N. urban population dataset and the MOD500 'urban' land cover

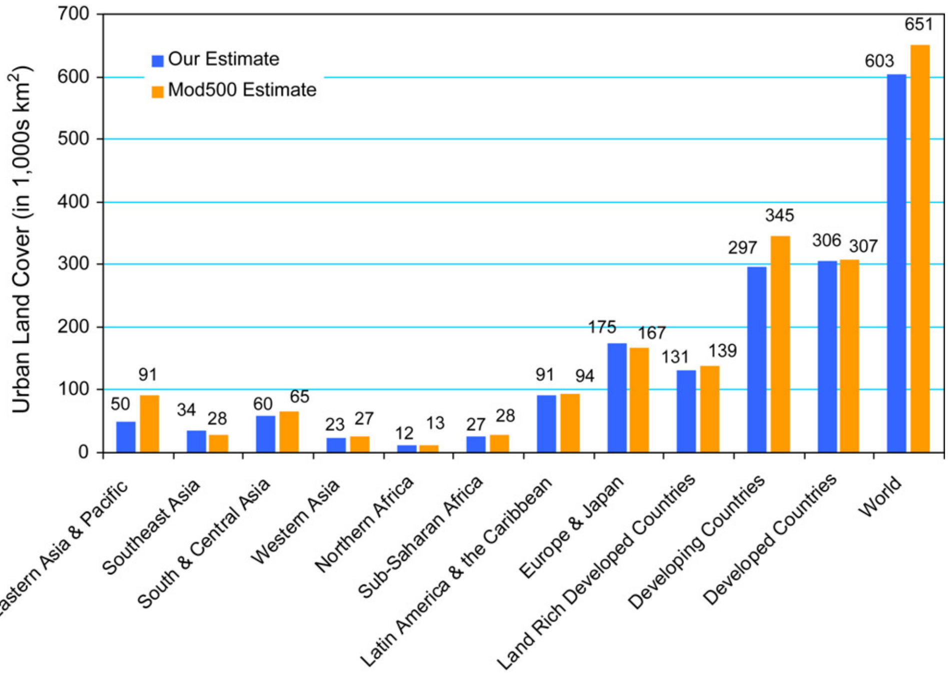


Fig. 4.1. A comparison of our estimates of urban land cover and the MOD500 map estimates for all regions, 2000.

Table 4.2
Characteristics of urban land cover in all world regions, 2000.

Region	Large cities			Total urban population (millions)	Total urban land cover (km^2)	Urban land cover as share of total land area (%)	Urban land cover as share of total arable land (%)
	Number of large cities	Total population in large cities (millions)	Urban land cover in large cities (km^2)				
Eastern Asia and Pacific	891	458	39,858	514	50,036	0.43	3.20
Southeast Asia	196	107	12,883	206	34,448	0.85	3.64
South and Central Asia	539	287	29,705	435	59,872	0.58	2.30
Western Asia	157	90	12,999	121	22,714	0.49	4.68
Northern Africa	115	53	5342	87	12,118	0.15	2.70
Sub-Saharan Africa	258	132	12,820	208	26,576	0.13	1.54
Latin America and the Caribbean	403	259	43,279	390	91,231	0.45	5.63
Europe and Japan	796	400	85,710	602	174,749	0.76	5.62
Land rich developed countries	291	226	93,995	268	131,180	0.50	4.62
Developing countries	2559	1386	156,886	1960	296,994	0.37	3.17
Developed countries	1087	626	179,705	870	305,929	0.62	5.14
World	3646	2012	336,591	2830	602,923	0.47	3.93

dataset – are not consistent, and that the differences between them cannot be reconciled without changing one or the other. The reason they cannot be reconciled is because of the intervention of density. This can be illustrated by looking at the numbers for Eastern Asia and the Pacific region in Table 3.2 presented earlier. As the table shows, 89% of the urban population in this region lives in large cities, but the built-up areas of these cities amount to only 55% of the MOD500 'urban' land cover. The two datasets will be consistent only if the overall density in small cities in this region were *one-fifth* of the overall density in large cities and this is clearly not the case. Once we take account of density, it becomes quite clear that we have to abandon or modify the relevant numbers in one or the other of the two datasets.

The Atlas of Urban Expansion (Angel et al., 2011a) presents our new urban land cover datasets and Table 4.2 summarises selected data for all world regions. For every country, the tables in the *Atlas* provide information on the total urban population, number of large cities, their total population and urban land cover, urban land cover in small cities, total urban land cover, urban land cover as a percent of the total land area, and urban land cover as a percent of the total amount of arable land. A discussion of the key results of the table follows. There are major differences in urban land cover amongst countries. The 20 countries with the highest areas of urban land cover are shown in Fig. 4.2.

It is clear from inspecting Fig. 4.2 that urban land cover is not simply a multiple of the urban population in each country, because densities vary considerably amongst regions, as shown earlier in Fig. 3.3. The variation in densities amongst countries is displayed in Fig. 4.3, a global map that shows the average density in large cities in every country.

The map displays the regional variations shown earlier in Fig. 3.3 in more detail. Densities are generally higher in less-developed countries than in more developed ones, or, more specifically in lower-income countries than in higher-income ones. Amongst more-developed countries, they are higher in Europe and Japan than in the U.S., Canada and Australia. Amongst less-developed countries, they are higher in Africa and in Asia than in Latin America and the Caribbean.

To conclude this section, we present a global map of urban land cover at the country scale. The map, Fig. 4.4, shows urban land cover in all countries as a share of their total land areas.

In the world as a whole, urban land cover occupied 0.47% of the total land area of countries. Urban areas occupied 0.85% of the land area of the countries of Southeast Asia but only 0.12% of the land in the countries of in Sub-Saharan Africa.

Amongst the countries that had large cities in 2000, 10 countries had more than 5% of their total land area occupied by cities: Singapore (56.6%), Bahrain (32.2%), Belgium (17.2%), the Palestinian Territories (West Bank and Gaza) (17.0%), the Netherlands (10.7%), Puerto Rico (8.4%), the Czech Republic (6.1%), the United Kingdom (5.7%), Italy (5.6%), and Germany (5.3%). Twenty-two countries had 2–5% of their land areas occupied by cities, amongst them Japan (4.2%), France (2.8%), and the Philippines (2.1%). Twenty-two additional countries had between 1 and 2% of their land area occupied by cities,

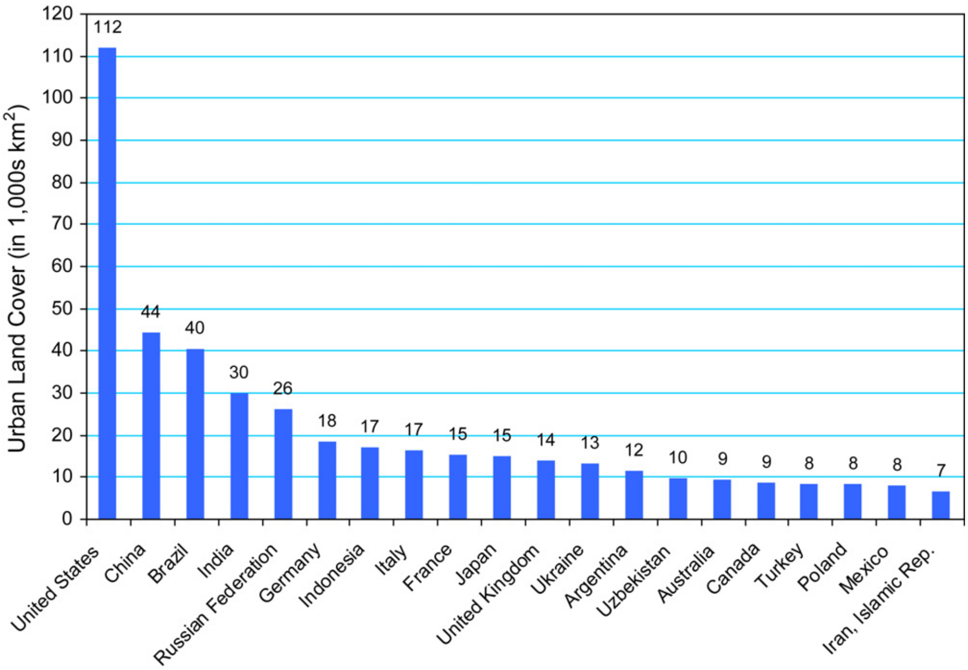


Fig. 4.2. The 20 countries with the highest areas of urban land cover, 2000.

amongst them the United States (1.2%), Bangladesh (1.1%), Turkey (1.0%), and India (1.0%). Twenty-eight more countries had between 0.5 and 1% of their land areas in urban use, amongst them Indonesia (0.95%), Pakistan (0.7%), Venezuela (0.7%), and China (0.5%). Twenty-seven countries had between 0.2 and 0.5% of their land in urban use, amongst them Brazil (0.48%), Argentina and Mexico (0.42%), and Egypt (0.26%). Eighteen additional countries had between 0.1 and 0.2% of their land in urban use, amongst them the Russian Federation (0.16%), Saudi Arabia (0.15%), and Australia (0.12%). The remaining 28 countries had less than 0.1% of their land in urban use, amongst them Canada (0.09%), the Democratic Republic of Congo (0.05%), Libya (0.03%), and Mongolia (0.02%).

In conclusion we note that the numbers presented here suggest that the common perception of cities taking

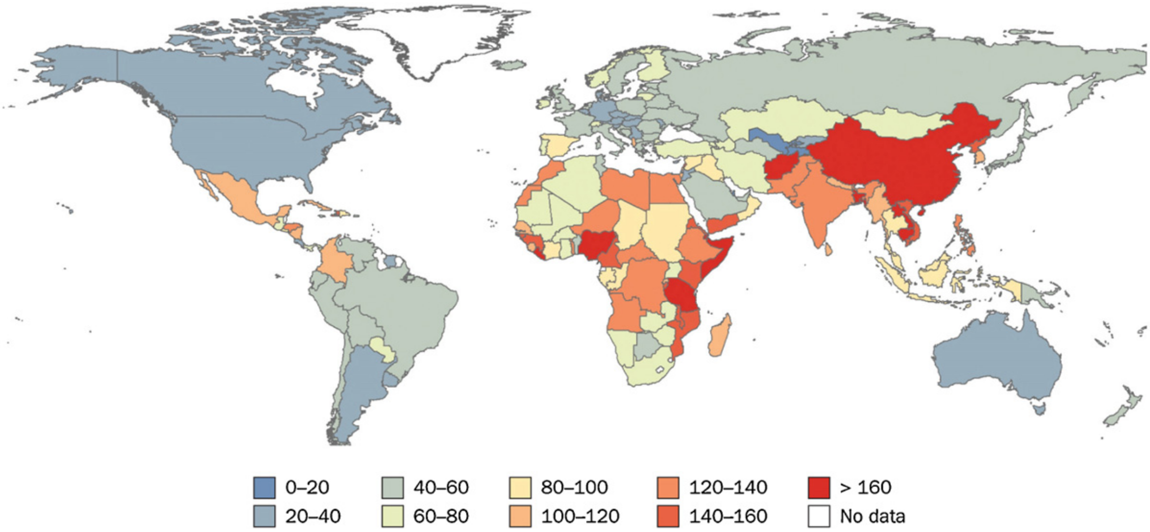


Fig. 4.3. Average density of large cities in all countries, 2000.

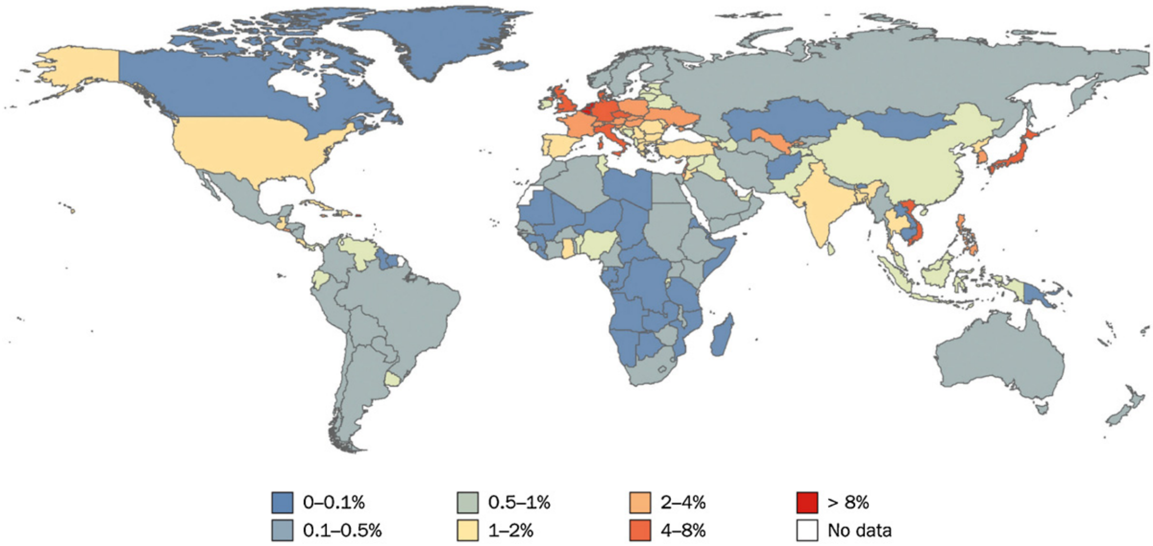


Fig. 4.4. Urban land cover as a share of total land area in all countries, 2000.

up a substantial share of the land of countries may be exaggerated. Cities certainly take up land but, on the whole, they are quite conservative in their use of land. Half the population of the world lived in cities in the year 2000 and occupied less than one-half of 1% of the land area of countries. To suggest that we are running out of land for urban expansion may therefore be an exaggeration. In formulating policies that aim to constrain urban expansion it may be useful for governments to compare urban land consumption in their countries with other countries that have higher or lower ratios of urban land cover to total land area. This may provide a 'reality check' for those who become overly concerned when open space is converted to urban use. The ratio of urban land cover to arable land is another matter, as a number of countries are concerned with their food security, seeking to keep enough land in cultivation to feed their entire population. In Section 7 of this paper we discuss a forthcoming research project that will focus on the effect of future urban expansion on the loss of arable land.

5. Modelling urban land cover in countries and cities

5.1. The classical economic theory of urban spatial structure

The differences in urban land cover amongst countries described in the previous section already suggest three key explanations of why urban land cover varies amongst countries: urban population matters, income matters, and the availability of plenty of land for urban expansion matters. In general, countries with more people living in cities can be expected to have more urban land cover, countries with higher levels of economic development, measured, say, by GDP per capita, can be expected to have more land cover, and land-rich countries, measured, say, by the amount of arable land per person in the country, can be expected to have more urban land cover. All three propositions make intuitive sense. The more people inhabit cities, the more space these cities will occupy. The higher the per capita income in the country, the more resources are available for building larger houses, for buying more cars, and for having wider roads, more expansive workplaces and shopping areas, larger gardens and parks, and more extensive public facilities. And the more arable land in the country, the less likely is land to be hoarded, the cheaper it will be to extend cities into agricultural areas, and the less public and official resistance will likely be encountered in efforts to convert rural land to urban use.

The three propositions discussed above are indeed some of the basic theoretical results obtained from the classical economic models of urban spatial structure. The theoretical foundation for the economic analysis of urban spatial structure was laid out by Alonso (1964), Mills (1967) and Muth (1969), refined by Wheaton (1976), and later restated by Brueckner (1987). The evidence presented in this study validates the key results of their theoretical insights and confirms the observation of Mills and Tan (1980, p. 314) that "[t]here are few cases in economics in which such a simple theory leads to so many testable implications". We introduce the basic elements of this theory here, and we largely use Brueckner's notation.

The stylised *city* in the classical analysis of urban spatial structure is circular, having a single Central Business District (CBD) where all jobs are concentrated. The CBD is surrounded by L households that occupy land in concentric circles around it. To simplify the analysis, every household residing at a distance x from the centre has one commuter who travels to work along a radial path, and all households are assumed to have identical annual incomes y and identical preferences. The annual cost per unit of travel to work is t and therefore the household's total cost of commuting is $t \times x$. Households spend their income on a quantity of housing q, on commuting $t \times x$, and on a composite good c which is assumed to be the same throughout the city. The price of housing p varies with distance from the centre and may thus be denoted $p(x)$. The preferences of all households for housing and the composite good are represented by quasi-concave utility function $v(c, q)$.

Equilibrium is attained when all households are settled. It requires that a common utility level u be achieved by a household at any location within the built-up area of the city. Households will select the most preferred combination of the composite good and housing affordable by their income, so that in equilibrium we must have:

$$\max_q v(y - t \times x - q \times p(x), q) = u \tag{1'}$$

for all households. The solution of this equation yields two inequalities:

$$\frac{\partial p}{\partial x} < 0 \quad \text{and} \quad \frac{\partial q}{\partial x} > 0. \tag{2}$$

Namely, the price of land declines with distance from the city centre whilst the quantity of housing consumed increases with distance from the centre.

Housing suppliers combine inputs of capital N and land l using a concave constant-returns production function $H(N, l)$ to produce housing. Concavity means that housing production exhibits diminishing marginal productivity of both capital and land. Constant returns to scale and free entry of housing producers are sufficient to determine an equilibrium land rent function $r(x)$ and a capital–land ratio (floor-area ratio, or building density) $S(x)$ that depend upon distance x from the city centre and satisfy:

$$\frac{\partial r(x)}{\partial x} < 0 \quad \text{and} \quad \frac{\partial S(x)}{\partial x} < 0. \tag{3}$$

so that both land rent and building density decline with distance from the city centre. Let $D(x)$ be the population density at distance x from the centre, and assume that all households have only one member. Because houses become larger as distance from the centre increases whilst building density declines, it follows that population density declines with distance too, namely

$$\frac{\partial D}{\partial x} < 0. \tag{4}$$

On the periphery of the city, urban housing producers must outbid agricultural users of land to convert land to urban use. Let the distance to the outer edge of the city be denoted by $\bar{x}$ and let r_a be the agricultural rent on the urban periphery. Since $(\partial r(x)/\partial x) < 0$, it follows that urban rent $r(x) > r_a$ inside the city and that $r(x) < r_a$ outside the city. In equilibrium, we must therefore have

$$r(\bar{x}, y, t, u) = r_a. \tag{5}$$

In equilibrium, the entire population of the city must also be accommodated inside the circle with the radius $\bar{x}$. Let θ be an exogenous variable denoting the share of land available for building in a ring x distance away from the centre. In equilibrium, we must have

$$\int_0^{\bar{x}} 2\pi \cdot \theta \cdot x \cdot D(x, t, y, u)\, dx = L \tag{6}$$

The classical theory thus provides an endogenous solution for the extent of the area that a city occupies, $A = 2\pi\theta\bar{x}$, given its population L, the income of that population y, the cost of transport t, the share of buildable land θ, and the agricultural rent on the urban periphery r_a. The following inequalities follow from solving the equilibrium equations (see Brueckner, 1987, pp. 831 and 840–844):

$$\frac{\partial \bar{x}}{\partial r_a} < 0, \quad \frac{\partial \bar{x}}{\partial t} < 0, \quad \frac{\partial \bar{x}}{\partial \theta} < 0, \quad \frac{\partial \bar{x}}{\partial L} > 0, \quad \frac{\partial \bar{x}}{\partial y} > 0, \tag{7}$$

and

$$\frac{\partial S}{\partial L} > 0 \quad \text{and} \quad \frac{\partial D}{\partial L} > 0. \tag{8}$$

The inequalities in (7) indicate that the outer radius of the city $\bar{x}$ will shorten if the agricultural rent r_a increases, if the transport cost t increases, and if the share of buildable land θ increases, and will lengthen if the city population L increases and if the income y of that population increases. As a consequence, if the outer edge of the city $\bar{x}$ increases because the share of buildable land θ decreased, then, other things being equal, more income will need to be spent on transport and less on housing, with the result that the area of the city will also decrease.

More generally, it follows that the total area of the city A will decrease if the agricultural rent r_a increases, if the transport cost t increases, and if the share of buildable land θ increases, and will increase if the city population L increases and the income y of that population increases.

One variable of interest in determining the area of cities is income inequality or the presence of informal settlements in the city where lower-income people reside. Instead of assuming that all households have the same income y, we can assume that the city has two groups of people, rich people with income y_r and poor people with income y_p. When the incomes of the two groups are unequal, we have $y_r > y_p$ and $y_r + y_p = 2y$, so that total income in the city remains the same. What happens to the area of the city A when income inequality, measured here simply as y_r/y_p, increases?

Extensions of the classical theory do not offer a clear theoretical answer to this question. Wheaton (1976), for example, shows that if we can assume that the two groups *have different preferences* for consuming housing and transport, then in equilibrium the welfare of both high-income and low-income people will increase when income inequality increases. In other words, in cities where incomes and preferences are identical, every household competes for the same location and the increased competition makes everyone worse off. In more heterogeneous cities, the rich do not compete for locations desired by the poor and vice versa, making it possible for both rich and poor to obtain better locations and better housing: "this reduced competition in turn allows the poor to bid somewhat less, expand their land consumption, and improve their situation" (6). One may surmise, although Wheaton does not discuss this implication directly, that under conditions of greater income inequality, the area of the city A will be larger because of reduced competition, and hence lower bid prices, for specific locations. Let G be the Gini Coefficient of income inequality in the city. The inequality implied here is

$$\frac{\partial \bar{x}}{\partial G} > 0. \tag{9}$$

A special case of the rich and poor residents of cities having different locational preferences are cities in developing countries where a substantial share of the urban population live in informal settlements: squatter settlements with no legal property rights or informal land subdivisions with questionable property documentation, both with minimal or incomplete infrastructure services. In such cities, we can say that the rich and the poor obtain land in different land markets and that the poor pay less for a unit of land (albeit of lesser quality) in the informal market than the rich pay in the formal one. We would expect the area A of such cities to be larger and their average density Δ to be lower than in cities with no informal land markets.

There is an alternative explanation that associates increased income inequality with a larger city area. We know, for example, that the income elasticity of demand for housing and land is positive, and we have seen earlier that the consumption of land in the city increases with income. It may well be that as income inequality increases, the rich move into luxury properties thereby consuming more land whilst the poor are pushed into consuming the minimum amount of land necessary for survival. In other words, it may be that the consumption of housing q increases *at a positive rate of increase*, namely

$$\frac{\partial^2 q}{\partial y^2} > 0. \tag{10}$$

If that were the case, we can show that as income inequality increases housing consumption increases and therefore the average density of the city decreases. This is illustrated in Fig. 5.1.

In this figure, we have a poor person with income y_1 who consumes q_1 housing, a rich person with income y_2 who consumes q_2 housing, and a middle-income person with income y_3 where $y_3 = (y_1 + y_2)/2$, who consumes q_3 housing. Because $y(q)$ is an increasing function of y, we can see that the average of q_1 and q_3 is larger than q_3. Namely,

$$q_3' = \frac{q_1 + q_2}{2} > q_3. \tag{11}$$

It follows that the poor person and rich person together will consume more housing (and land) than two middle-income persons with the same total income. More generally, if the *rate* of housing consumption increases with income then a city with more income

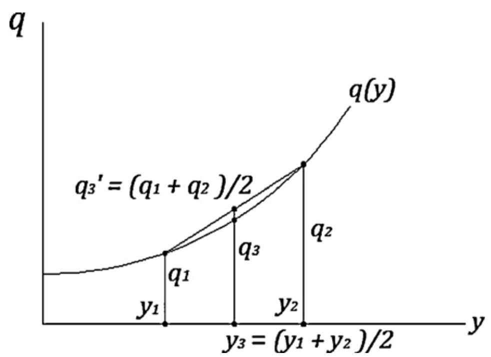


Fig. 5.1. Housing demand q as an increasing function of income y.

inequality will have a larger area. Unfortunately, there is no theoretical basis for assuming that the rate of consumption of housing increases with income and this explanation is therefore left for further investigation.

One of the recognised weaknesses of the classical monocentric city model is that it assumes that all jobs are situated *a priori* in the Central Business District (CBD) and that all travel occurs on radial routes to the CBD. It has long been observed that places of employment have been decentralising, in some cities for a century or more (Mills, 1972, pp. 34–58). In the 100 largest metropolitan areas in the U.S. in 2000, for example, only 22% of employment was located within 3 miles (4.8 km) from city centres (Glaeser, Kahn, & Chu, 2001). Commuting patterns in that same year show that only 19% of all commuters travelled from the suburbs to the city centre, whilst 44% travelled within suburbs, 29% travelled within the central city, and 8% commuted from central city to suburb (U.S. Census data in O'Sullivan, 2007, Fig. 7-5, p. 135).

That said, there is considerable empirical evidence that employment density, residential density, travel cost and land rents still decline as distance from the CBD increases. Our own preliminary examination of employment data for 36 U.S. cities in 2002, for example – clearly some of the most sprawled cities in the world – shows that the average gradient of the employment density curve, assuming a constant decline with distance from the CBD, was -0.1 ± 0.015 and that it was significantly different from 0 (p-value < 0.05) in 30 out of the 36 cities studied (the average R^2 was found to be Z). Travel cost in the same cities, measured by vehicle miles travelled (VMT) per household, is clearly non-zero at the CBD and then appears to increase at a declining rate as distance from the CBD increases.

Bertaud and Malpezzi have documented the decline of residential densities with distance from the CBD circa 2000 in a global representative group of 48 cities they studied in all but four outliers (the highly regulated cities of Johannesburg, Moscow, Seoul, and Brasilia) (Bertaud & Malpezzi, 2003). What is more, according to McMillen, for example, who studied one hundred and fifty years of land values in the Chicago metropolitan area, "[t]he inadequacy of the monocentric model should not be overstated. The [Chicago] CBD continues to dominate land values (McMillen, 1996, p. 122). And whilst Chicago maybe considered one of the more monocentric cities in the U.S., Bangkok, the capital of Thailand, is certainly polycentric, yet prices $P(r)$ there declined exponentially, as expected, with distance r from the CBD in both 1996 and 2006 (see Fig. XIII. The R^2 values of the functions $\ln P(r) = P(0) - \beta \times r$ for the two dates were 0.91 and 0.93 respectively).[1] In an important sense, therefore, the spatial patterns predicted by the classical monocentric model of urban spatial structure still appear to hold. We therefore used this model in our study to generate a set of hypotheses that can be tested using our empirical evidence.

Does the empirical evidence from our new universe of cities support the results of the classical model of urban spatial structure and its extensions? As we shall see in the following sections, it does.

5.2. Models that explain variation in urban land cover amongst countries, 2000

The theoretical discussion in the previous section yields several testable hypotheses. The first set of such hypotheses focuses on the total urban land cover A_j in a country j with n cities, $A_j = \sum_{i=1}^{n} A_{ij}$, and seeks to explain variations in this total area in the year 2000 amongst all countries. The hypotheses are stated for individual cities in the country, and are summarised in the following Table 5.1. If they are true for individual cities, they should also be true for the sum of all cities in the country.

We tested these hypotheses using a set of multiple regression models with total urban land cover in the country in 2000 as a dependent variable. Because our estimates of urban land cover in large cities are more robust than our estimates of total urban land cover, we also tested these hypotheses with two additional variables as dependent variables: (a) the total urban land cover in large cities in the country in 2000, and (b) the built-up area of individual large cities worldwide in 2000.

The descriptive statistics for all the variables used in estimating the models to explain variations in urban land cover in countries and in countries with large cities are given in Table 5.2.

5.2.1. Sources of data

The population of large cities was obtained from Brinkhoff's www.citypopulation.de. Data on GDP per capita was obtained from the World Bank's 2000. *World Development Indicators* website, online at http://econ.worldbank.org. Data on arable land was obtained from the World Resources Institute's *Earth Trends* website. Data on gasoline prices was obtained from GTZ's *Interna-*

[1] Calculated by the authors from data for 172 land sales in 1996 and 2006 on main roads, supplied by Dr. Sopon Pornchokchai, President, Thai Appraisal Foundation. Sales price data was divided into ten rings with 17 observations in each ring, and weighted averages were calculated for the value and the distance from the CBD in each ring.

Table 5.1
Five testable hypotheses derived from the classical theory of urban spatial structure.

Inequality	Hypothesis	Independent variables used
$\frac{\partial A}{\partial L} > 0$	1. The higher the population L of the city, the larger its area A	*Population*: Total city population, 2000
$\frac{\partial A}{\partial y} > 0$	2. The higher the average per capita income y in the city, the larger its area A	*Income*: Per capita gross domestic product in the country (in 2000 U.S.$), 1990
$\frac{\partial A}{\partial r_a} < 0$	3. The higher the agricultural land rent r_a around the city, the smaller its area A	*Arable land*: Arable land and permanent crop land per capita in the country, 2000 (proxy variable)
$\frac{\partial A}{\partial t} < 0$	4. The higher the cost of transport t in the city, the smaller its area A	*Gasoline price*: Price of 1 l of super gasoline (in U.S.$) in 1998
$\frac{\partial A}{\partial G} > 0$	5. The greater the share of informal settlements in the city, the larger its area A	*Informal settlements*: Share of urban population with unimproved water supply and sanitation, 2000 (percent)

Table 5.2
Data used for multiple regression models with urban land cover in the country and in all the large cities in the country in 2000 as dependent variables.

Variable	N	Minimum	Maximum	Mean	Std. deviation
Descriptive statistics					
Total population in large cities	208	0	412,484,124	9,673,011	35,677,848
Total area of large cities (hectares)	208	0	8,231,509	161,823	663,443
Total urban population, 2000	208	4929	459,132,808	13,607,863	43,330,421
Total urban land cover (hectares)	208	203	11,192,972	289,867	953,696
GDP per capita, 1990 (in 2000 U.S.$)	173	129	46,822	4559	7789
Arable land per capita in 2000 (m^2)	208	5	26,419	2693	2910
Percent of urban population with unimproved water and sanitation, 2000	191	0.01	60	15	17
Price (U.S. Cents per litre) of super gasoline in 1998	159	1	121	56	27
Valid N (listwise)	143				

tional Fuel Prices – 2005 report. Data on the shares of the urban population with unimproved water and sanitation in 2000 was calculated by averaging the share of those with unimproved water supply and those with unimproved sanitation given in table form in the WHO/UNICEF Joint monitoring Programme (JMP) website (WHO/UNICEF).

It is important to know whether the variables to be used in the models as independent variables are correlated with each other. If two or more of the independent variables are highly correlated, a model will suffer from a *collinearity* problem. The coefficients of each of the correlated variables will then no longer be robust: they will change erratically if one or more of the correlated variables are added to or removed from the model. The Pearson correlations amongst the variables used in the models for countries for which data was available are shown in Table 5.3.

Table 5.3 shows that gasoline prices are higher in richer countries, whilst the share of the urban

Table 5.3
Pearson correlations amongst the independent variables used to explain country urban land cover (146–191 countries), 2000.

Variables	GDP per capita	Arable land per capita	Informal settlements	Price of gasoline
GDP per capita, 1990 (in 2000 U.S.$)	1			
Arable land per capita in 2000 (m^2)	−0.046	1		
Informal settlements: proportion of urban population with unimproved water and sanitation, 2000	−0.498*	−0.013	1	
Price (US Centre per litre) of super gasoline in 1998	0.502*	−0.049	−0.156	1

Note: Values with asterisks are correlated at the 0.01 significance level (2-sided).

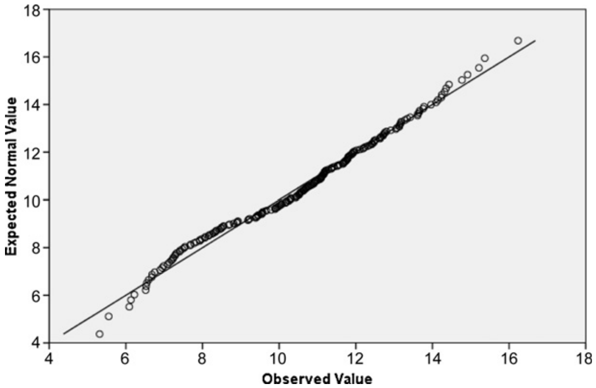


Fig. 5.2. Normal *Q–Q* plot of the log of country urban land cover in 2000.

population without adequate services is lower. The reader should note that in the presence of multicollinearity amongst two independent variables, the coefficient of one can vary substantially when the other one is introduced into the model. The robustness of the coefficients in the models presented below suggests that the models do not suffer from multicollinearity problems.

5.2.2. The models

To test each one of the hypotheses outlined in Table 5.1 under *ceteris paribus* conditions – namely, all other things being equal – we tested a series of multiple regression models. These models are expected to explain variations in urban land cover amongst countries in a comprehensive way, seeking to include a complete set of relevant factors and determining the effect of each individual factor on urban land cover given the effects of all other factors. Only when no important independent variables are omitted from a particular model can the model be relied upon to produce correct estimates of the contribution of each independent factor to variations in country urban land cover.

We opted for using both dependent and independent variables in *logarithmic* forms, and we did this for two reasons. First, the logarithmic forms of the country urban land cover variable as well as a host of other independent variables were typically found to be normally distributed: a precondition for using multiple regression models. The results of the *Q–Q* test for normality of the *Log Country Urban Land Cover* variable, for example, are shown in Fig. 5.2. The fact that the observations for all countries 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 country urban land cover for a given percent change in the independent variable. If the coefficient of the *Log Income* variable, for example, is +0.2 it means that a 10% increase in income is associated with a 2% increase in country urban land cover. This allows for a simple and ready interpretation of the coefficients of the different independent variables in the models.

The set of the five models tested is shown in Table 5.4. The dependent variable in all models, as noted above, is *Log Country Urban Land Cover* in 2000.

Table 5.4
Multiple regression models (in log form) with country urban land cover in 2000 as a dependent variable.

Independent variables	Coefficients and levels of significance				
	Model 1	Model 2	Model 3	Model 4	Model 5
Total urban population, 2000	0.942	0.963	0.949	0.902	0.896
Signif. (2-sided)	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Income: GDP per capita, 1990 (U.S.$)		0.185	0.218	0.229	0.104
Signif. (2-sided)		*0.000*	*0.000*	*0.000*	*0.021*
Arable land per capita, 2000			0.198	0.191	0.207
Signif. (2-sided)			*0.000*	*0.000*	*0.000*
Price of 1 l of super gasoline (U.S. cents)				−0.205	−0.285
Signif. (2-sided)				*0.007*	*0.000*
Informal settlements: percent of urban population with unimproved water and sanitation					−0.083
Signif. (2-sided)					*0.000*
Constant	−3.042	−4.731	−6.276	−4.748	−3.443
Signif. (2-sided)	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
No. of countries	206	173	171	146	142
R-squared	0.931	0.943	0.950	0.930	0.937
Adjusted *R*-squared	0.931	0.943	0.949	0.928	0.934

Model 1, shown in the second column from the left in Table 5.4, uses only the total urban population in the country in logarithmic form as an independent variable to explain the variation in Log Urban Land Cover in all 206 countries for which we have data. The R^2 and adjusted R^2 of the model are 0.93 and 0.93 respectively, indicating that the model explains more than 90% of the variation in Log Urban Land Cover. We can say with 99% confidence that the coefficient of Log Urban Population is significantly different from zero (significance is shown in italics below each variable). Model 1 therefore accepts Hypothesis 1: Countries with more people living in urban areas can be expected to have higher amounts of urban land cover than countries with fewer people living in urban areas. The coefficient of urban population in the model suggests that a 10% increase in the urban population will lead to a 9.3% increase in urban land cover. The coefficient of Log Urban Population varies between 0.90 and 0.96 in the five models in Table 5.2, suggesting that it is quite robust. A 10% increase in the urban population is associated with a 9.3 ± 0.1% increase in urban land cover.

Model 2 introduces income into the model. This model explains 94% of the variation in urban land cover. The coefficient of *Log Income* is positive and significant, with a value of 0.18, indicating that Hypothesis 2 must be accepted: countries with higher incomes per capita can be expected to have more urban land cover than countries with lower incomes per capita. In other words, the higher the income per capita in a country, the more urban land is likely to be used, on average, by individual urban dwellers. The coefficient of 0.18 indicates that a 10% increase in per capita GNP is associated with a 1.8% increase in urban land cover. The coefficient of *Log Income* varies between 0.10 and 0.23 in all models. An increase of 10% in GNP per capita is associated with a 1.8 ± 0.3% increase in urban land cover.

Model 3 introduces arable land per capita into the model. This model explains 95% of the variation in urban land cover. The coefficient of *Log Arable Land* is positive and significant, with a value of 0.21, indicating that Hypothesis 3 must be accepted: countries with higher amounts of arable land per capita can be expected to have more urban land cover than countries with lower amounts of arable land per capita. In other words, the higher the amount of arable land per person in the country, the less expensive and the more plentiful it is, and the easier it may be to convert it to urban use. The coefficient of 0.21 indicates that a 10% increase in arable land per capita is associated with a 2.1% increase in urban land cover. The coefficient of *Log Arable Land* in all models varies between 0.19 and 2.1. An increase of 10% in arable land per capita is associated with a 2.0 ± 0.0% increase in urban land cover.

Model 4 introduces the price of gasoline into the model to test the effect of transport costs on urban land cover. This model explains 93% of the variation in urban land cover. The coefficient of *Log Gasoline Price* is negative and significant, with a value of −0.21, indicating that Hypothesis 4 must be accepted: countries with higher transport cost can be expected to have less urban land cover than countries with lower transport costs. In other words, other things being equal, the higher the cost of transport, the more compact cities will be: households and firms will choose to occupy less land in closer proximity to urban centres, so as to save on the cost of travel. The coefficient of −0.21 indicates that a 10% increase in the cost of gasoline is associated with a 2.1% decrease in urban land cover. The coefficient of *Log Gasoline Price* in the two models presented here varies between −0.21 and −0.29, suggesting that an increase of 10% in gasoline prices may be associated with a 2.5 ± 0.4% decrease in urban land cover.

Model 5 introduces informal settlements into the model. This model also explains 93% of the variation in urban land cover. The coefficient of *Log Informal Settlements* is negative and significant, with a value of −0.08, indicating that Hypothesis 5 must be *rejected*: Other things being equal, countries with greater shares of their urban populations living in informal settlements can be expected to have less, and not more, urban land cover than countries with fewer people living in informal settlements. In other words, in contrast to our theoretical discussion earlier, the more people live in informal settlements, the more likely they are to be overcrowded, taking up less land. The coefficient of −0.08 is small, indicating that a 10% increase in the share of the urban population living in informal settlements is associated with a 0.8% increase in urban land cover.

As noted earlier, the robustness of coefficients in the models suggests that they do not suffer from serious collinearity problems. The fact that three of the independent variables are indeed correlated with each other, as we saw in Table 5.3 earlier, does not reduce the very high explanatory power of the model, but it does suggest that the independent effects of the individual independent variables may not be accurate, calling for further research into the matter. This is particularly important in determining the effect of gasoline prices on urban land cover. As we shall see later, this effect is

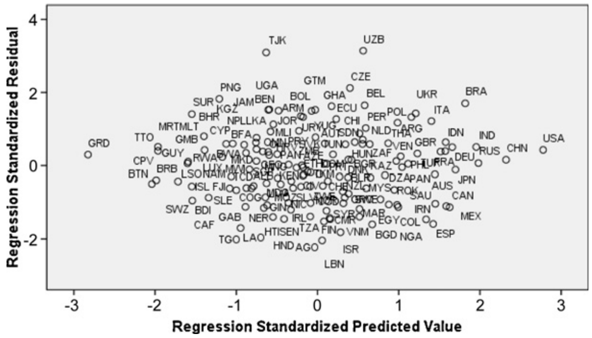


Fig. 5.3. Scatter diagram for Model 5, with country urban land cover in 2000 as a dependent variable.

statistically insignificant when we look at individual cities, rather than at whole countries, suggesting that more research may be needed to determine exactly how gasoline prices affect urban land cover.

It is important to inquire whether the models presented here suffer from the absence of a key independent variable or, to use a statistical term, from omitted variable bias. If an important independent variable were omitted from the model, then the error term would still include it, and the error term will be correlated with the dependent variable. Conversely, if no important variable were omitted, then the error term will not be correlated with the dependent variable. To test for omitted variable bias we examine the scatter plots of the residual error of the model for each city in our sample against the predicted value for that city. More specifically, in Model 5, for example, we examine the standardised error in predicting the *Log of Country Urban Land Cover* against the predicted value of *Log of Country Urban Land Cover* for all countries. The scatter plot for Model 5 is shown in Fig. 5.3, with 3-letter labels for all countries. The values for each country are all within a clearly defined box: from −3 to +3 on the *X*-axis and from −2 to +2 on the *Y*-axis; they are also clustered together with no major outliers. This suggests that the error terms in Model 5 are indeed random and we can therefore assume that the model does not suffer from heteroscedasticity or omitted variable bias. Scatter plots for other models are similar and will not be shown here.

We tested similar models to those shown in Table 5.2 with the total land cover in large cities in the country as a dependent variable (in log form) rather than total urban land cover. As the reader may recall, we arrived at estimates of total urban land cover in each country by calculating urban land cover in small cities, rather than by measuring the total 'urban' land cover directly in the MOD500 map. We did measure the total amount of urban land cover in large cities in the MOD500 map, and these measurements do not suffer from any bias that our calculations of total urban land cover may suffer.

The multiple regression models using the logarithm of the total land cover in large cities in every country as the dependent variable are summarised in Table 5.5. The reader may note that the coefficient in the models, the levels of significance, and the percent of variation explained by the models as measured by their R^2 and

Table 5.5
Multiple regression models (in log form) with total land cover in large cities in each country in 2000 as a dependent variable.

Independent variables	Coefficients and levels of significance				
	Model 1	Model 2	Model 3	Model 4	Model 5
Total population in large cities, 2000	0.999	0.968	0.952	0.922	0.924
Signif. (2-sided)	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Income: GDP per capita, 1990 (U.S.$)		0.213	0.236	0.250	0.134
Signif. (2-sided)		*0.000*	*0.000*	*0.000*	*0.004*
Arable land per capita, 2000			0.184	0.159	0.178
Signif. (2-sided)			*0.000*	*0.000*	*0.000*
Price of 1 l of super gasoline (U.S. cents)				−0.255	−0.307
Signif. (2-sided)				*0.001*	*0.000*
Informal settlements: percent of urban population with unimproved water and sanitation					−0.074
Signif. (2-sided)					*0.002*
Constant	−4.257	−5.342	−6.688	−5.134	−4.166
Signif. (2-sided)	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
No. of countries	158	141	141	134	131
R-squared	0.868	0.910	0.924	0.931	0.937
Adjusted *R*-squared	0.868	0.909	0.922	0.929	0.934

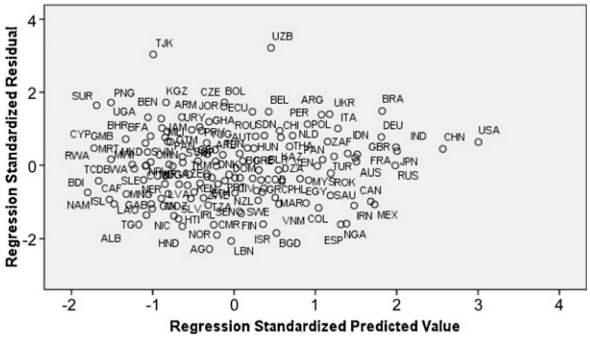


Fig. 5.4. Scatter diagram for Model 5, with total land cover in large cities in each country in 2000 as a dependent variable.

adjusted R^2 are quite similar to the models using the logarithm of total urban land cover in the country as a dependent variable. There is therefore no need to examine the models of Table 5.5 one by one. The scatter diagram for Model 5 in Table 5.5 is shown in Fig. 5.4. It is also quite similar to the scatter diagram in Fig. 5.3.

5.3. Models that explain variations in land cover and density in the universe of cities, 2000

To conclude this section, we also examine a similar set of models to those presented earlier using the urban land cover in individual cities (in log form), rather than the total urban land cover in countries, as a dependent variable. We then present similar models with the average population density in the city (also in log form) as the dependent variable. The additional information used to construct the models is presented in Table 5.6.

The models using urban land cover in individual cities (in log form) as a dependent variable are presented in Table 5.7.

Model 1, shown in the second column from the left in Table 5.7, uses only the population of the city in logarithmic form as an independent variable to explain the variation in Log Urban Land Cover in all 3629 cities for which we have data. The R^2 and adjusted R^2 of the model are 0.47 and 0.47 respectively, indicating that the model explains half of the variation in the Log Urban

Table 5.6
Data used for multiple regression models with city land cover and average city population density in 2000 as dependent variables.

Variable	*N*	Minimum	Maximum	Mean	Std. deviation
Descriptive statistics					
City population, 2000	3646	100,000	34,450,000	551,834	1,417,622
City land cover, 2000 (hectares)	3646	85	684,766	9232	26,760
Average city population density (persons per hectare)	3646	2	1559	107	117
Valid *N* (listwise)	3646				

Table 5.7
Multiple regression models (in log form) with land cover of individual large cities in 2000 as a dependent variable.

Independent variables	Coefficients and levels of significance				
	Model 1	Model 2	Model 3	Model 4	Model 5
City population, 2000	0.853	0.840	0.840	0.841	0.838
Signif. (2-sided)	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Income: GDP per capita, 1990 (U.S.$)		0.314	0.277	0.246	0.246
Signif. (2-sided)		*0.000*	*0.000*	*0.000*	*0.000*
Arable land per capita, 2000			0.278	0.288	0.288
Signif. (2-sided)			*0.000*	*0.000*	*0.000*
Informal settlements: percent of urban population with unimproved water and sanitation				−0.017	−0.017
Signif. (2-sided)				*0.039*	*0.042*
Price of 1 l of super gasoline (U.S. cents)					−0.005
Signif. (2-sided)					*0.818*
Constant	−2.448	−4.614	−6.461	−6.298	−6.317
Signif. (2-sided)	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
No. of cities	3,646	3,527	3,527	3,509	3,511
R-squared	0.472	0.670	0.706	0.706	0.706
Adjusted *R*-squared	0.471	0.670	0.706	0.706	0.706

Land Cover of individual cities. Model 1 therefore accepts the individual city variation of Hypothesis 1: cities with more people living in them can be expected to have higher amounts of urban land cover than cities with fewer people living in them. The coefficient of city population in the model suggests that a 10% increase in the urban population will lead to an 8.5% increase in urban land cover. The coefficient of Log City Population varies between 0.84 and 0.85 in the five models in Table 5.6, suggesting that it is quite robust. A 10% increase in the city population is associated with an $8.4 \pm 0.0\%$ increase in urban land cover. The reader should note that whilst the coefficient is similar to that found for countries in Table 5.4, the explanatory power of the city-based models is weaker: they explain only 47–71% of the variation in urban land cover amongst cities, whilst the earlier models explained 93% of the variations in total urban land cover amongst countries.

Models 2 and 3 show similar results to those shown for countries earlier and we need not discuss them further here. Model 4 shows that, other things being equal, cities with a larger share of informal settlements occupy less urban land cover, leading to the rejection of Hypothesis 5. However, the coefficient of informal settlements is smaller: a 10% increase in the share of informal settlements is associated with a 0.05% decrease in urban land cover.

Model 5 introduces gasoline prices. The effect of gasoline prices on urban land cover is no longer significant at the individual city level. We therefore cannot accept or reject Hypothesis 3 at the city level: cities in countries with higher gasoline prices may or may not have larger urban land covers than cities in countries with lower gasoline prices.

The scatter plot for Model 3 is shown in Fig. 5.5, with 3-letter labels for countries in which the individual cities were located, but not for the individual cities

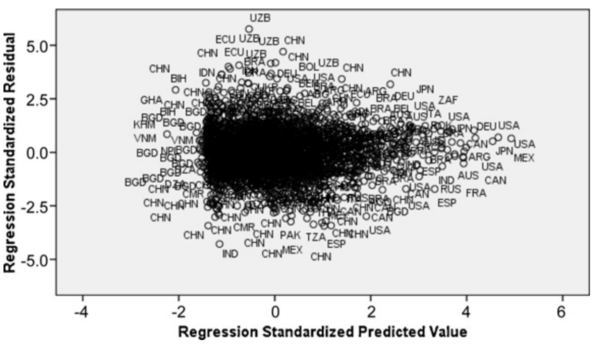


Fig. 5.5. Scatter diagram for Model 4, with land cover in individual large cities in 2000 as a dependent variable.

themselves. The values for all cities are all within a clearly defined box: from −2 to +4 on the *X*-axis and from −5 to +5 on the *Y*-axis; they are also clustered together with no outliers. This suggests that the error terms in Model 4 are indeed random and we can therefore assume that the model does not suffer from heteroscedasticity or omitted variable bias. Scatter plots for other models are similar and will not be shown here.

We also tested a fourth set of models using *the average population density in individual cities* in the universe as a dependent variable. These models were necessary to estimate the relationship between density and city size. The classical economic theory of urban spatial structure predicts that the density of a city will increase when its population increases, all other things being equal. The inequalities in Eq. (8) indicate that building density and population density both increase when the population L of the city increases. If we define the average population density in the city, Δ, as the ratio of its population to its area, $\Delta = L/A$, it will also follow that the average density Δ in the city will increase if the agricultural rent r_a increases, if the transport cost t increases, and if the population L increases, and will decrease if the income y increases. This allows us to formulate several hypotheses shown in Table 5.8.

The models of the average population density in an individual city (in log form) as a dependent variable are presented in Table 5.9. These produce similar results to the three sets of models discussed earlier in this section. Hypotheses 1–4 are accepted, whilst Hypothesis 5 cannot be accepted or rejected. The models explain more than 40% of the variations in average population density in the universe of cities. The dependent variable in the models, Log Density, is also normally distributed (its normal *Q*–*Q* graph is not shown). The coefficients of the independent variables are robust, and the models do not appear to suffer from omitted variable bias.

For purposes of this paper, the key result of this set of models is the robust relationship between the city population and its average population density. On average, the models in Table 5.9 predict that a doubling of the city population is associated with a $16.0 \pm 0.0\%$ increase in density. As the reader may recall, this result was used in estimating the average density of small cities in Section 3.2 above.

To conclude, as predicted by the classical economic theory of the spatial structure of cities, their areas are largely a function of their population size: larger cities occupy more land, and countries with large urban populations have larger amounts of urban land cover. The theory also predicts that higher incomes will increase land consumption, and we do find that cities in richer

Table 5.8
Testable hypotheses concerning the average population density of cities.

Inequality	Hypothesis	Independent variables used
$\frac{\partial \Delta}{\partial L} > 0$	1. The higher the population L of the city, the higher its average density Δ	*Population*: Total city population, 2000
$\frac{\partial \Delta}{\partial y < 0}$	2. The higher the average per capita income y in the city, the lower its average density Δ	*Income*: Per capita gross domestic product (in 2000 U.S.$), 1990
$\frac{\partial \Delta}{\partial r_a} > 0$	3. The higher the agricultural land rent r_a, the higher its average density Δ	*Arable land*: Arable land and permanent crop land per capita in the country, 2000 (proxy variable)
$\frac{\partial \Delta}{\partial F} < 0$	4. The greater the share of people informal settlements F in the city, the lower its average density Δ	*Informal settlements*: The share of the urban population with unimproved water supply and sanitation in 2000
$\frac{\partial \Delta}{\partial t} > 0$	5. The higher the cost of transport t in the city, the higher its average density Δ	*Gas price*: Price of 1 l of super gasoline (in U.S.$) in 1998

countries consume more land than cities in smaller countries. Urban economic theory also predicts that higher agricultural land prices on the urban periphery will constrain urban expansion. We used the amount of arable land per capita in the country as a proxy for agricultural land prices on the urban periphery, assuming that larger supplies of agricultural land will keep its prices lower everywhere. Again, our empirical results agree with the classical theory: urban land cover in countries with ample arable land is higher than urban land cover in countries with limited supplies of arable land. The classical theory also predicts that higher transport cost will constrain urban expansion: other things being equal, cities with higher transport costs will be smaller in area than cities with lower transport costs. Our empirical findings agree with the theory. We used gasoline prices as a proxy for transport cost, and we found that countries with lower gasoline prices have larger amounts of urban land cover than countries with higher gasoline prices.

Whilst this finding is still preliminary and is limited to our analysis of countries and not to individual large cities, it has two important implications. First, gasoline prices are subject to taxation and can thus be considered to be policy variables. If it is indeed the case that levels of urban expansion can be controlled by taxing gasoline, and if governments decide that limiting urban expansion is in the public interest, then increasing the taxes on gasoline – its popularity with voters aside – may be an effective way to limit urban expansion. Second, if oil supplies decline whilst demand for oil rises in the future, gasoline prices may increase without government intervention. These increases may naturally lead to more compact cities without the imposition of taxes on gasoline. More generally, the interplay between increases

Table 5.9
Multiple regression models (in log form) with the average population density of individual large cities in 2000 as a dependent variable.

Independent variables	Coefficients and levels of significance				
	Model 1	Model 2	Model 3	Model 4	Model 5
City population, 2000	0.147	0.160	0.160	0.160	0.160
Signif. (2-sided)	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Income: GDP per capita, 1990 (U.S.$)		−0.316	−0.279	−0.253	−0.252
Signif. (2-sided)		*0.000*	*0.000*	*0.000*	*0.000*
Arable land per capita, 2000			−0.276	−0.286	−0.286
Signif. (2-sided)			*0.000*	*0.000*	*0.000*
Informal settlements: percent of urban population with unimproved water and sanitation				0.014	0.014
Signif. (2-sided)				*0.094*	*0.096*
Price of 1 l of super gasoline (U.S. cents)					−0.003
Signif. (2-sided)					*0.868*
Constant	2.448	4.625	6.462	6.331	6.344
Signif. (2-sided)	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
No. of cities	3646	3525	3525	3507	3499
R-squared	0.026	0.395	0.460	0.462	0.462
Adjusted *R*-squared	0.026	0.395	0.460	0.462	0.461

in household income and increases in gasoline prices may determine whether densities continue to decrease in developing-country cities. Surely, if oil shortages rise precipitously and alternative sources of cheap energy for fueling cars cannot be found, the effect on urban densities in cities everywhere may be more profound. Our models show that if the real price of oil will double every decade, densities are not likely decline. If it triples or quadruples every decade, it should not surprise us if densities will begin to increase everywhere.

Our models also show that, other things being equal, the share of the urban population in informal settlements has a negative, rather than a positive effect on urban land cover as predicted by the classical economic theory. These settlements typically house many low-income people on relatively small amounts of land and may thus reduce overall land consumption in the city. That said, the effect of informal settlements on the overall consumption of land be cities requires further study.

All in all, the models examined here are robust and are able to explain a very large amount of the variation in urban land cover amongst cities and countries. These variations are explained by very few independent variables, suggesting that variations in climate, in cultural traditions, or in the policy environment in different countries matter less than the fundamental forces giving shape to the spatial structure of cities: population, income, low-cost land on the urban periphery, and inexpensive transport. The more people live in cities, the higher their income, the more land is available for expansion, and the cheaper the cost of transport, the faster cities will expand. For the past two centuries this pattern prevailed: urbanisation, economic development, and the invention of various forms of cheap urban transport have led to massive urban expansion. In the following section, we project urban expansion in 10-year intervals to 2050 assuming that the forces shaping cities will continue to effect urban expansion in coming decades in much the same way they did in the past two centuries, before urban population growth slows down to reach a plateau.

6. Projecting urban land cover in all countries, 2000–2050

6.1. Historical Increases in Urban Land cover

Urban expansion is ubiquitous. It is concomitant to urbanisation, economic development, and increasingly affordable urban transport, three of the most powerful forces shaping human societies in the past two centuries. We assume here that urbanisation, economic development, and the availability of inexpensive transport will continue in the coming decades. This necessarily means that urban expansion will continue as it cannot be decoupled from the forces that are shaping it. That said, the future is certainly unpredictable. If people abandon the cities in large numbers, if incomes stagnate or decline for long periods of time, if expansion into peripheral lands is effectively blocked by strict regulation, if more and more people live in crowded conditions in informal settlements, and if transport costs or gasoline prices increase precipitously, cities are likely to become more and more compact. For the purposes of this paper, however – despite increasing concerns with sustainability, often at the expense of efficiency and equity concerns – we assume that the pattern of urban expansion observed over the last two centuries will not change radically in the next few decades. Our projections of urban land cover from 2000 to 2050 are therefore predicated on assumptions that are largely based on past trends, allowing for possible increases in gasoline prices or in the effectiveness of urban containment policies that may halt or slow down the observed density declines of the past.

The reader may recall that between 1990 and 2000, urban land cover in a global sample of cities was found by the authors to increase at an average rate 3.66% per annum, more than twice the rate of urban population growth, 1.66%, during this period. At these growth rates, the world's urban land cover will double in only 19 years, whilst the world's urban population will double in 43 years.

We examined the rate of growth of the urban population and its concomitant urban land cover in a global historical sample of 30 cities between 1800 and 2000 (see Angel et al., 2010). 28 of the thirty cities studied increased their areas more than 16-fold during the twentieth century. The remaining two cities, London and Paris, increased their urban land cover by 2000 since 1874 and 1887 respectively. Fig. 6.1 shows the pattern of 16-fold urban expansion in cities in six world regions during the past two centuries.

The steeper the curves shown in Fig. 6.1, the faster cities were expanding. Cities in less-developed regions, particularly in Asia and Africa, were expanding faster than cities in more-developed countries in recent decades. Cities in Latin America and the Caribbean, a highly urbanised region, are now expanding at slower rates than cities in other, less-urbanised regions. And within regions, some cities are expanding at much slower rates than others in the same region: Johannesburg, Buenos Aires, and Sydney are the prime examples.

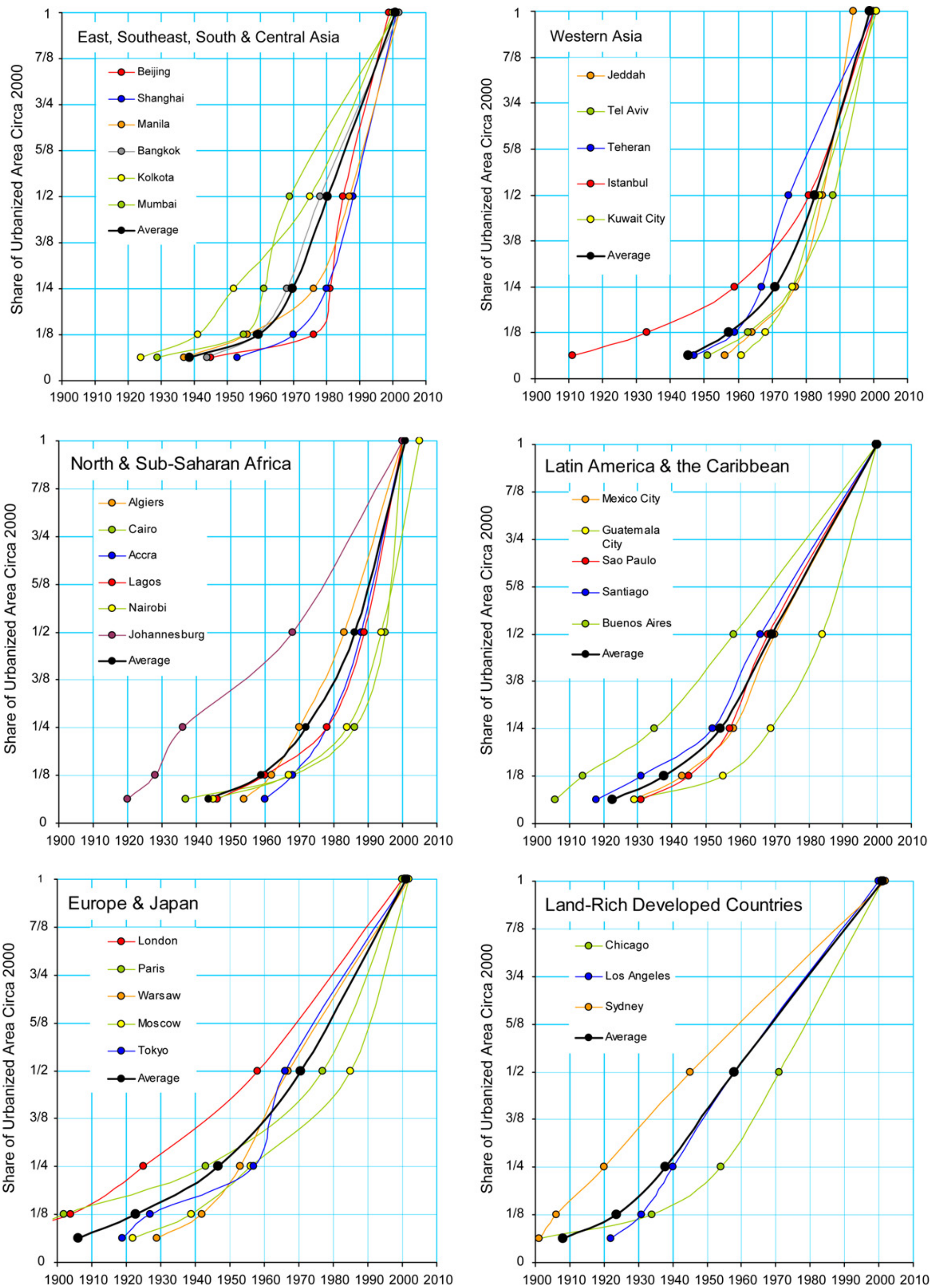


Fig. 6.1. Urban expansion in a global sample of 30 cities, 1900–2000.

These observations suggest that urban land cover can be projected to increase in all cities and countries but not at the same rate. The projected increases are largely due to two main factors: the projected growth in the urban population of countries and the projected decline in urban densities. Clearly, the projected growth of the urban population will continue to be more pronounced in the poorer and less urbanised countries and less pronounced in richer and more urbanised ones. Density decline, as we shall see below, is not significantly different in less-developed and more-developed countries at the present time, but long-term trends suggest that where densities are already exceptionally low, as in the U.S. for example, the rate of density decline is slowing down and densities are reaching a plateau. Significant *increases* in urban population density have not been registered in any country during the last several decades.

6.2. Urban population projections, 2000–2050

We first discuss the projected increases in the urban population in different countries and regions. Two main factors account for this projected increase: natural population growth in the country as a whole and in cities in particular, and the migration of people from the countryside to the cities. The rate of population growth has been shown to decline significantly with economic development: richer families have fewer children. Urbanisation has also gone hand in hand with economic development, with the result that urban families have fewer children than rural ones. Generally, therefore, we can expect more developed countries to be more urbanised, and to experience slower rates of rural–urban migration as well as slower rates of natural population growth in cities. In contrast, less-developed countries can be expected to be less urbanised and to experience faster rates of rural–urban migration as well as higher rates of natural population growth in cities. These trends can be observed in Fig. 6.2 and Table 6.1, both of which are based on recent U.N. projections (U.N., 2008, file 3).

Several patterns can be observed in both figure and table. First, the world urban population is expected to increase: from 3 billion in 2000 to 5 billion in 2030 and to 6.4 billion in 2050. Second, the rate of increase of the world urban population is expected to slow down: from 2% per annum in 2000 to 1.65 in 2030 and to 1.14% in 2050. Third, the urban population in less-developed countries will grow at a rate *five times faster* than the urban population in more-developed countries. Fourth, the urban population of the more-developed countries will stabilise at around 1 billion people. Fifth, almost all the growth in the world urban population will take place in less-developed countries: it will increase from 2 billion in 2000 to 4 billion in 2030 and to 5.5 billion in 2050. Sixth, within the less-developed countries the fastest growth in the urban population will occur in Sub-Saharan Africa, followed by South and Central Asia.

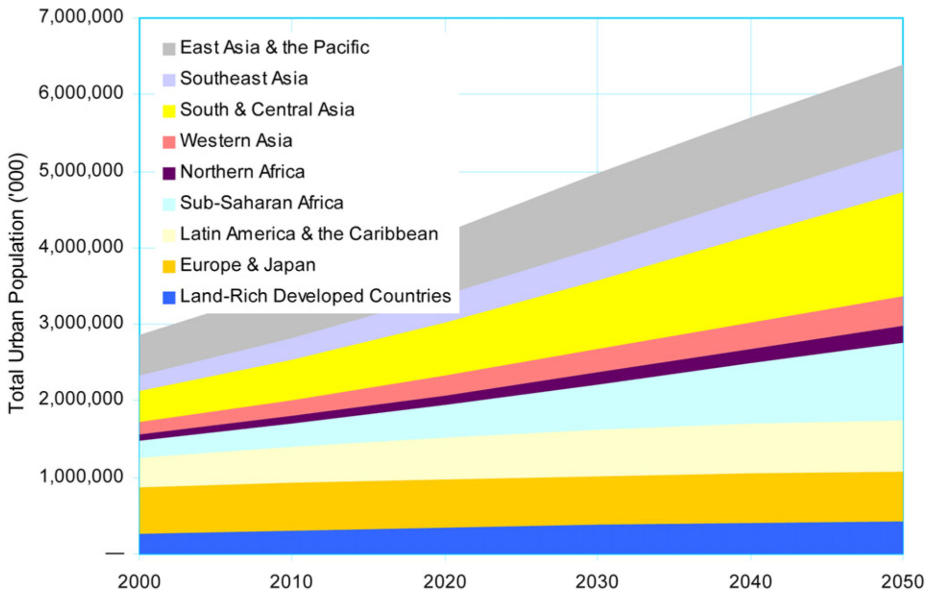


Fig. 6.2. Urban population projections for different world regions, 2000–2050. *Note:* Urban population totals for each region are shown as cumulative, so that the total world urban population is seen as the sum of all regional populations.
Source: U.N. 2008. World Urbanisation Prospects: the 2007 Revision, File 3.

Table 6.1
Urban population projections for different world regions, 2000–2050.

Region	Urban population ('000)										
	2000	Annual growth rate (%)	2010	Annual growth rate (%)	2020	Annual growth Rate (%)	2030	Annual growth rate (%)	2040	Annual growth rate (%)	2050
East Asia and the Pacific	517,808	2.67	676,086	2.05	829,877	1.43	957,030	0.91	1,047,771	0.53	1,105,254
Southeast Asia	206,683	3.27	286,579	2.44	365,769	1.84	439,465	1.42	506,485	1.03	561,580
South and Central Asia	406,151	2.51	522,270	2.72	685,217	2.7	897,250	2.32	1,132,092	1.89	1,368,296
Western Asia	163,087	2.22	203,587	2.03	249,445	1.67	294,920	1.38	338,476	1.08	377,265
Northern Africa	84,167	2.39	106,877	2.27	134,047	2.01	163,815	1.71	194,340	1.35	222,442
Sub-Saharan Africa	210,046	3.7	304,090	3.48	430,685	3.21	593,917	2.85	790,099	2.45	1,009,641
Latin America and the Caribbean	393,208	1.79	470,187	1.42	541,737	1.06	602,256	0.75	649,477	0.48	681,383
Europe and Japan	603,134	0.21	615,652	0.17	626,196	0.17	636,618	0.08	641,597	−0.04	638,840
Land rich developed countries	269,694	1.36	308,949	1.13	346,025	0.91	378,910	0.73	407,479	0.59	432,456
Less developed countries	1,981,149	2.6	2,569,675	2.31	3,236,777	1.99	3,948,653	1.65	4,658,742	1.34	5,325,861
More developed countries	872,829	0.58	924,601	0.5	972,220	0.44	1,015,528	0.33	1,049,076	0.21	1,071,296
World	2,853,978	2.02	3,494,276	1.86	4,208,997	1.65	4,964,182	1.4	5,707,818	1.14	6,397,158

6.3. Projecting the decline in urban population density

Surely, the increases in the urban population will lead to the expansion of urban areas. Cities occupy land and city people use that land. Land in urban use includes all land in residential, commercial, industrial, and office use; land used for transport, parks, and public facilities; protected land, and vacant land. Clearly, the more people there are in cities, the more land is needed to accommodate them. They key metric for estimating *how much* land will be required to accommodate the urban population is the average urban land per capita, or more commonly its reciprocal, the *average population density* in urban areas. This measure is simply the ratio of the urban population and the actual area that the city occupies. If, for example, that density remains unchanged, then the doubling of the urban population will result in the doubling of the area of the city. If density increases, when the population of a city doubles its land area will less than double. And if density declines, when the population of a city doubles its land area will more than double.

In the past, researchers have found it difficult to compare average densities because there was considerable confusion regarding the actual *area* of the city. With the advent of satellite imagery we can now identify the built-up area of a city by its impervious surfaces (pavements, rooftops, and compacted soils). We can then measure the *built-up area density* of a city as the ratio of the population and the built-up area within an administrative boundary that contains that area.

In our previous study of densities (Angel et al., 2010), we have shown that average density in the built-up areas of a global sample of 120 cities *declined* at a mean annual rate of $2.0 \pm 0.4\%$ between 1990 and 2000. There was no significant difference in the rate of decline between more-developed and less-developed countries. Average urban census tract densities declined at $1.9 \pm 0.3\%$ per annum in 20 U.S. cities between 1910 and 2000. Urbanised area densities declined at the long-term annual rate of $1.5 \pm 0.3\%$ in a global sample of 30 cities between 1890 and 2000.

Three figures from our previous study are reproduced here to illustrate the decline in density. Fig. 6.3 shows that between 1990 and 2000 average built-up area densities declined in 75 out of the 88 (6 out of 7) developing-country cities, in all 13 cities in land-rich developed countries (The U.S., Canada and Australia), and in all 19 cities in Europe and Japan in the global sample (all cities below the 45° line experienced a density decline). As noted earlier, during the 1990s the average rate of decline was $2.0 \pm 0.4\%$ per annum.

Fig. 6.4 summarises the results of our examination of the density graphs for the global sub-sample of 30 cities. Urban densities peaked, on average, in 1894 ± 15 and then began to decline, and latest city in the sample to attain a density peak was Guatemala City in 1950. The

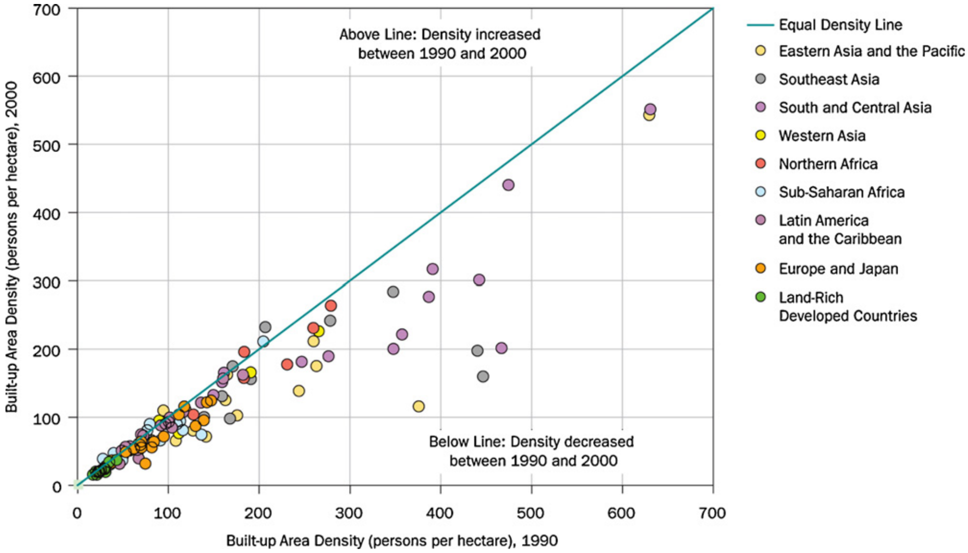


Fig. 6.3. The decline in the average density of the built-up areas in a global sample of 120 cities, 1990–2000.

average long-term annual rate of density decline from peak in the twentieth century was $-1.5 \pm 0.3\%$ per annum.

Fig. 6.5 illustrates the changing rate of decline in average tract densities in 20 U.S. cities between 1910 and 2000. Annual rates of decline in average tract density, based on two data points ten years apart, appear to have peaked in 1940s and 1950s, when they averaged 3% per annum and are now on the decrease: they averaged only 0.3% per annum in the 1990s. In fact, between 1990 and 2000 six out of 20 cities registered a modest increase in average tract density: New York, Washington, Los Angeles, St. Paul, Syracuse, and Nashville. Hence, whilst average densities in U.S. cities have been in general decline for almost a century, they may slowly be reaching a plateau. The data shown in red in the graph are for the 20 U.S. cities for which we have data from 1910 to 2000. The data shown in blue is for a larger set of 65 cities and metropolitan areas for which average tract densities could be calculated from 1950 onwards.

Based on the results of our earlier study, we projected urban land cover in all countries based on three density scenarios:

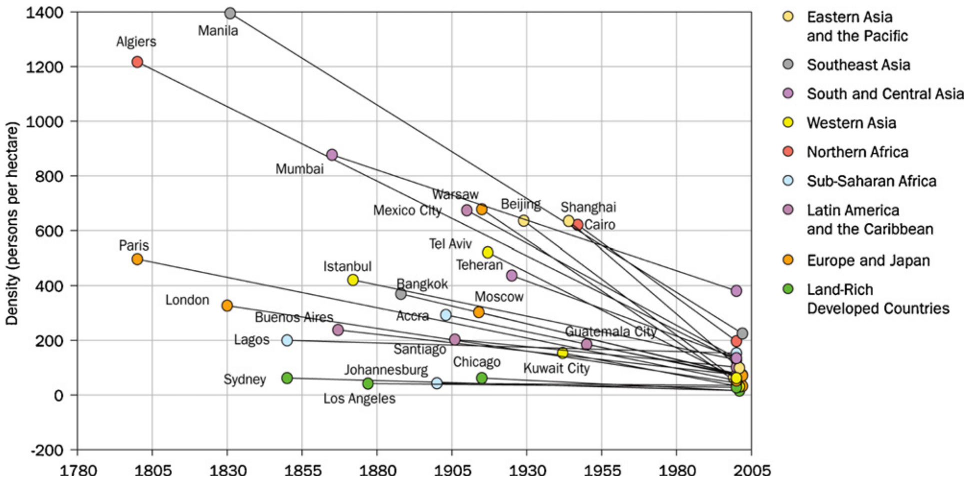


Fig. 6.4. The decline in average density of urbanised areas in a global historical sample of 30 cities, 1800–2000.

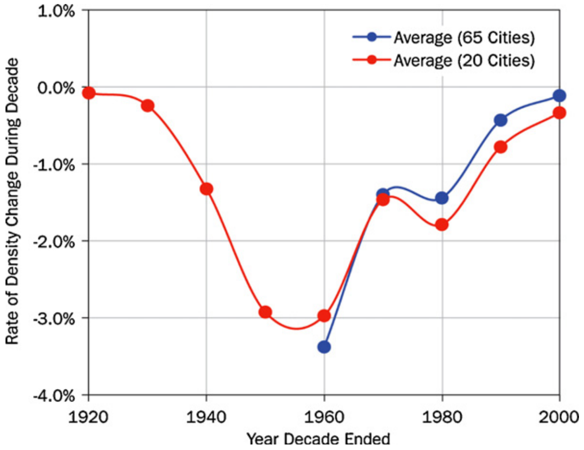


Fig. 6.5. Average rate of annual tract density change in 20 cities (red) and 65 cities (blue) in the U.S., 1910–2000. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

1. *High projection*: assuming a *two percent (2%) annual rate of density decline*, corresponding to the average rate of decline in our global sample of 120 cities, 1990–2000.
2. *Medium projection*: assuming a *one percent (1%) annual rate of density decline*, corresponding to (yet lower than) the long-term rate of density decline in the twentieth century observed in our historical sub-sample of 30 cities.
3. *Low projection*: assuming constant densities, or a *zero percent (0%) annual rate of density decline*, corresponding to the observed rate of urban tract density decline in the 1990s in U.S. cities.

We selected these three projections as the most realistic ones. Surely, it may be argued that in the future effective policies will be found for increasing urban densities, resulting in reductions of the projected urban land cover. However, no such policies have been identified in any country at the present time. On the whole, there are very few cities in the world where densities are increasing and, to the best of our knowledge, no city where densities are increasing as a result of conscious policies. We therefore urge the reader to consider our three projections as the most realistic projections at the present time. In some countries, in China and India, for example, the high projections may prove to be more appropriate, whilst in others, say in the United States for example, the low projection may prove to be more realistic. Low projections may also be associated with the increase in gasoline prices, because of monopolistic pricing practises, declining supplies, the increasing cost of production, or increased taxation. If the models discussed earlier are correct, then the doubling of gasoline prices every decade may be sufficient to keep densities from declining.

6.4. Projections of urban land cover in countries and world regions, 2000–2050

The three projections of urban land cover for all world regions are presented graphically in Figs. 6.6–6.9 and in Table 6.2. Projections for all countries for 2000–2050 are presented in Angel et al., 2010. Several patterns can be observed in the figures and in the annex. First, comparing Figs. 6.5–6.7 we can see that a 1 or 2% annual decline in urban densities has a major impact on urban land consumption. At constant densities, the world's urban land cover, for example, will only double between 2000 and 2050, as the world's urban population doubles. At a 1% annual rate of density decline it will triple. At a 2% annual rate of decline it will increase more than fivefold. Second, because urban land consumption is a function of both urban population growth *and* density decline, regions that will experience rapid population growth will multiply their urban land cover much faster than regions experiencing slow urban population growth. Urban land cover in Sub-Saharan Africa, for example, will expand at the fastest rate: if densities there decline, on average, at 2% per annum, then urban land cover will need to expand *more than 12-fold* between 2000 and 2050.

To conclude this section, we note that less-developed countries are likely to experience much higher levels of urban expansion than the more-developed countries. It may be reasonable to assume that urban expansion in land-rich developed countries will be slower, given that urban densities there are already lower and density declines may be reaching a plateau. We do note that between 1990 and 2000 densities in both land-rich developed countries and in Europe and Japan declined at the rate of 2% per annum.

If we assume that urban containment strategies in more-developed countries become much more effective in the coming decades and that densities in more-developed countries remain unchanged (low projection), urban land cover there will grow by 63% between 2000 and 2030, and by 114% between 2000 and 2050. Urban land cover in the more-developed countries will therefore increase from 305,816 km^2 in 2000 to 499,974 km^2 in 2030 and to 655,476 km^2 in 2050. In other words, at a 1% annual decline in

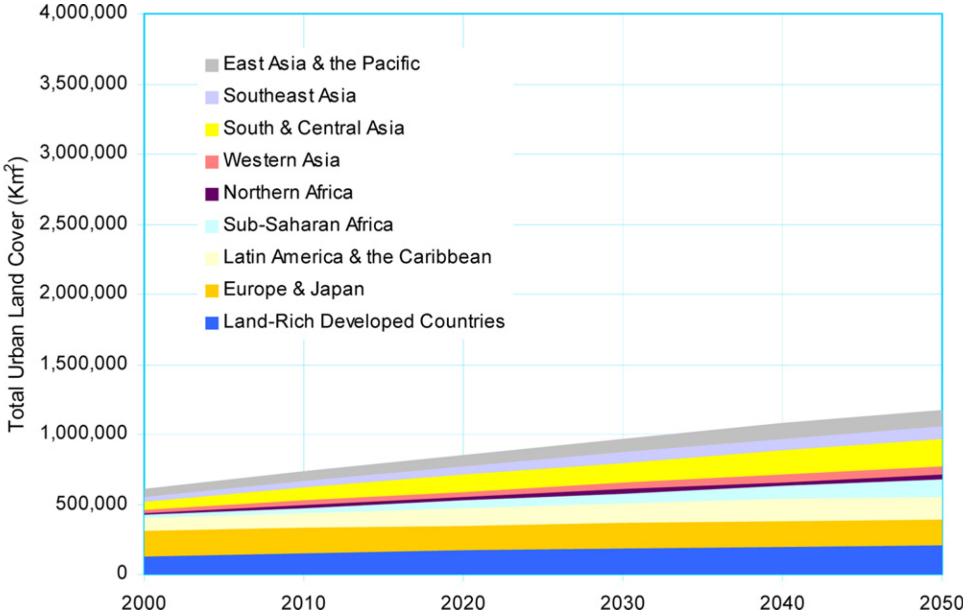


Fig. 6.6. Low projections of urban land cover in world regions assuming that average densities in the year 2000 remain unchanged.

average densities, urban land cover in more-developed countries will double in 50 years. If incomes continue to increase relative to gasoline prices and densities continue to decline at the 2% rate as they did in the 1990s, then urban land cover in more-developed countries will more than double between 2000 and 2030, and will triple between 2000 and 2050.

The situation is likely to be even more critical in less-developed countries, where most urban population growth will take place. Assuming that densities there decline, on average, by only 1% per annum

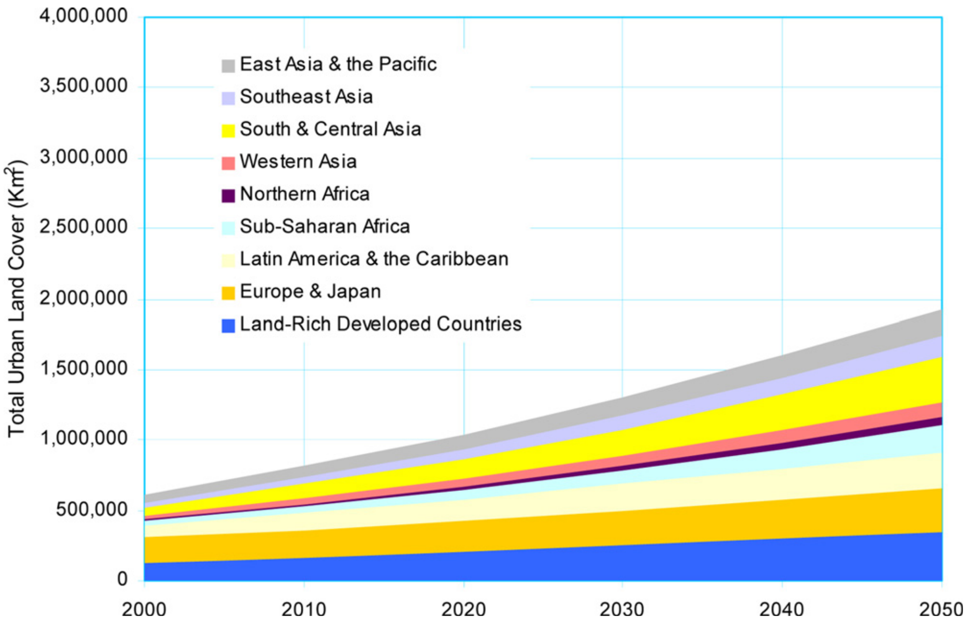


Fig. 6.7. Medium projections of urban land cover in world regions assuming that average densities in the year 2000 will decline at 1% per annum.

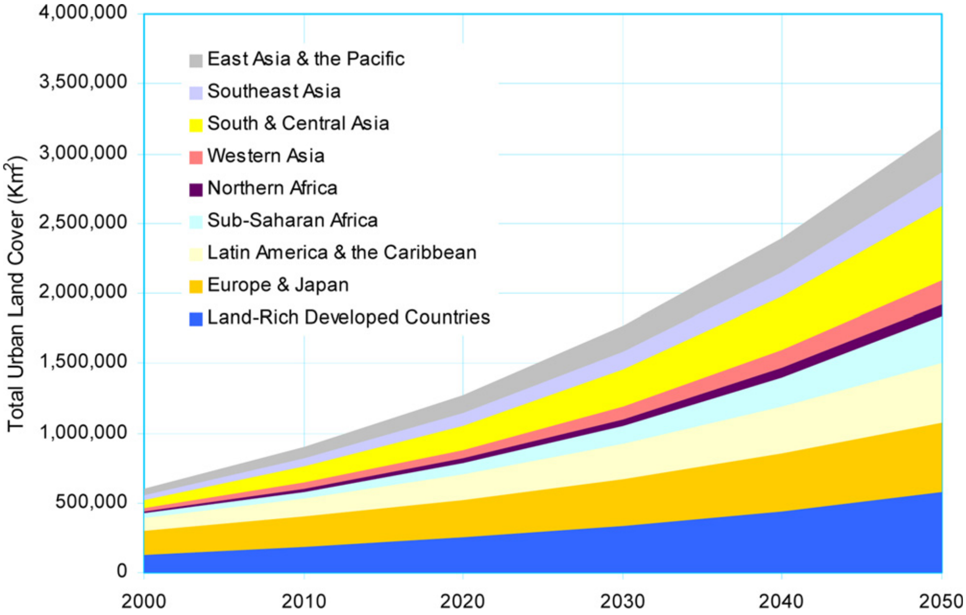


Fig. 6.8. High projections of urban land cover in world regions assuming that average densities in the year 2000 will decline at 2% per annum.

(medium projection), urban land cover will grow by 158% between 2000 and 2030, and by 315% between 2000 and 2050. In other words, at the medium projection, urban land cover in less-developed countries will grow from 297,048 km^2 in 2000 to 767,226 km^2 in 2030 and to 1,233,461 km^2 in 2050. Assuming that densities in less-developed countries decline, on average, by 2% per annum (high projection) as they did in the 1990s, urban land cover will grow by 249% between 2000 and 2030, and by 585% between 2000 and 2050. In other words, urban land cover in less-developed countries will grow from 297,048 km^2 in 2000 to 1,035,647 km^2 in 2030 and to 2,033,633 km^2 in 2050.

The implications of this massive expansion will be explored in the concluding section of this paper.

7. Directions for future research

The availability of a new universe of named large cities and better estimates and projections of urban land cover in all countries and regions makes it possible to explore the effects of present and future urbanisation and urban land cover on several important global issues. Three such issues have been identified for further study: (1) the effect of urban land cover on carbon emissions; (2) the projected loss of arable land due to urban expansion; and (3) the vulnerability of low-lying coastal cities to the rise in ocean levels. We briefly discuss the present state of our investigations into these research topics in this section.

7.1. The effect of urban land cover on carbon emissions

We are interested in testing the following hypothesis:

> Other things being equal, the larger the amount of land in urban use in a country, the larger the total volume of its CO_2 emissions.

It has been noted that urban areas generate intra-urban travel and the more spread out they are, the greater the number of vehicle miles travelled, and the greater the amount of carbon dioxide emissions. It has also been observed that multi-story buildings emit less carbon that single-story ones (see Dodman, 2009, for a recent review of the literature). If we can accept the above hypothesis, then we can conclude that urban land cover is a significant contributor to CO_2 emissions. In other words – other things being equal – the larger the amount of land in urban use in a given country, the greater the CO_2 emissions in that country.

If the above hypothesis is true, then the emerging concerns with global warming and the recognised need to slow it down may call for discouraging fragmented urban expansion at low densities, encouraging infill development, removing regulatory barriers to higher-density urbanisation, and preparing adequate lands for

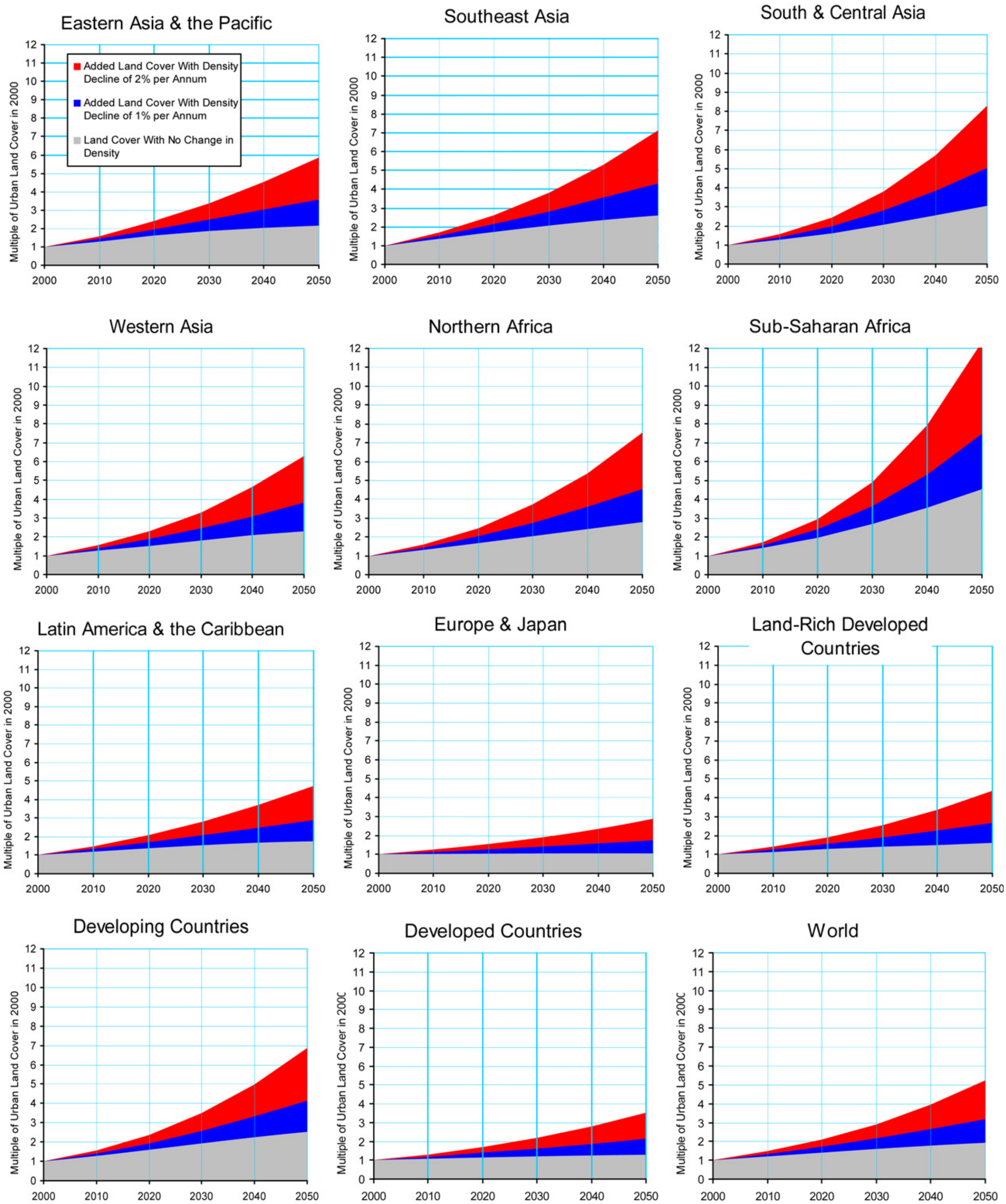


Fig. 6.9. Projections of urban land cover for world regions, 2000–2050. *Note:* The projections of urban land cover are shown as multiples of the regional urban land cover in 2000. The grey area projects urban land cover assuming average country densities remain unchanged. The blue and red areas project the added urban land cover assuming a 1% and 2% annual decline in average country densities respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Table 6.2
Projections of urban land cover for world regions, 2000–2050.

Region	Urban land cover, 2000 (km^2)	Annual density decline (%)	Urban land cover projections (km^2)				
			2010	2020	2030	2040	2040
East Asia and the Pacific	50,036	0	65,610	80,604	93,128	102,196	108,100
		1	72,510	98,450	125,710	152,459	178,227
		2	80,136	120,247	169,690	227,442	293,847
Southeast Asia	34,448	0	47,876	60,635	72,190	82,467	90,619
		1	52,911	74,060	97,446	123,027	149,406
		2	58,476	90,457	131,538	183,534	246,328
South and Central Asia	59,872	0	76,161	97,511	124,412	153,609	182,187
		1	84,171	119,100	167,938	229,158	300,376
		2	93,023	145,469	226,693	341,864	495,237
Western Asia	22,714	0	28,685	34,846	41,189	47,216	52,591
		1	31,702	42,561	55,599	70,438	86,708
		2	35,036	51,985	75,051	105,081	142,957
Northern Africa	12,104	0	15,385	19,569	24,006	28,448	32,535
		1	17,003	23,901	32,404	42,439	53,641
		2	18,791	29,193	43,741	63,311	88,439
Sub-Saharan Africa	26,576	0	38,316	53,339	72,806	96,251	122,685
		1	42,346	65,148	98,278	143,590	202,274
		2	46,799	79,572	132,661	214,211	333,493
Latin America and the Caribbean	91,298	0	109,894	126,611	140,646	151,697	159,414
		1	121,452	154,644	189,852	226,305	262,829
		2	134,225	188,882	256,273	337,608	433,332
Europe and Japan	174,637	0	178,279	181,256	184,409	185,970	185,299
		1	197,029	221,386	248,927	277,435	305,506
		2	217,750	270,402	336,016	413,885	503,695
Land rich developed countries	131,180	0	151,564	169,830	185,981	200,007	212,267
		1	167,504	207,430	251,048	298,375	349,969
		2	185,121	253,356	338,879	445,123	577,002
Less developed countries	297,048	0	381,927	473,115	568,375	661,885	748,132
		1	422,094	577,864	767,226	987,416	1,233,461
		2	466,487	705,804	1,035,647	1,473,051	2,033,633
More developed countries	305,816	0	329,843	351,085	370,390	385,977	397,566
		1	364,533	428,817	499,974	575,810	655,476
		2	402,871	523,758	674,894	859,008	1,080,697
World	602,864	0	711,770	824,200	938,765	1,047,862	1,145,698
		1	786,628	1,006,680	1,267,200	1,563,226	1,888,936
		2	869,358	1,229,562	1,710,542	2,332,059	3,114,330

Note: Urban land cover in the year 2000 is taken from Table 3.1 above.

urban expansion at densities that can sustain public transport.

For the first time, our research team now has estimates of the amount of land cover in each country, as well as for land cover in large cities in the year 2000. We also have data on the total amount of CO_2 emissions in the year 2000 from the World Resources Institute's website (accessed March 2010). And we can use these data, together with IMF data on the GDP of countries in the year 2000 (IMF website accessed March 2010) to test the above hypothesis.

We know that countries that are richer in terms of per capita income also have a larger share of their population in urban areas, and we should expect urban areas to use more resources per capita and therefore to generate higher levels of CO_2 emissions per capita than rural areas. We also know from the models presented in Section 5 that cities in high-income countries consume more land per person than cities in low-income countries.

Before turning our attention to the effect of urban land cover on CO_2 emissions in a given country, we can safely assert that the total volume of CO_2 emissions from all sources is largely a function of the total volume of resource use in the country – i.e. the more resources used, the higher the level of emissions. We should therefore expect the volume of CO_2 emissions to be largely dependent, first and foremost, on the Gross

Domestic Product (GDP) of the country. This is indeed the case. Variations in GDP amongst 148 countries in 2000, measured in U.S.$, explained 84% of the variation in CO_2 emissions. This is shown in Fig. 7.1 and in model 1 in Table 7.1. Model 1 suggests that a 10% increase in country GDP is associated with a 9.5% increase in total CO_2 emissions.

Variations in urban land cover amongst 152 countries in the year 2000, measured in square kilometres of the built-up areas of large cities in logarithmic form, explained 78% of the variations in CO_2 emissions. This is shown in Fig. 7.2 and in Model 2 in Table 7.1. The data suggests that a 10% increase in urban land cover in the country is associated with an 11.3% increase in total CO_2 emissions in the country.

Variations in urban land cover amongst 152 countries in the year 2000, measured in square kilometres of the urban land cover of large cities in logarithmic form, explained 78% of the variations in CO_2 emissions. This is shown in Fig. 7.2 and in Model 2 in Table 7.1. The data suggests that a 10% increase in urban land cover in the country is associated with an 11.3% increase in total CO_2 emissions in the country.

We can see that variations in urban land cover explain only slightly less of the variation in total levels of CO_2 emissions amongst countries than variations in GDP. The question is whether variations in urban land cover explain variations in levels of CO_2 emissions amongst countries *once we have accounted for variations in levels of GDP*. Indeed, as noted earlier, the hypothesis articulated above seeks to examine the effect of differences in urban land cover on differences in carbon dioxide emissions only once we have accounted for variations in levels of resource use.

This hypothesis is tested in Model 3 in Table 7.1. Model 3 is a multiple regression model with the logarithm of total CO_2 emissions in the country as a dependent variable and both the logarithm of GDP and the logarithm of urban land cover in large cities in the country as independent variables. The scatter plot of the model shown in Fig. 7.3 suggests that there is no significant heterogeneity of variance or a distinctive pattern.

Model 3 needed to be checked for a multicollinearity problem because, as noted earlier, GDP and urban land cover are known to be correlated. The SPSS statistical

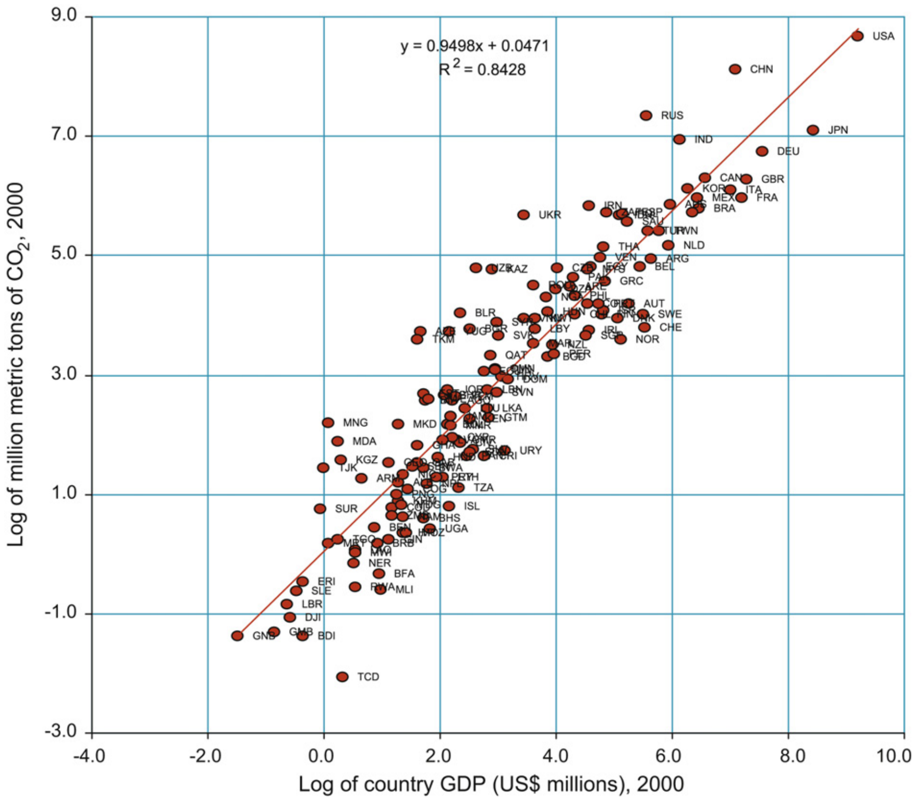


Fig. 7.1. CO_2 emissions as a function of country GDP (in log form), 2000.

Table 7.1
Regression models with log of total country CO_2 emissions, 2000, as a dependent variable.

Independent variables	Coefficients and levels of significance		
	Model 1	Model 2	Model 3
Log of GDP (U.S.$ billions), 2000	0.950	–	0.604
Signif. (2-sided)	*0.000*		*0.000*
Log of urban land cover in large cities (km^2), 2000	–	1.126	0.499
Signif. (2-sided)		*0.000*	*0.000*
Constant	0.047	−3.955	−1.949
Signif. (2-sided)	*0.705*	*0.000*	*0.000*
No. of observations (countries)	148	152	148
R-squared	0.843	0.781	0.887
Adjusted *R*-squared	0.842	0.779	0.885

program used to test the model indicates that the *tolerance* of the logarithm of urban land cover is 0.283 and therefore that its *variance inflation factor* (VIF), the reciprocal of tolerance, is 3.534. Several analysts suggest that a VIF value less than 4 is acceptable and indicates that there may not be a severe multi-collinearity problem in the model (See, for example, Andrews, n.d.) Collinearity diagnostics in SPSS further show that no variable has a *condition index* greater than 15, also suggesting that there is no serious multi-collinearity problem with Model 3. This leads us to conclude with a 95% level of confidence that the coefficient of the logarithm of urban land cover in Model 3 is significantly different from 0.

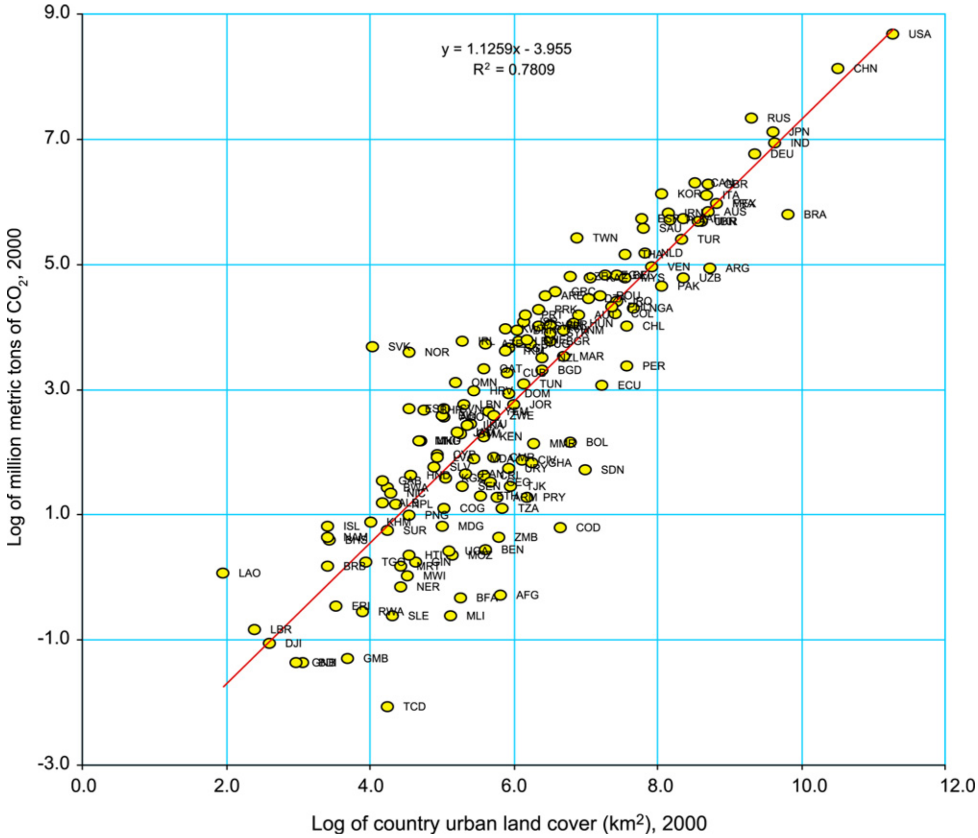


Fig. 7.2. CO_2 emissions as a function of urban land cover in large cities (in log form), 2000.

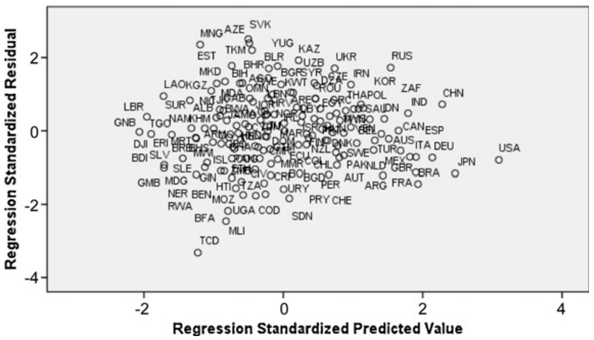


Fig. 7.3. Scatter plot of model 3 with carbon emissions in the country as a dependent variable (in log form).

If we can be satisfied that the model presented here has no serious multicollinearity problem, then the hypothesis stated earlier must be accepted, and we must conclude that, other things being equal, the larger the urban land cover in a given country, the greater the total amount of carbon dioxide emissions in the country is likely to be.

This finding, if it can be supported by further research along the lines suggested here, has serious policy implications: it suggests that, in the interest of slowing down global warming, there may be value in discouraging fragmented urban expansion at low densities, in encouraging infill development, in removing regulatory barriers to higher-density urbanisation, and in preparing adequate lands for urban expansion at densities that can sustain public transport. Surely, the containment and densification of urban areas may carry political, economic, and social costs, and it should not be surprising if these costs will be shouldered by some and not by others. And whilst it is not clear that societies may necessarily opt for choosing these strategies over others as their most cost-effective strategies to confront carbon emissions, they would clearly need to be carefully considered as some amongst many strategies than can effectively contain the increase in carbon emissions.

7.2. The projected loss of arable land due to urban expansion

Fig. 7.4 shows urban land cover as a share of the arable and permanent crop land in all countries. In the world at large, the area in urban use amounted to 3.93% of the arable land and permanent crop area in the year 2000. Cities thus occupied less than one twenty-fifth of the area occupied by arable land on the planet in 2000. The ratio of urban land to arable land was higher in more-developed countries (5.1%), than in less-developed countries (3.2%). Amongst world regions, it was highest in Latin America and the Caribbean (5.6%) and in Europe and Japan (5.6%), and lowest in Sub-Saharan Africa (1.5%).

A visual comparison of the map in Fig. 7.4 with the map in Fig. 4.4 presented earlier suggests that urban land as a share of *arable* land in a given country is correlated with urban land as a share of the *total* land area in that country. This is indeed the case: a linear regression model with the former as an independent variable and the latter as a dependent one explains more than half the variation in the latter ($R^2 = 0.52$).

Data on the urban land as a share of arable land in all countries is presented in Angel et al., 2010. The Annex

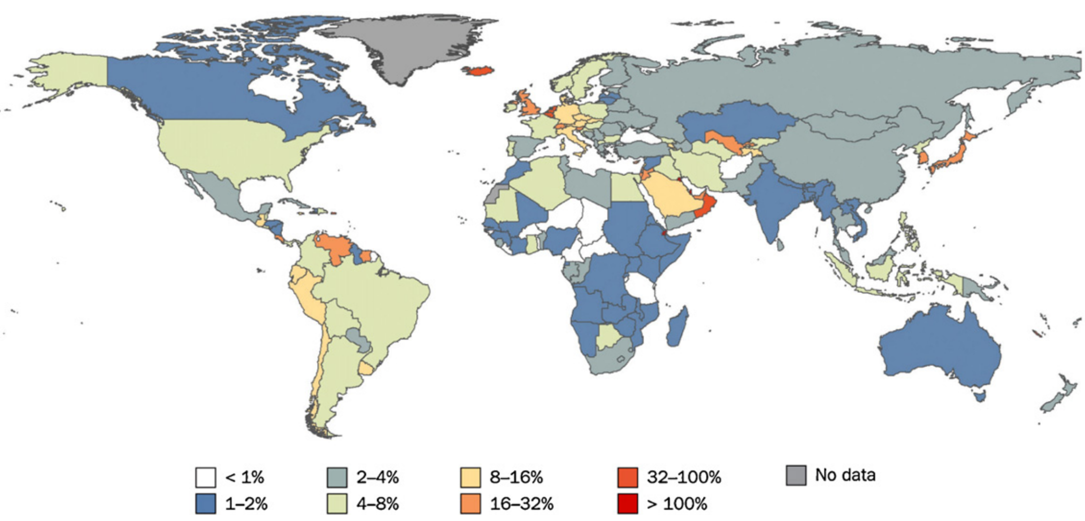


Fig. 7.4. Urban land cover as a share of arable land in all countries, 2000.

shows that amongst the countries that had large cities in 2000, five countries had more land in urban use than arable land: Singapore, Bahrain, Kuwait, Djibouti, and Qatar. Urban land cover in three countries was more than half the arable land cover: Puerto Rico (91%), Iceland (86%), and Belgium (59%). Urban land cover in 12 countries comprised 20–50% of arable land cover, amongst them the Netherlands (38%), Japan (31%), and the United Kingdom (23%). Urban land cover in 14 more countries comprised 10–20% of arable land cover, amongst them the Republic of Korea (18%), Venezuela (17%) and Germany (15%). Urban land in 29 additional countries comprised 5–10% of arable land cover, amongst them Egypt (8%), the United States (6.3%) and Brazil (6.2%). Urban land cover in 45 more countries comprised 2–5% of arable land cover, amongst them Iran (4%), Argentina (4%), China (3.0%), and the Russian Federation (2.1%). Urban land cover in 35 more countries comprised 1–2% of arable land cover, amongst them India (1.8%) and Canada (1.7%). The 12 remaining countries had urban land cover that comprised less than 1% of arable land cover, amongst them Tanzania (0.9%) and Afghanistan (0.4%).

We note that the numbers presented here suggest that the common perception of cities taking up a substantial share of the arable land of countries may be exaggerated. Cities occupied less than one twenty-fifth of the area occupied by arable land on the planet in 2000. But that said, the future expansion of cities into arable lands remains a cause for concern, particularly in countries like China that are worried about food security, i.e. producing enough food themselves to feed their own populations without relying on food imports. More generally, if massive global urban expansion is to take place in the coming decades, we must ask ourselves how much of it will displace cultivated land. The displacement of cultivated land by urban land cover will require bringing new land into cultivation where possible as well as increasing land productivity. Both will be necessary, in fact, to produce the increased amount of food that will be required to feed a growing global population, a population that is also likely to have more resources that can be spent on better foods, on more varied foods, and on foods that require a lot of land to produce them (e.g. beef).

In this paper, we projected urban land cover into the future, but we do not know how much of the projected urban expansion will displace cultivated land. We should certainly not assume that *all* the projected expansion will displace cultivated land, but since cities are often located in farming regions and are often surrounded by farmland, we can suspect that considerable amounts of farmland will be lost to urban expansion.

In our proposed research, we plan to use the MOD500 land cover map for the year 2000 as our database. This land cover map contains information on 16 different types of land cover, including several types of land covers associated with cultivated and permanent crop land. We can create equidistant buffers around every one of the 3,646 urban clusters in our universe of large cities, buffers that correspond to the projected increase in urban land cover in each cluster in every decade from 2000 to 2050, assuming that cities will expand evenly in all directions at the country's projected rate of urban expansion. We can then superimpose these buffers on the MOD500 land cover map to determine how much cultivated land will be lost to urban expansion in every decade, given our low, medium and high projections of the growth in urban land cover in the country. This will make it possible to obtain a first estimate of how much cultivated land will be lost in every country in every decade given our projections of urban expansion.

The projected losses of cultivated land may or may not be a cause for alarm, depending on the projected increases in population, on the projected extension of cultivation to new areas, on the loss of arable lands to desertification, flooding or abandonment, and on the increases in agricultural land productivity. The results of this proposed research will provide the quantitative data necessary for more rigorous assessments of the effects of urban expansion on the loss of farmland, a subject that often generates heated yet ill-informed debate.

7.3. The vulnerability of low-lying coastal cities to the rise in ocean levels

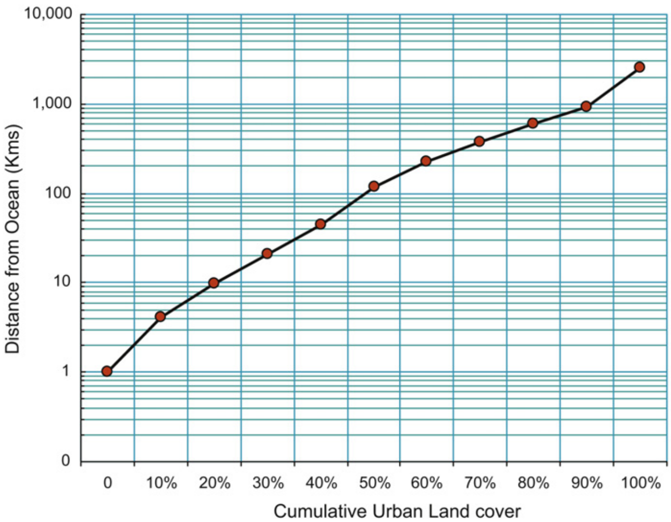
The most reliable assessment to-date of the amount of land in urban use that is located in the Low Elevation Coastal Zone (LECZ) is the work of McGranahan, Balk and Anderson (2007). The authors define the zone as ''land area contiguous with the coastline up to a 10-metre rise in elevation'' (21). They estimate urban land cover in the zone in the year 2000 to be of the order of 279,000 km^2, and the cities in the zone to house some 360 million people (Table 1, 24). They use the GRUMP urban land cover map discussed earlier in Section I to estimate urban land cover. They use the *Shuttle Radar Topography Mission* (SRTM) elevation dataset (NASA, 2003) to distinguish a 10-m rise in elevation above sea level. They do acknowledge that ''[s]ea-level rise is not expected to reach anything like 10 m above the current mid-tide elevations, at least in the foreseeable future'', and that ''the principal reason for choosing this elevation is that estimates based on elevations below 10 m could not be considered globally reliable.'' (2007, pp. 21–22). As noted earlier in our paper, Potere et al. found the GRUMP map, which is based on night lights, to be quite inaccurate. Its estimation of global 'urban' land cover, 3,532,000 km^2 is more than five times the estimate of the MOD500 map, 657,000 km^2. We consider both the 10-m elevation bracket and the GRUMP global urban map to be insufficiently accurate for assessing the vulnerability of low-lying coastal cities to rising ocean levels in a rigorous manner.

Our global urban land cover map identifies 3646 named large cities and associates each one with its population and its urban land cover. We conjecture that it can provide a better estimate of the population and urban land cover in low-lying coastal areas than the GRUMP map. It is more difficult to determine the elevation of low-lying cities so as to assess their vulnerability to the rise of ocean levels. This requires the employment of a more precise elevation model, such as the one expected to become available by Infoterra (www.infoterra.com) by 2014.

For now, we can easily determine the distance of the centroids of named large cities from the coast to inquire how much urban land cover is located at what distance from the ocean. The total urban land cover of large cities in 2000 was 339,840 km^2 (Table 3.1). We have calculated the cumulative land cover in deciles in Fig. 7.5.

The figure shows that 10% of global urban land cover in large cities is located within 4 km from the coast, 20% within 10 km, 30% within 21 km, and 50% within 116 km. Even though low-lying lands in river deltas often extend more than 100 km from the coast, we can assume that most low-lying cities will be closer than 40 km from the ocean. In terms of orders of magnitude, we expect the urban land cover in large cities that are closer than 40 km from the coast to be of the order of 136,000 km^2. We can add an estimated 86,000 km^2 of land cover for small cities within 40 km of the coast using the model described in Section 2, to obtain an estimated total urban land cover of 222,000 km^2 within 40 km of the coast. In a future research project, we aim to use our new global map of urban land cover and the Infoterra elevation dataset to assess more accurately how much of the urban land cover identified in the year 2000 is vulnerable to the projected increases in ocean levels between 2000 and 2050.

To conclude, our new urban land cover map of 3646 named large cities and our new estimates of urban land cover in all countries and world regions provides us with a research instrument for investigating a set of issues that are directly related to urban land cover, its consequences, and its implications. As the next stage of our investigation, we intend to pursue these issues further and we encourage other interested researchers to do so as well. Together, using these new geographic tools, we may shed important light on the social, economic, and environmental consequences of the projected global urban expansion in the years to come. For now, we can only



Cumulative Urban Land Cover Decile	Distance from the Coast (kms)
1	4
2	10
3	21
4	44
5	116
6	229
7	380
8	609
9	928
10	2,497

Fig. 7.5. Cumulative urban land cover as a function of distance from the ocean, 2000.

speculate on what these consequences might be and ponder the policy implications of the coming transformation of our world into a planet of cities. We now turn to the outline of these policy implications in the concluding section of this paper.

8. Conclusion: making room for a planet of cities

The forces driving global urban expansion – population growth, urbanisation, rising per capita incomes, cheap agricultural lands, efficient transport, and the proliferation of informal settlements – are formidable. Accordingly, absent a highly effective policy intervention or a very steep increase in gasoline prices, there is little reason for urban expansion at declining densities to come to a halt anytime soon.

In this paper, we have sought to provide a quantitative dimension to future urban expansion, so as to present what we believe to be the necessary information for an intelligent discussion of plans and policies to manage urban expansion, whether to reverse it, contain it, guide it, or let it be. Our main concern is with the developing countries, where most urban population growth (and most urban expansion) will take place in coming decades. Effective containment strategies that champion sustainability and that are truly capable of constraining land supply for urban development are also likely to affect land markets in ways that will adversely affect the access of the urban poor to affordable housing. This is a cause for concern because it situates the three key goals of urban planning – efficiency, equity and sustainability – in direct conflict with each other.

The availability of reliable information regarding the amount of land that is likely to be needed to accommodate the growing population of many cities in the developing countries is clearly necessary for informed decision-making at the present time. Our paper offers a practical starting point for an urban planning strategy based on making a realistic assessment of the lands that will be needed to accommodate projected population growth. Given the rapid pace of urban growth, it also calls for a type of planning that is minimalist in nature, focused on making the absolute minimum preparations for urban expansion now instead of spending years planning for that expansion whilst it is taking place.

Such minimal preparation calls for plans that have three simple components (see Angel, 2008): (1) designating the areas for the planned expansion of the city or metropolitan agglomeration, areas that make available at least 20 years and preferably 30 years of land supply, given realistic population and density projections; (2) planning the arterial road (and infrastructure) grid into the expansion area with approximately 1-km between parallel roads of 25–30 m width that can carry public transport, and acquiring the right-of-way for these roads now through regulatory takings or eminent domain; and (3) identifying high-priority open spaces in the expansion area that need to be protected aggressively from urban development and creating the institutional and financial mechanisms for ensuring that they remain open in the face of pressure, be it by the formal or the informal sector, to occupy them.

Our recommended strategy for managing urban expansion in the coming decades is discussed at greater length in the Policy Focus Report published by the Lincoln Institute of Land Policy titled *Making Room for a Planet of Cities* (Angel et al., 2011b). It rejects any planning agenda for cities, especially those in developing countries, that takes the need for urban containment as a given. The refusal to plan for urban expansion at realistic densities as a matter of principle, in the belief that it should not occur, in the hope that it will not occur, or in fear of the ire of those who oppose it, may be a costly mistake.

That said, allowing densities in developing-country cities to decline to the very low levels now prevalent in the U.S., for example, may be a detrimental error too. Urban densities in developing-country cities – now averaging more than *four times* those of the U.S. – must remain within a range that can support public transport so as to limit carbon emissions, and that can allow cities to accommodate their expected population growth whilst keeping housing plentiful and affordable and whilst conserving land and energy. This may sometimes call for densification and sometimes for decongestion. Our main concern is that densification, as a goal, as a trend, or as a hope, should not be *assumed*. In fact, given the preponderance of evidence to the contrary, planning for urban expansion in developing countries assuming that density decline will persist for some time may be more realistic and more appropriate. Average urban densities in developing-countries are typically much higher than those in U.S. and European cities, and increasing their densities by containing urban expansion may incur substantial social costs:

> What is the sense, it is frequently asked, of further densification given that densities are already high and associated with a range of problems including infrastructure overload, overcrowding, congestion, air pollution, severe health hazards, lack of public and green space and environmental degradation? (*18*).

Indeed, densities in poor parts of many developing-country cities are as high, or even higher, than those existing in the overcrowded cities in Europe and the U.S. in the late 19th century, where lower densities were strongly advocated in the name of public health and safety. That said, in most parts of developing-country cities densities are not stifling but certainly high enough to support public transport (i.e. more than 30 p/ha within walking distance of stations, see Pushkarev & Zupan, 1982), a key threshold for making cities more sustainable.

We believe that the adoption of the urban containment ideology in developing countries may be counter-productive at the present time. It may lead to estimates of land needs and infrastructure investments that are insufficient for, say, 20–30 years of planned expansion at realistically projected densities. Cities may thus continue to expand in an unplanned fashion, failing to guide development in more desirable directions, failing to protect even a limited selection of high-priority open spaces from development, creating land supply bottle-necks that keep the cost of land and housing out of reach for the urban poor, and failing to secure the necessary rights-of-way for the arterial roads that can eventually carry public transport into newly-inhabited areas. It may indeed be more realistic and more sensible for the rapidly growing cities in developing countries to refrain from curbing sprawl, to assume instead that densities can continue to decline slowly whilst remaining sustainable, and to make adequate room for their projected expansion.

Surely, the containment of urban expansion may yet occur. Cities cannot and will not expand indefinitely and are likely to continue to occupy a very small share of the total land area of the planet, now of the order of less than one-half-of-one-percent. The search for cost-effective and politically-acceptable infrastructure strategies, regulations, and tax regimes that can lead to the significant containment of low-density cities, so as to make them more sustainable, must continue. In parallel, appropriate strategies for managing urban expansion at sustainable densities in rapidly growing developing-country cities must be identified and effectively employed. No matter how we choose to act, however, we should remain aware that conscious and conscientious efforts to contain urban expansion in developing countries where the population of cities is still growing at rapid rates and where densities are still sustainable may be both unrealistic and counterproductive at the present time.

Acknowledgments

The first phase of our five-year study of global urban expansion involved the collection and analysis of satellite imagery and census data in the global sample of 120 cities. It was supported by the grant from the Research Committee of the World Bank to the Transport and Urban Development Department of the Bank. We are grateful to Christine Kessides of that department for helping us obtain this grant, and to Deborah Baulk of the Centre for International Earth Sciences Information Network (CIESIN) of Columbia University for providing the census data for the sample of cities. The team that worked on this phase of the study included Shlomo Angel, Stephen Sheppard, and Daniel Civco as principal investigators, assisted by Jason Parent, Anna Chabaeva, Micah Perlin, Lucy Gitlin, and Robert Buckley.

The second phase involved the administration of a survey by local consultants in each of the 120 cities in the global sample. The survey included questions on the latest census; the status of metropolitan area planning, regulation, and enforcement; general housing market conditions; informal settlements; and financial institutions that provide mortgage loans. Supported by a grant from the National Science Foundation, the team included Shlomo Angel, Stephen Sheppard, and Daniel Civco as principal investigators, assisted by Lucy Gitlin, Alison Kraley, Jason Parent, and Anna Chabaeva. The local consultants that conducted the survey in each city are listed in Angel et al. (2010).

In the third phase we created a set of metrics for measuring urban spatial structure and a python script for calculating these metrics with ArcGIS software. This team included Shlomo Angel, Jason Parent, and Daniel Civco. Part of this research was undertaken by Jason Parent within the University of Connecticut's Centre for Land Use Education and Research (CLEAR) and its Department of Natural Resources and the Environment (NRE) under Grant NNL05AA14G: Incorporating NASA's Applied Sciences Data and Technologies into Local Government Decision Support in the National Application Areas of Coastal Management, Water Management, Ecologic Forecasting, and Invasive Species. This work was sponsored by the National Aeronautics and Space Administration.

The fourth phase involved the collection, geo-referencing, and digitising of maps at 20–25 year intervals for the period 1800–2000 for a global sample of 30 cities; the analysis of census data for 20 U.S. cities for the 1910–2000 period and 65 cities for the 1950–2000 period; the statistical modelling of the results of the all phases; and the preparation of this policy focus report. The Lincoln Institute of Land Policy supported Shlomo Angel with a two-year fellowship for research and report preparation. His team for this phase included Alejandro Blei, who prepared all the historical data, Jason Parent, and Daniel Civco. Chun Il Kim helped with the statistical models. Ann Le Royer and Robyn Salbo helped with the editing of the manuscript. Craig Cook and David Garratt helped with the graphics.

We are grateful to Gregory K. Ingram, the president and CEO of the Institute for arranging the fellowship support for our work, and for his constructive comments during this phase of the study. We also appreciate the staff of the Institute for their active support of this study, as well as for their gracious hospitality.

The authors also thank a number of people who provided useful comments and suggestions, as well as support and encouragement during the study: Richard Arnott, Ralph Gakenheimer, Alain Bertaud, Robert Bruegmann, Lucy Gitlin, Daniella Gitlin, Annemarie Schneider, Wendell Cox, Gershon Ben Schahar, Aharon Gluska, Robert Buckley, Benjamin de la Vega, Geoffrey Hyman, Martim Smolka, George Martine, Daniel Kozak, Shue Tuck Wong, Armando Carbonell, Edesio Fernandez, John Volin, and James Hurd.

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