

Measuring and Modeling Global Urban Expansion¹

by

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The process of urban expansion – conversion of land to urban uses – has been viewed with sufficient alarm to prompt attempts by the public sector to regulate it for over 300 years, and probably much longer. Historically, this expansion was concentrated in the most developed and most affluent countries of the world, where increasing urbanization was associated with economic development. In the past several decades, urban expansion has been perceived as a significant problem globally, as the share of population in urban areas increases and urbanization increases or even accelerates in countries around the world. Urban areas may then expand at astonishing rates in cities that often lack either preparation or planning for the expansion.

At the same time, for reasons unrelated to the pace of urbanization, global capacity to monitor the process of urban expansion through remote sensing has expanded dramatically. It is now possible to have access to roughly 20 years of satellite images of virtually any city, with data collected in a consistent and comparable fashion (unlike aerial photographs, which are available for an even longer time span in selected areas).

This paper reports some results from a study based on a global sample of 120 cities, chosen to be globally representative of the urban population in places having population of at least 100,000. Satellite images have been used to estimate total urban land use at two points in time for each city, and these data have been matched to population, income, and many other economic variables collected both from public sources and by field researchers in each city. We describe the process of measurement and summarize the patterns of expansion (both within the urban area and in the peri-urban zone), population density, and other information for the sample. We then present a series of estimates that examine the relationship between observed urban land use and other variables. From this we draw some preliminary lessons that can serve to usefully inform policy discussions concerning urban expansion. We conclude with a discussion of research problems whose solution may be available via enhanced data collection and global collaboration between scholars and policy makers.

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1. Introduction

From the perspective of global urbanization, the first decade of the 21st century will be seen not as the time when the problems associated with urbanization first became apparent (these have been widely understood since the 19th century and perhaps earlier) nor as the time when the basic outlines of policy solutions first attained widespread recognition if not agreement. The importance of infrastructure provision, legal institutions that recognize and seek to internalize the externalities (positive and negative) intrinsic to high density settlements, and awareness of the specific importance of housing provision for human health and social order have been understood and discussed to some degree since the cities of the classical civilizations. What sets the present time apart are two facts. One is that for the first time in history these policies directly affect the welfare of a majority of humans living on earth. The other is that for the first time, we have at our disposal in the form of remotely sensed data and some basic theories of urban form the opportunity to measure and model urban expansion on a global scale. The first of these facts is a central rationale for both increasing concern amongst policy makers and for publication of the present volume. The second is the central focus of this paper.

Like many aspects of economic and public policy, urban development policies have often fallen prey to the tendency to assume that there must be a 'local' explanation for what is better understood as part of a global phenomenon. For example, internal migration from the countryside to an urban area increases the demand for housing and results in higher prices for dwellings in the city and conversion of land from non-urban to urban uses in and around the city. This in turn leads to demands for extension of infrastructure provision and complaints about loss of access to open space. This story has been repeated (and documented) in hundreds of places ranging from 17th century London to 21st century Beijing. Frequently, the explanation is that the unique attractions of the particular city under consideration relative to the rural origins of the migrants is the source of the problem, and a variety of rural development strategies coupled with building restrictions in the cities is offered as a solution. These are almost never successful in halting the urban expansion, although they may impose considerable costs on the citizens and generate a variety of rents to be dissipated throughout the economy.

In other regions where internal migration is less important or non-existent, different local explanations become the focus of concern. There are many cities in North America and Europe whose populations have been stable or declining for several decades, but where new structures continue to be built on what was non-urban land. Perhaps the most obvious explanation for this is simply that land is a

normal good and in these cities real household income has continued to increase. As their income rises households purchase more of many different goods, but in particular they seek to purchase more housing and more land. This leads to lower density, expanding cities even when population is constant or slightly declining. The policy implications of this explanation are not particularly palatable, since few would support putting the brakes on income growth, so alternative local explanations are sought: road building and automobile ownership are identified as likely culprits, along with particular types of commercial development or general “white flight.” Numerous campaigns and local organizations have come together to oppose road building, discount retailers, and a variety of other proposed causes of urban expansion.

From a policy perspective, the difficulty with such localized explanations is not so much that they are false (although they sometimes are) but that they are only partly true. Road building and other factors that reduce transportation costs probably do encourage urban expansion, as does population growth from internal migration. Building an understanding of urban expansion requires that we be able to explain very different outcomes that emerge from apparently similar situations, as well as similar outcomes that emerge from very different situations. For example, Ibadan, Nigeria and Seoul, Korea have been experiencing urban expansion during the period of 1990-2000 of about 2.5% per year. Per capita GDP in Nigeria during this period was stagnant or declining slightly but urban population grew at nearly 3% per year. In Seoul, urban population growth was a tiny 0.5% but income growth was a robust 5% per annum during the period. To plan our cities and design effective urban policies we need to understand how these and other contributing factors of urban expansion combine and interact to produce urban outcomes. Because of limits in the local variation in values for these contributing factors, we cannot hope to achieve such an understanding by examining what appear to be the localized causes of expansion.

The data to measure total urban land use in a format for comparison with other economic variables have been available for decades in selected cities or developed countries. What has not been available is consistently measured data on urban development from a global cross section of cities over time. This has now changed. Using remotely sensed data we can assemble data on a global scale, and measure total urban land cover using the same type of data and same analytic approach in each urban area. These data are now available to cover a span of at least 20 years, so that for the first time we have the opportunity to measure and track the process of urban expansion in a very diverse cross section of economic, social and environmental conditions. This in turn permits us to test our models of

urban expansion to a degree not previously possible. This has the potential for identifying both strengths and weaknesses in our theories of these processes, and may promote development and refinements of these models.

This paper reports on one attempt in this direction. In the following sections we describe the data we have collected for this purpose, and provide a summary of the techniques we have used to measure the urban footprint in a global sample of cities. We describe an approach for measuring the “micro structure” of each urban area using the data we have assembled, and summarize our findings by global region. We then identify the primary driving forces for urban expansion that would be suggested by economic theories of urban land markets, and explicitly identify a set of testable hypotheses implied by these theories. Using our data we estimate the relation that holds between measured urban footprint and these variables as a way of testing the theory. Following this, we identify some policy implications of the research, and propose a simple “rule of thumb” for testing the extent of preparation for urban growth pressures as a way of helping to ensure that urban planning provides a realistic foundation for urban policy rather than wishful thinking about future scenarios.

Finally, we note that the combination of economically and politically important problems coupled with the data and theoretical resources to do something effective about the problems provides an opportunity for identification of an agenda for future research and study. We suggest a set of problems that are at present poorly understood, are significant for urban economic policy, and that might benefit from study in the coming decade.

2. Data

In order to measure and model global urban expansion we need to combine two types of data. First is the information required to measure the expansion of urban land use, and second is information on the economic and policy conditions that influence the pace of expansion so that we can test our models of urban expansion and determine the quantitative and qualitative nature of the relationships. For the first we rely upon remotely sensed satellite data and for the second we rely upon a variety of sources including data collected by field researchers deployed to each city in our sample. We discuss each in turn below.

Our data are collected for a global sample of 120 cities. These were randomly selected from a larger random sample constructed by UN Habitat for data collection in connection with their Urban Observatory program. The larger sample has been constructed to be representative of the global urban population in cities having population over 100,000 persons. The figure below shows the location of each city, with dots sized to indicate population and shaded to indicate per capita income. The table lists the cities by global region.

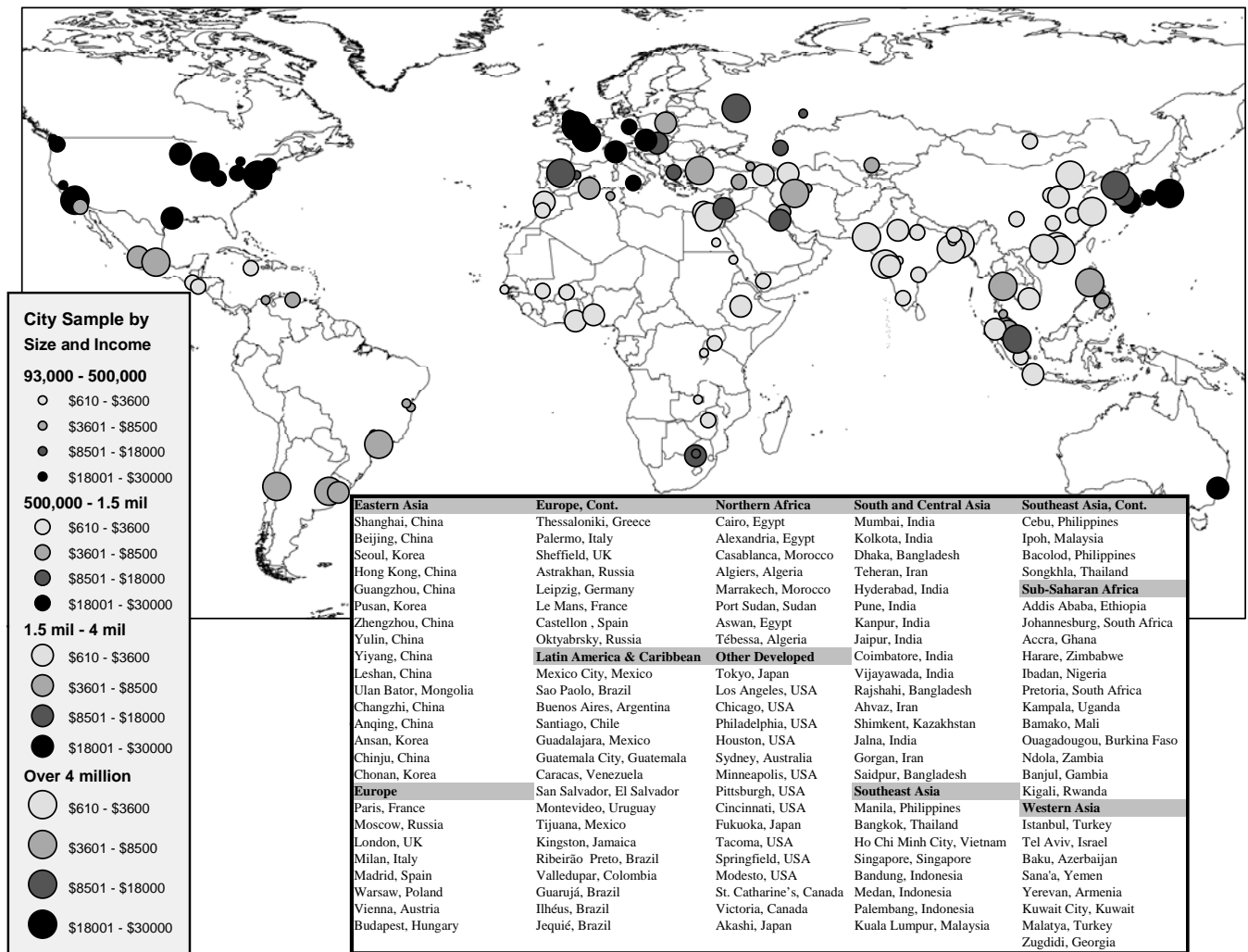


Figure 1: Global Sample of Cities

Remotely sensed data

For each of the cities in our sample, we obtained Landsat thematic mapper satellite images for dates that are relatively near the national census dates and for which cloud-free images are available. Images were obtained for two time periods: approximately 1990 and approximately 2000. The actual image dates vary and the sample mean time period between images is just over 11 years. The images themselves provide data on reflected light intensity in 7 spectral bands (3 visual and 4 infrared). These

data are used to classify each point as urban (covered with impervious built structures or surfaces), water, or non-urban (everything else) in each time period. The light intensity data that constitute the images provide values for grids of pixels each of which represents a square region 28.5 meters on a side.

There are several commercial and non-commercial data sources that provide information on global land cover. Some of these can be very useful but we chose to develop our own classification for several reasons. First, many of global land cover classifications that have been undertaken are done at relatively coarse scales (typically 1 km grids) that obscure the microstructure of the urban areas including the open spaces interior to the built-up city. Even for those that are done at finer scale, the usual practice is to “fill in” small interior open spaces and classify them as urban. Our approach has been to regard such spaces as non-urban so that we can distinguish between new capital investment and building at the urban periphery and “infill” development building inside the built up area, and this will be discussed further below.

The actual classification of land cover was done using Erdas Imagine utilizing an iterated supervised cluster analysis approach. Three passes were used for each of the two images for each city. The goal was to provide a very simple classification suited to purposes of our research: to classify each pixel as ‘urban’ or ‘non-urban’ and then in post-processing to remove water pixels (which are easily identified using unsupervised classification).

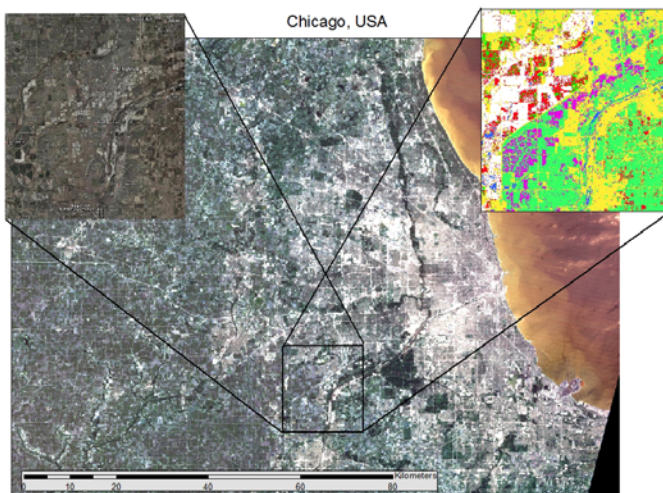


Figure 2: Chicago Landsat Image

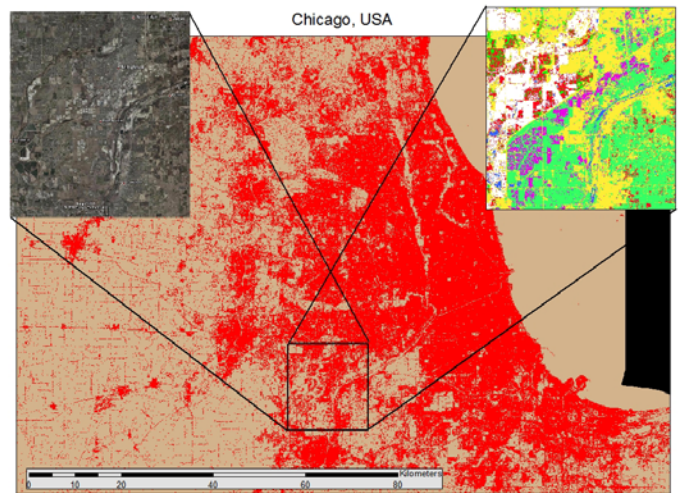


Figure 3: Chicago Urban Land Cover

Figures 2 and 3 above present stylized views of ‘before’ and ‘after’ classification using actual data for the Chicago, USA metro area. Figure 2 shows the actual Landsat image covering most of the city.

After completing the analysis the result was the data shown in Figure 3, where pixels are colored red if they were ultimately categorized as predominantly under urban cover and tan if not. The small insets showing a region in the southwestern suburban fringe show the image for the region available online from Google Earth (on the left of each figure) and the ultimate classification showing the urban dynamic discussed in section 3 below.

All of the land cover classifications produced for our study are available for download from <http://www.williams.edu/Economics/UrbanGrowth/DataDownload.htm> in a format that will display in Google Earth. These images include links to photographs taken at ‘ground truth’ points (used for evaluating the accuracy of our classifications). The areas representing urban land cover have been filtered to eliminate all areas that do not represent at least 10 hectares of contiguous urban land cover. This greatly reduces the amount of data to be downloaded. The image for Chicago is shown in Figure 4 below.

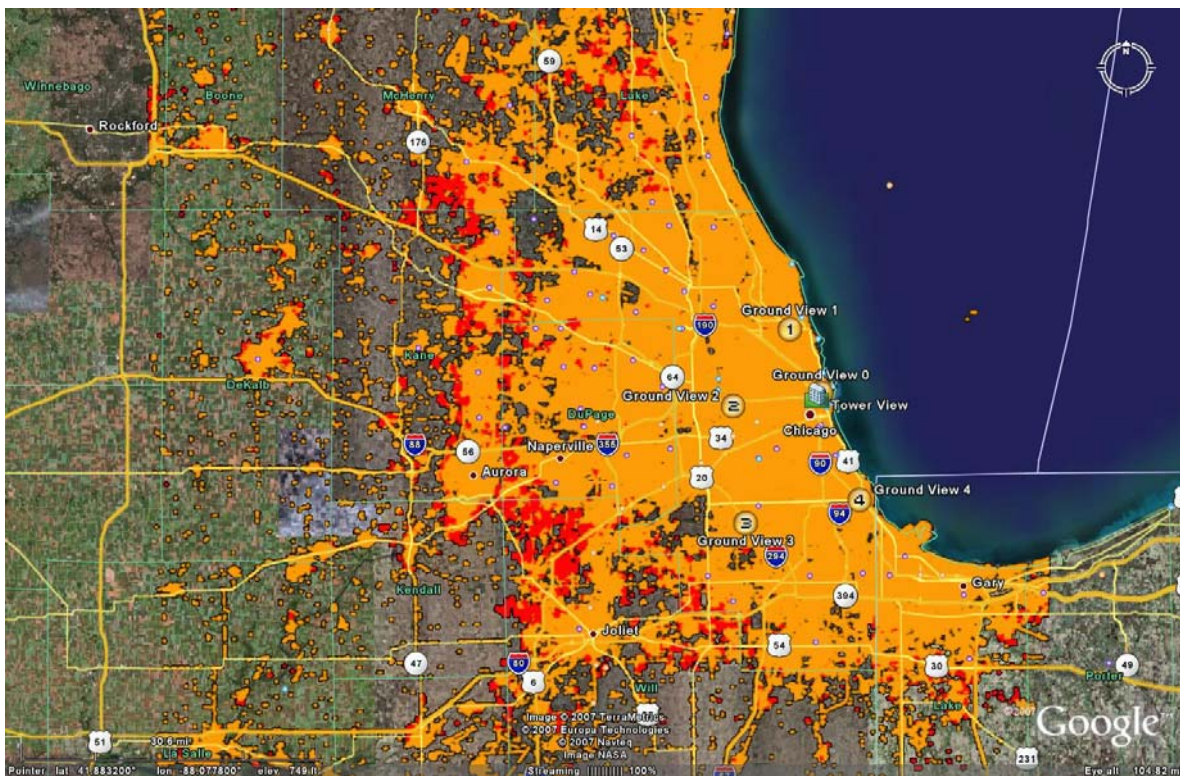


Figure 4: Chicago Urban Land Cover Available via Google Earth

An important advantage of the approach we have followed is that **identical** procedures and **identical types of source data** were applied for all 120 cities in both time periods. This is essential if we want to reliably combine and compare data from different time periods for the same city, and also if we

want to use the data to assemble a panel data set that compares a cross-section of cities around the globe over time. Such data are central to our approach of measuring and modeling urban expansion. Further details concerning the remote sensing data and classification procedure are provided in Angel, Sheppard and Civco (2005).

Economic and policy conditions

The urban land cover data described above are then matched with population data for jurisdictional boundaries in each area, obtained from the Center for International Earth Science Information Network's Global Rural-Urban Mapping Project. Using growth rates observed for each jurisdiction during 1980 through 2000 we interpolate to obtain population estimates for the dates of each image. There are many cases where the Landsat images did not provide complete coverage of the jurisdictional boundaries for which population data were available. In these cases we sometimes purchased additional Landsat images, but in other cases made use of an interpolation procedure using our land cover classification and distance from the urban center to apportion the jurisdiction population between portions covered by our remote sensing images and the portions not covered. In general the data include not only the jurisdictions covering the central city and largest contiguous regions of classified urban land cover, but extend to peripheral jurisdictions until the mean size of contiguous urban cluster falls below 25 hectares. This provides coverage that approximates a "metro area" definition for all cities even though for most of the cities we lack the data on labor markets and commuting patterns generally required for formal definition of such areas.

We also interpolate national per capita GDP to the date of the satellite image to provide an estimate of income levels in each city matched to the remote sensing data. Data on biome type, availability of shallow groundwater aquifer, air transport links, and the value of agricultural land (approximated by agricultural output per hectare) were obtained from World Development Indicators or from sources described more fully in Angel, Sheppard and Civco (2005).

Table 1 below presents descriptive statistics for the central variables used in our modeling for two times periods and 120 cities. Use of a globally representative sample provides extensive variation in the data, with cities ranging from under 9 square kilometers to over 4200, and population in the 'metro area' ranging from 93,000 to over 27 million persons.

In addition to the variables used in the models of urban expansion presented below, Table 1 provides information on additional variables that are likely to be of interest. While the sample includes many primate cities (of rank 1 in the national urban system) it includes cities down to rank 196 as well. The rate of automobile ownership varies across the sample even more than per capita income, although in general it is income rather than automobile ownership that turns out to be the most important factor influencing total urban land cover. In part this may be because increased automobile ownership does not necessarily imply reduced transportation costs, since congestion can slow travel considerably below the maximum speed of the vehicle. The average non-rush hour travels speeds are seen to vary widely. These have been collected by our field researchers.

Table 1: Descriptive Statistics for Sample

Variable	Mean	Std. Dev.	Min	Max	Obs
Total urban land (km ²)	402.81	635.11	8.92	4,268.00	240
Total Population	3,363,025.00	4,459,765.00	93,040.91	27,200,000.00	240
Per capita income (ppp \$)	\$9,914.08	\$9,916.70	\$609.88	\$35,354.00	240
Agricultural rent (ppp\$ / ha)	\$3,347.65	\$12,569.78	\$68.84	\$150,542.90	240
Fuel cost (ppp\$ / US gallon)	\$0.62	\$0.36	\$0.02	\$1.56	240
Air linkages	108.21	133.39	0	659	240
Shallow ground water	0.24	0.43	0	1	240
East Asia	0.13	0.34	0	1	240
Europe	0.13	0.34	0	1	240
Latin America	0.13	0.34	0	1	240
North Africa	0.07	0.25	0	1	240
South Central Asia	0.13	0.34	0	1	240
Southeast Asia	0.10	0.30	0	1	240
Sub-saharan Africa	0.10	0.30	0	1	240
West Asia	0.07	0.25	0	1	240
Other Developed Countries	0.13	0.34	0	1	240
Years between images	11.24	2.21	5.19	16.97	240
Change in total urban land	115.21	126.09	3.19	549.66	240
Growth rate in urban land	0.05	0.05	0	0.36	240
Urban rank	19.09	38.05	1	196	240
Cars per 1000 in country	139.47	180.55	0.39	573.28	238
Non rush hour travel speed (KPH)	27.11	13.64	2.61	75	198*
Maximum urban slope (%)	25.96	14.96	4.16	78	240

3. Measuring Urban Expansion

Before proceeding to discuss models of observed urban expansion, it is necessary to make a few observations concerning our measures of urban land, the calculations of ‘urban dynamics’ and the microstructure of urban land markets.

Urban use and urban cover

As implied in the discussion above, since our approach to measurement of global urban expansion relies upon the use of satellite images in order to have comparable data for all cities, we actually measure urban cover (buildings and roofing material, asphalt, concrete and other impervious surfaces) rather than urban land use. What this means in principle is that we do not necessarily measure total land consumption by urban residents or producers. From the perspective of a satellite image, an urban worker who purchases a 1 hectare plot adjacent to her home and plants a large and elaborate flower garden is essentially indistinguishable from a rural peasant who grows vegetables on the 1 hectare field next to his farm house. From the perspective of urban land use theory, however, these two are very different. Irwin, et al. (2006), for example, are skeptical of reliance on urban cover as the measure of urban land use, and criticize the work of Burchfield, *et al.* (2006) and others for such reliance. They advocate instead use of cadastral data with associated recorded types of activities and uses actually taking place on the land.

While the use of cadastral data is no doubt interesting, there are two responses to be made. First is that many of the most interesting urban areas in the world have very limited cadastral systems and the data recording actual land uses may either be non-existent or so prone to error that they represent little improvement over remote sensing data. Second, in practice at the scale of land use in modest to large urban areas, it seems to make very little difference. Irwin, et al. (2006) compare remotely sensed with cadastral data in particular areas of the US and while they find the total amounts of land in each category different, the qualitative nature of changes and even the rates of change of different types of land use are similar using either measure.

Finally, we note that if one is interested in the ecological, economic or social value of open space then use of urban land cover data may be preferable. From the perspective of maintaining habitat for a variety of species or providing positive externalities for which residents are willing to pay, our hypothetical urban gardener may be as productive, even more so, than the peri-urban farmer. In any event, it should be acknowledged that the measure of urban expansion and urban land consumption used below is based on urban cover. We maintain the hypothesis that this measurement is very highly correlated with actual urban land use in consumption and production. In a sense, the empirical estimates derived below and compared with theoretical predictions of the comparative static properties of models of urban land use provide a test of this hypothesis.

Open space and infill development

We referred above to the desire to provide measurements of the microstructure of urban land markets, and to characterize the dynamic of urban expansion. What do we mean by these terms?

The simplest theories of urban land markets identify urban land use as clustered around a central business district of the city, with density of urban land use gradually diminishing as distance from the city increases. Eventually the value of land in urban use falls to the level where land is more valuable in agricultural use than in urban use. That distance identifies the maximum extent of urban land use. Up to this distance, land should all be in urban use and after that distance all land is in agricultural use.

Real cities, of course, are never like this. There are areas of open, unbuilt land within – sometimes deep within – the urban area. We might regard these as mild departures from the “ideal type” of human settlement represented by our theory. Alternatively, we might note that these spaces arise for several reasons: land may be preserved for use as a public good (like a park), land may be owned by a person with idiosyncratic preferences who prefers the land this way (like our urban gardener discussed above), the land itself may be heterogeneous so that some areas are more difficult to build on due to slope or drainage, and finally the dynamic structure of the urban economy may generate greater volatility of structure prices in some areas than in others. Areas with higher volatility present land owners with increased incentive to hold land vacant since, as observed by Titman (1985) and others, vacant land is equivalent to an option to buy a building in the future with an exercise price equal to construction costs.

Sheppard (2006) considers this issue explicitly in modeling the microstructure of urban land use, in which different parts of the city have different levels of coverage by urban surfaces versus open space. The issue is certainly relevant for understanding why some cities achieve much higher gross population densities than others and exhibit more compact spatial structure. Measurement of this microstructure at different points in time allows us to describe more completely the emerging dynamics of urban expansion. In a simply “von Thunen” style city, urban growth takes a very simple form: an increase in population or income simply adds another growth ring onto the periphery of the urban area. Again, actual cities exhibit more complex growth behavior because of the presence of interior unbuilt spaces. Using our classification of land use at two different points in time (T_1 and T_2)

we can reveal considerable complexity. By combining the two classifications and undertaking considerably GIS computation, we divide and measure the land in the urban area into 9 categories:

	Category	Description
1.	Urban T_1	Land that was urbanized in T_1 (and remains so at time T_2)
2.	Interior Open T_1	Land that was unbuilt in T_1 but surrounded by land in urban use in T_1
3.	Exterior Open T_1	Land that was unbuilt in T_1 and was not surrounded by urban use
4.	Infill	Land that was Interior Open T_1 but under urban cover in T_2
5.	Outspill	Land that was Exterior Open T_1 but under urban cover in T_2
6.	Urban T_2	Urban T_1 + Infill + Outspill
7.	Interior Open T_2	Land that was unbuilt in T_2 but surrounded by land in urban use in T_2
8.	Captured Open T_2	Exterior Open T_1 but interior open in T_2
9.	Exterior Open T_2	Land that was unbuilt in T_2 and was not surrounded by urban use

Figure 5 below shows the final classification of Chicago into these land types.

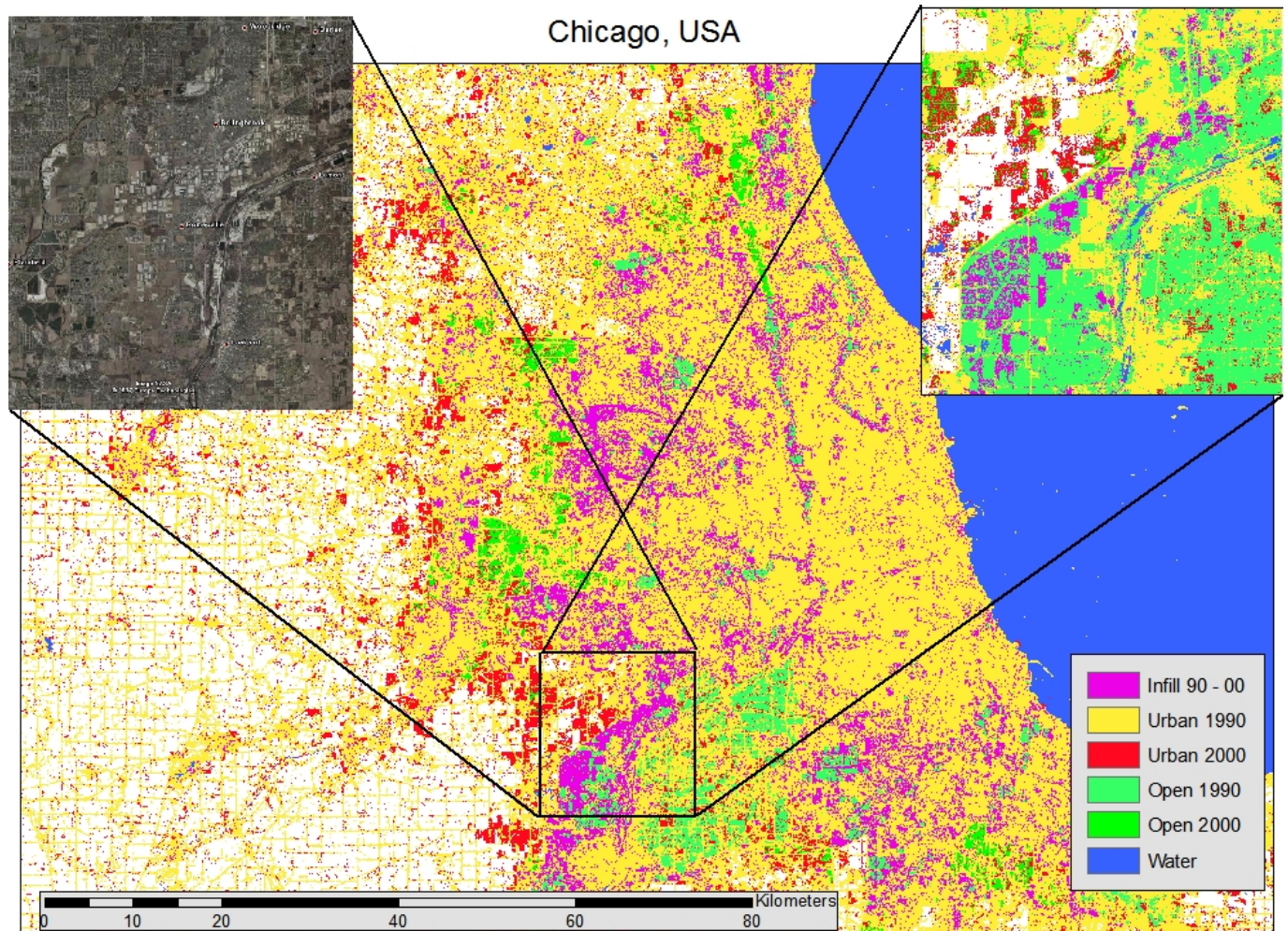


Figure 5: Chicago showing the microstructure and dynamics of urban expansion

Interestingly, there is considerable variation across the globe in the dynamics of urban expansion. In all countries, most urban expansion consists of outspill – new development on what was exterior open space. In some regions (such as North America and other non-European developed countries) urban expansion consists of a relatively high share of infill. In others (such as East Asia or South Asia) urban expansion involves very little infill. Table 2 below summarizes the regional patterns observed in our sample.

Table 2: Division of urban expansion between infill and outspill

Regional variation in infill and outspill					
Region	Infill	% Infill	Outspill	% Outspill	Freq.
East Asia	12.608	6.159	234.849	93.841	16
	<i>14.714</i>	<i>4.962</i>	<i>282.265</i>	<i>4.962</i>	
Europe	22.174	14.231	116.851	85.769	16
	<i>31.165</i>	<i>9.166</i>	<i>111.874</i>	<i>9.166</i>	
LAC	19.489	17.339	68.138	82.661	16
	<i>26.967</i>	<i>10.955</i>	<i>68.371</i>	<i>10.955</i>	
North Africa	7.248	9.263	77.807	90.737	8
	<i>8.553</i>	<i>7.578</i>	<i>69.979</i>	<i>7.578</i>	
Other Developed	73.309	22.830	184.889	77.170	16
	<i>85.016</i>	<i>20.012</i>	<i>157.840</i>	<i>20.012</i>	
South Central Asia	7.815	7.554	74.883	92.446	16
	<i>9.628</i>	<i>5.155</i>	<i>55.208</i>	<i>5.155</i>	
Southeast Asia	16.461	12.646	113.593	87.354	12
	<i>22.892</i>	<i>7.007</i>	<i>124.924</i>	<i>7.007</i>	
Sub-saharan Africa	9.590	9.216	75.170	90.784	11
	<i>13.376</i>	<i>7.131</i>	<i>54.653</i>	<i>7.131</i>	
West Asia	9.562	9.179	96.786	90.821	8
	<i>12.056</i>	<i>4.686</i>	<i>100.448</i>	<i>4.686</i>	
Total	21.881	12.525	121.517	87.475	119
	<i>41.119</i>	<i>11.235</i>	<i>147.691</i>	<i>11.235</i>	

While Sheppard (2006) provides some discussion of how we might derive a theory to help explain these differences, and Cunningham (2006) provides suggestive empirical evidence on development probabilities for individual parcels in a single US city (Seattle), at this point it must be observed that standard economic theories have little to offer by way of an explanation for these differences.

Our main concern here, however, is with measuring and modeling overall urban expansion. Traditional monocentric urban models do make clear predictions about the variables that are likely to impact urban land use, and the qualitative impacts of changes in these variables. The next section summarizes these.

4. Modeling Urban Expansion

There is no need here to derive a complete model of urban land use. Comparative static predictions are available from any of several thorough and clear presentations, for example Brueckner (1987) derives urban land values and the extent of urban development \bar{x} in the context of a closed urban model with housing producers. This model can be easily extended to include both a class of land consumers who are households purchasing housing from the housing producers and firms who purchase land as an input used in production of an export good. Within this context, total urban land use will depend upon the urban population L , household income y , the value of agricultural rent r_f , transportation costs t , the productivity of land in making the export good f_i , and the productivity of land in production of housing h_i . The impacts of changes in any of these variables are summarized in table 3.

Table 3: Comparative static predictions concerning urban expansion

No.	Comparative Static Result	Description of prediction and hypothesis
1.	$\frac{\partial \bar{x}}{\partial L} > 0$	An increase in population will increase urban land use and urban expansion.
2.	$\frac{\partial \bar{x}}{\partial y} > 0$	An increase in household income will increase urban land use and urban expansion.
3.	$\frac{\partial \bar{x}}{\partial r_f} < 0$	An increase in the opportunity cost of non-urban land (agricultural rents) will reduce urban land use and limit urban expansion.
4.	$\frac{\partial \bar{x}}{\partial t} < 0$	An increase in transportation costs will reduce urban land use and limit urban expansion.
5.	$\frac{\partial \bar{x}}{\partial f_i} > 0$	An increase in marginal productivity of land in production of (or demand for) the export good will increase urban land use and urban expansion.
6.	$\frac{\partial \bar{x}}{\partial h_i} > 0$	An increase in marginal productivity of land in production of housing will increase urban land use and urban expansion.

As noted above in table 1 and discussion surrounding, we have assembled measures of population and per capita income. In addition, we have relatively direct measures of agricultural rents (value added in agriculture per hectare of land in cultivation) and transport costs (price per gallon of motor fuel). As an proxy for the productivity of land in production of the export good, we use extent of air linkages between the city airport and other international airports. This is suggested by Wu and Yusuf (2004) who find a strong correlation between total freight shipments from cities and the extent of such air travel linkages. Finally, as a proxy for the marginal productivity of land in housing production we use the presence of shallow aquifers in the region where the city is located. Such aquifers make it

relatively easy to dig wells to provide water for housing. The presence of such aquifers has been found (by Burchfield *et al.* (2006)) to be strongly associated with urban expansion.

5. Estimation

Table 4 presents the parameter estimates using our data for three models. We discuss each in turn.

Table 4: Model estimates

Models of total urban land cover		OLS	OLS	Instrumental
Variable		Estimate	Estimate	Variables
				Estimate
Population		0.7405**	0.763**	0.3722*
σ		0.059	0.063	0.183
Income		0.5479**	0.5235**	0.5352**
σ		0.045	0.063	0.134
Agricultural rent		-0.2385**	-0.2315**	-0.1609*
σ		0.033	0.039	0.095
Fuel Cost		-0.1212**	-0.1468*	-0.2072**
σ		0.061	0.065	0.059
Air Linkages		0.0637*	0.0449	0.1451*
σ		0.038	0.044	0.071
Shallow Groundwater		0.2452*	0.1336	0.0312
σ		0.128	0.127	0.175
East Asia			-0.0541	0.3209
σ			0.224	0.397
Europe			-0.2914*	-0.3082
σ			0.142	0.229
Latin America			-0.3643*	-0.3191
σ			0.159	0.272
North Africa			-0.3947	-0.4341
σ			0.288	0.395
South-Central Asia			-0.5336*	-0.2817
σ			0.222	0.364
Southeast Asia			-0.4025*	-0.2313
σ			0.226	0.364
Sub Saharan Africa			0.0588	0.0048
σ			0.192	0.378
West Asia			0.1273	0.1179
σ			0.215	0.335
Constant		-8.8289**	-8.6998**	-3.8249
σ		0.885	1.010	2.670
Number of observations		240	240	240
Clusters		120	120	120
F		116.11**	75.25**	12.12**
R^2		0.82	0.84	0.77
Root MSE		0.55	0.52	0.62
H_0 : Regressors are exogenous				
Wu-Hausman F test:				4.0171**
Durbin-Wu-Hausman χ^2 test:				12.3577**

Each model shares some basic similarities. The dependent variable is always the natural log of total urban land cover measured in square kilometers. The first five variables enter as the natural log of the variable named. All other variables are dichotomous.

The first model is the simplest: straightforward OLS estimates of the impact of the central variables of the model on total urban land use. We see that all variables are statistically significant at either the 10% level (single *) or the 5% level or better (double **). All parameter estimates are of the sign predicted by the theoretical result presented in Table 3. While not definitive, it is worth noting that the for such a simple model the share of total variance explained by the central variables – 82% – is surprisingly high.

The second model continues with simple OLS estimation but extends the specification to account for unmeasured factors that may be constant over time and across all cities within a given region. This addresses the idea that “all cities in region X are special” often put forward in discussion of global urban expansion. This model changes very little in the values of the estimated parameters. We see that Europe, Latin America, South and Southeast Asia all have cities that tend to be more compact (less urban land cover *ceteris paribus*) than the cities in “other developed” countries (the excluded case) but inclusion of these variables adds little to the overall explanatory power of the model.

A natural concern in these types of models concerns the bias that arises from endogenous covariates. Population and income surely do appear to affect the overall level of urban land use. On the other hand, cities with large amounts of urban land cover might provide attractive locations so that population tends to move towards such cities. The result is a correlation between random variation in measurements of right hand side variables (such as population, income etc.) and the error term of the model being estimated. The result is inconsistent estimation of the parameters.

To address this problem, we present as the final model an instrumental variables approach to estimation. For instruments we use the biome in which the city is located (a classification that reflects the local climate and types of natural plant life) as well as the location and measures of the topography. The Wu-Hausman and Durbin-Wu-Hausman tests given in the last two lines of the table easily reject the hypothesis of regressor exogeneity suggesting that the IV approach is truly required in this case. Fortunately, the impact on parameter estimates is not large. The elasticity of urban land use with respect to income is almost unchanged. The elasticity with respect to population falls from

around .75 to under .4. Overall, however, it must be observed that the hypotheses identified above are largely supported. This helps to build our confidence in making use of a standard theoretical approach in analysis of global urban expansion and suggests at least tentative acceptance of these parameter estimates for some policy recommendations. We turn to these in the next section.

6. Policy conclusions and application

In the introduction we referred to policies to control urban expansion by limiting rural to urban migration or fighting road building, and noted that such efforts seemed to meet with very little success in actually limiting the extent of urban expansion. The model estimates presented above help us to understand, at least in part, why this might be true. The variation in urban expansion across global cities can be largely explained as a consequence of population and income growth, along with fuel prices, agricultural land values, and some other aspects that define the economic context for the city.

It is instructive to identify the cities whose actual urban expansion from T_1 to T_2 was much less than would be expected from the model. We calculate this difference as a percentage of the overall size of the urban area and rank them in order of the difference between actual and expected urban growth. Table 5 below presents the 12 cities whose expansion was the smallest relative to model-based expectations, and the 12 cities whose expansion was the largest.

The first thing to note is that these under- and over-performing cities are not uniformly the richest or poorest. Nor are they the largest or smallest in their countries. The less expansive cities do tend to be lower ranked in their respective urban hierarchies, and perhaps less affluent on average. Both groups, however, include a variety of cities. What we do note is that the cities that expanded less are often constrained by topography and coastal locations: Hong Kong, Victoria, Thessaloniki, Guaruja and Palermo are all constrained in this way and therefore might be expected to expand less for a given level of income, population etc. There are some coastal or port cities in the more expansive group as well, but many (like Chicago) are 'coastal' but relatively unconstrained in terms of their ability to expand inland.

Table 5: cities with more and less urban expansion than expected

Expected Expansion Rank	City	Urban Rank	Urban Land T ₁	Urban Growth Rate	Population T ₁	Pop Growth Rate	Per capita GDP T ₁	Income Growth Rate	Growth Prep Rate	New Urban to Prepare	Prepare / Actual
1	Hong Kong	4	75	2.19%	4,322,297	0.82%	\$1,514	8.73%	4.77%	43	1.90
2	Songkhla	2	14	2.92%	219,751	0.98%	\$4,459	3.51%	2.24%	3	0.65
3	Victoria	16	81	2.85%	238,436	0.67%	\$23,268	1.76%	1.21%	9	0.37
4	Guaruja	70	31	1.89%	798,401	1.15%	\$6,727	1.29%	1.22%	3	0.59
5	Thessaloniki	2	52	2.33%	770,764	0.77%	\$13,857	1.77%	1.27%	9	0.46
6	Saidpur	25	9	5.31%	502,692	1.39%	\$1,184	2.43%	1.91%	2	0.26
7	Bacolod	7	13	11.56%	461,590	1.29%	\$3,908	0.26%	0.78%	1	0.04
8	Palermo	7	74	0.74%	824,435	0.03%	\$21,015	1.34%	0.68%	7	0.88
9	Chinju	24	32	5.43%	330,240	0.42%	\$10,398	5.02%	2.72%	8	0.39
10	Kigali	1	11	9.28%	335,538	1.17%	\$1,245	-0.85%	0.16%	0.3	0.01
11	Rajshahi	4	11	5.66%	490,564	1.82%	\$1,155	2.43%	2.12%	3	0.27
12	Aswan	15	13	1.63%	225,969	2.29%	\$2,727	1.90%	2.10%	4	1.14
109	Marrakesh	4	194	2.28%	613,373	1.94%	\$3,326	0.31%	1.12%	28	0.42
110	London	1	1,573	1.49%	9,932,047	0.09%	\$21,535	1.93%	1.01%	175	0.62
111	Cairo	1	366	2.73%	10,132,863	1.57%	\$2,617	1.90%	1.73%	103	0.51
112	Coimbatore	23	99	4.56%	551,696	1.06%	\$1,666	3.50%	2.28%	23	0.40
113	Zhengzhou	23	404	4.47%	3,457,936	2.47%	\$1,326	8.73%	5.60%	294	0.92
114	Beijing	2	1,056	2.17%	8,639,446	2.13%	\$1,399	8.72%	5.43%	603	2.23
115	Ipoh	2	145	3.61%	521,338	2.00%	\$5,459	4.85%	3.43%	57	0.77
116	Chicago, IL	3	3,748	1.06%	7,550,456	1.04%	\$27,884	1.80%	1.42%	650	1.25
117	Sao Paulo	1	1,264	1.76%	10,678,860	1.70%	\$6,325	1.29%	1.50%	222	0.76
118	Tokyo	1	2,318	0.70%	25,106,290	0.56%	\$22,641	1.12%	0.84%	279	1.13
119	Ibadan	3	209	2.38%	1,565,805	2.88%	\$895	-0.12%	1.38%	44	0.48
120	Yulin	46	846	4.77%	4,065,112	-2.78%	\$1,793	8.72%	2.97%	227	0.50

Several of the more expansive cities also clearly play major roles as world cities with influence far beyond their own national economies. London, Cairo, Beijing, Sao Paulo and Chicago arguably fall into this category. There may be more to be learned about the factors that influence urban expansion through this type of evaluation and consideration.

One thing, however, is clear from the parameter estimates presented above. Economic development alone is likely to lead to urban expansion simply through the increase in per capita income. Whether it is possible for urban growth policies to limit expansion in the context of a developing economy city is not at all clear. There are many planning policies, particularly in developing economies, that seem to be predicated on the assumption that this is in fact possible, but even the most vigorous initiatives to limit urban expansion will have to contend with the processes of income and population growth, both of which tend to be relatively high in developing country cities.

Whether one wants to call these planning policies is unclear. They are policies that identify what many urban designers regard as a desirable outcome, but the model estimates we present above call into doubt the extent to which they can be called planning (in the sense that planning involves, at least in part, a **preparation** for what is likely to take place in the future). The consequences of these “planning but not preparation” policies is often that cities, who do not want (or are unable) to incur the costs of providing infrastructure to newly developing areas, do not plan or set aside any areas for future development. This does little to stop the development from taking place, but does ensure that it will be done in an uncoordinated fashion so that when efforts are finally made to extend infrastructure to the newly built areas it will be more difficult and costly than would be true if some minimal preparations for urban expansion were undertaken.

Using the estimated models presented above, it is possible to make forecasts of urban expansion that take into account all of the variables considered. It might be more helpful (and realistic) however to propose an easily-remembered and simple “rule of thumb” or “reality check” for planning policy. It might be conveniently designated as the “50-50” planning rule. It derives from the simple observation that based on the models above, the elasticity of total urban land use with respect to population and with respect to per capita income are both on the order of 0.5. The rule of thumb can be stated as follows:

Using recent history or reasonable expectations about the future, compute the sum of one half the expected percentage rate of growth of population plus one half the expected percentage rate of

income growth. The result is an approximation of the percentage increase in total urban land to be expected each year.

Because the result is expressed as a percentage increase, it can be applied to whatever type of measure of total urban land area is available to the planning authority. In the final three columns of table 5 this type of analysis is presented, using the actual rates of population and income growth observed from T_1 to T_2 . Applying the “50-50” planning rule to these rates yields the annual percentage change in total land urban that might be expected – in the column labeled “Growth Prep Rate”. Multiplying this rate times the size of the urban area and the elapsed time between T_1 and T_2 yields a suggested amount of new urban expansion for which preparations should be considered. Sometimes this amount is relatively modest – 3 to 4 square kilometers of new urban development for less expansive cities over a 10 year span. For large expansive cities, however, the areas can be very significant. Thus the “50-50 *planning rule*” would suggest that Sao Paolo should be considering preparations for well over 200 square kilometers of new urban development during the next decade.

These amounts seem large, but in hindsight they are almost never sufficient! The final column in Table 5 presents the ratio between the amount of urban expansion preparation suggested by the “50-50 *planning rule*” and the actual amount of measured urban expansion observed between times T_1 and T_2 . There are a few cities (Beijing and Hong Kong) for which such preparations would have been more than is required. For most cities, however, such preparations would still be insufficient. Averaged over our entire sample of cities, application of the 50-50 *planning rule* would have provided for about half of the actual urban expansion that took place.

7. Agenda for research on global urban expansion

The discussion above has presented an approach for measurement and modeling of global urban expansion. Using the measured urban expansion we have provided empirical tests of the models and found that our expectations are generally confirmed. There remain, however, several important avenues for future research and collaboration. We conclude with seven suggestions for consideration.

1. Collection and analysis of global data is expensive and difficult. There is a great need to coordinate data collection efforts. This coordination could be promoted by UN-Habitat, the World Bank, or a major foundation with interests in the area.

2. What is the scope for urban growth policies to affect the levels of urban expansion? If the variables used in the models in this paper explain 80% of total variation in urban land use, does this imply that policies can explain at most 20%?
3. Several forces of social change continue to affect cities in ways that are not fully understood. Changing social and economic roles for women, for example, may have significant implications for evolving urban form. At present these are poorly understood.
4. Econometric techniques for evaluating the accuracy of land use classifications are surprisingly limited. Most evaluations focus on the probability of correctly classifying individual pixels but this is rarely the measure of accuracy of greatest interest for urban policy. What is important for policy analysis is to obtain accurate measurement of total urban land use at the geographic scale of interest to the policy maker. Sometimes this will be as small as a neighborhood, sometimes as large as the entire metropolitan area, but never as small as a pixel.
5. What impacts do various urban outcomes have on health and human welfare? For example, reductions in interior open space result in more compact cities with potentially less commuting, but also reduce the accessibility to open space for inner city residents.
6. What is the potential for employment decentralization to reduce total commuting and hence total energy use in cities that are not compact and have relatively low densities?
7. Urban policies, particularly in settings where governments change frequently, can be a source of uncertainty and volatility in structure prices and expectations. To what extent does policy variability alter the microstructure of urban expansion?

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