Global trends toward urban street-network sprawl

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We present a global time series of street-network sprawl—that is, sprawl as measured through the local connectivity of the street network. Using high-resolution data from OpenStreetMap and a satellite-derived time series of urbanization, we compute and validate changes over time in multidimensional street connectivity measures based on graph-theoretic and geographic concepts. We report on global, national, and city-level trends since 1975 in the street-network disconnectedness index (SNDi), based on every mapped node and edge in the world. Streets in new developments in 90% of the 134 most populous countries have become less connected since 1975, while just 29% show an improving trend since 2000. The same period saw a near doubling in the relative frequency of a street-network type characterized by high circuity, typical of gated communities. We identify persistence in street-network sprawl, indicative of path-dependent processes. Specifically, cities and countries with low connectivity in recent years also had relatively low preexisting connectivity in our earliest time period. We discuss implications for policy intervention in road building in new and expanding cities as a top priority for sustainable urban development.

climate change policy | transportation | urban sprawl | urban development

As economic growth leads to an increasingly motorized world, energy use and greenhouse gas emissions from transportation are predicted to increase dramatically. The sector's energy use is expected to rise by ∼44% between 2015 and 2040 under current policies, with CO_2 emissions from transport oil combustion rising by almost as much (1). Global energy and integrated assessment models indicate that even under aggressive efficiency and electrification scenarios, transportation energy and emissions will see more limited reductions compared to other sectors (1, 2).

Most global analyses, however, model transportation energy demand as a function of income, energy prices, and technology and take little to no account of how the physical structure of urban centers shapes household decisions on vehicle ownership and travel (3, 4) or of community decisions on transport infrastructure and services. While a large body of research shows that cities with high population density, connected street networks, and fast and frequent public transportation systems tend to have less vehicle travel at a given income level (5–7), such insights are hard to capture in global analyses. One reason is that there are limited data on urban spatial structure at the metropolitan level and even fewer sources at the higher-resolution neighborhood level where household travel decisions are shaped. Thus, policy makers have little insight into underlying trends and the characteristics of new development, let alone about how these trends may affect future energy use and emissions.

In previous work (8), we began to fill this gap through creating a global dataset of street-network sprawl. Intuitively, connected street networks such as grids increase accessibility by walking, bicycling, and public transportation, as more destinations can be reached in a given window of time. In contrast, disconnected networks that are dendritic or are dominated by culs-de-sac favor travel by private car. In that paper (8), we created and reported 1) a summary measure, the street-network disconnectedness index (SNDi), and 2) a multidimensional classification of empirical types, based on analysis at the scale of individual nodes (intersections) and edges (street segments). We qualitatively validated their ability to capture and distinguish established urban planning-related characteristics of neighborhoods, globally, and showed that SNDi is associated with household car ownership and mode choice decisions in several high-income countries.

Our previous work focused on the stocks of streets, i.e., the characteristics of the entire network in a given place. In this paper, we focus on the dynamics of street-network sprawl and address the question of how patterns of street-network sprawl are changing among and within countries, worldwide. We couple our SNDi measure and empirical types with remote sensing data on urban growth to create a time series and identify trends in the characteristics of new urban development from 1975 to 2014. We validate this approach using data on building construction dates (*SI Appendix*).

Our paper is structured as follows. First, we discuss the connectivity of recent (post-2000) development at the national scale, as measured by low SNDi. Second, we characterize the ongoing trends in street-network sprawl in regions, countries, and cities, identifying a global decline in street connectivity since 1975, a peak in US street-network sprawl in 2000, and continued low levels of sprawl in places such as Japan. Third, we analyze trends in a multidimensional classification that identifies empirical street-network types and document a rise in the prevalence of networks typical of gated communities, a rise which comes at the expense of the irregular grid. Fourth, we explore persistence in street-network sprawl, i.e., the degree to which local- and country-level connectivity tends to reproduce itself over time, and discuss the potential role of path dependence. We conclude

Significance

The pattern of new urban and residential roads represents an essentially permanent backbone that shapes new urban form and land use in the world's cities. Thus, today's choices on the connectivity of streets may restrict future resilience and lock in pathways of energy use and CO_2 emissions for a century or more. In contrast to the corrective trend observed in the United States, where streets have become more connected since the late 20th century, we find that most of the world is building ever-more disconnected "street-network sprawl." A rapid policy response, including regulation and pricing tools, is needed to avoid further costly lock-in during this current, final phase of the urbanization process.

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with implications for policy, including the potential of market-based and regulatory approaches.

Recent Urban Development

Environmental impacts are governed by the connectivity of the entire stock of streets, which is the product of decades or centuries of accumulated decisions by private developers and municipal governments. Policymakers, however, can normally affect only the increment of new streets that are added to the stock each year. Recently developed streets are therefore the best reflection of current urban planning policies and real-estate market forces, and we begin by discussing the considerable heterogeneity in our composite measure, SNDi, around the world in the most recent time period of our analysis, 2000 to 2014 (Fig. 1 and Tables 1 and 2).

That the United States stands out for its disconnected streets comes as no surprise given the large literature on its automobile-oriented development patterns (e.g., ref. 9). Within the United States, the highest levels of sprawl are found in the states of Georgia, West Virginia, Maryland, Kentucky, and Virginia. Georgia is dominated by metropolitan Atlanta, which regularly features at the top of city-level sprawl rankings (e.g., ref. 10), while urban growth in Maryland and Virginia is largely accounted for by the suburbs of Washington, DC. Los Angeles, CA; Raleigh, NC; and New York, NY are 3 of the 10 most sprawling global cities identified in Table 1; this reflects recent suburban and exurban development in places like New Jersey, rather than the urban cores.

Fig. 1 and Tables 1 and 2 also reveal the sprawling streets of parts of Europe such as Ireland, Norway, and the Balkan region; Southeast Asia, particularly Thailand, the Philippines, Sri Lanka, and Indonesia; and parts of Central America. All these countries have recently built streets with average SNDi ≥ 5.5 (see Fig. 1 for the global distribution). In Ireland, for example, the 2001 to 2008 housing boom led to an upswing in suburban development characterized by car dependency and poor public transportation service, despite moderately high densities in the form of apartment buildings and duplexes (11, 12). In Southeast Asia, developer-driven urban growth caters to a new middle class, with access centered around the private automobile, often in the form of gated communities (e.g., ref. 13); we discuss the experience of countries such as Indonesia and the Philippines in more detail in ref. 8. In Central American countries such as Guatemala and El Salvador, meanwhile, the combination of weak planning institutions and high rates of crime has led to a boom in developer-led, middle-class housing on the urban fringe, again typified by gated communities (14). For example, Guatemala City—the third most sprawling in Table 1—was originally established under Spanish colonial rule on a geometric grid, but the contemporary city is characterized by informal settlements, many of which arose after earthquakes in 1917 to 1918 and 1976, and by "fortified spaces" for the wealthy that are isolated from the rest of the city (15).

The most connected streets in the recent period are found in South America, where Bolivia, Argentina, Peru, and Uruguay have SNDi ≤ 2.0. Japan, much of North Africa and the Middle East, South Korea, and China also lie in the lower quartile of SNDi. Most of these places were characterized by low levels of sprawl in previous time periods as well; the extent of this persistence over time is discussed further in *Persistence*.

Trends in Urban Development

An examination of trends in street-network sprawl since 1975 provides a complementary picture to the cross-sectional analysis of recent urban development and helps indicate the direction of market preferences and planning policies. As discussed in *Materials and Methods* and in *SI Appendix*, we use remote-sensing data on the year that each grid cell was developed to assign each edge and node as "undeveloped" or to 1 of 4 epochs: <1975, 1975 to 1989, 1990 to 1999, and 2000 to 2014. The trends for geographic regions and income groupings are shown in Fig. 2 *A* and *B*, while numerous details are evident at increasing levels of disaggregation (Fig. 2 *C* and *D*). Plots and tabulated rankings for all countries are provided in *SI Appendix*.

Trends by World Region. The last 4 decades have seen a striking global trend toward increased street-network sprawl, as reflected

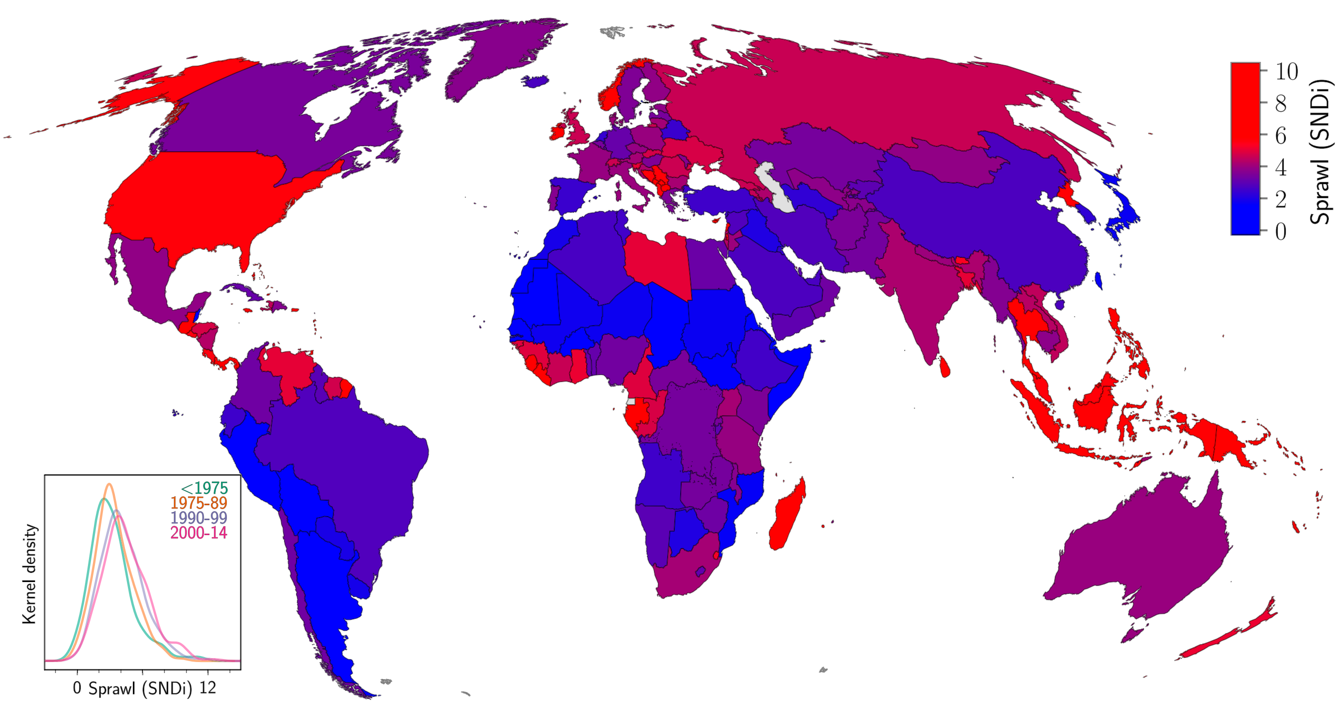

Fig. 1. SNDi for streets added years 2000 to 2014. *Inset* charts the distribution at the country level of SNDi for streets added in each of our 4 time periods.

Table 1. Cities listed in order of recent urban street-network sprawl

	Sprawl (SNDi)				N (nodes)			
	<1990	1990 to 1999	2000 to 2013	Stock	<1990	1990 to 1999	2000 to 2013	Stock
Bangkok, Thailand	6.8	7.6	8.1	7.3	74,000	30,000	46,000	150,000
Guatemala City, Guatemala	3.8	5.6	7.5	4.5	22,000	7,300	4,700	34,000
Cebu City, Philippines	6.1	6.9	7.3	6.6	5,700	2,300	4,500	12,000
Los Angeles, CA, USA	3.6	6.2	6.3	3.9	250,000	26,000	9,700	290,000
Raleigh, NC, USA	4.8	5.4	6.3	5.6	11,000	21,000	19,000	51,000
Palembang, Indonesia	4.7	5.6	6.3	5.2	15,000	19,000	3,900	39,000
New York, NY, USA	2.9	5.2	6.3	3.1	320,000	42,000	3,500	360,000
San Salvador, El Salvador	4.4	7.1	6.1	5.0	11,000	1,700	4,700	17,000
Belgrade, Serbia	2.9	6.6	6.0	4.2	9,100	2,200	4,000	15,000
Tijuana, Mexico	4.3	3.6	6.0	4.4	15,000	9,200	8,500	33,000
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
Gombe, Nigeria	1.6	3.7	2.0	2.0	1,800	560	4,500	6,900
Busan, South Korea	1.3	1.6	1.8	1.4	16,000	4,100	4,200	24,000
Tokyo, Japan	1.1	1.6	1.8	1.1	660,000	38,000	97,000	800,000
Marrakesh, Morocco	1.1	1.5	1.7	1.3	6,300	2,200	3,600	12,000
Madrid, Spain	0.7	1.5	1.7	1.1	28,000	12,000	15,000	55,000
Buenos Aires, Argentina	−0.1	0.9	1.6	0.3	120,000	17,000	26,000	160,000
Bamako, Mali	0.6	1.0	1.6	1.1	13,000	7,500	16,000	36,000
Luanda, Angola	2.0	2.2	1.5	1.8	12,000	10,000	28,000	51,000
Lubumbashi, Democratic Republic of Congo	1.7	1.8	1.3	1.5	6,700	2,300	7,700	17,000
Khartoum, Sudan	0.2	0.6	0.7	0.5	56,000	14,000	38,000	110,000

Shown are the top 10 and bottom 10 cities with ≥3,000 street nodes, ordered by SNDi in recent development. A full list of 200 cities is in *SI Appendix*. While the text mentions Atlanta, GA and Washington, DC, neither one is represented separately in our cities dataset.

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in the rightward shift of the distributions of SNDi (Fig. 1, *Inset*). Moreover, new development in almost all geographic regions shows a marked rise in SNDi, at least until the turn of the century (Fig. 2*A*). Sprawl in Latin America, Asia, and the European Union rises monotonically and, except in the European Union, nearly uniformly throughout our time series. Globally (Fig. 2*B*, thick dark gray line), street-network sprawl rose during the first 2 time periods and flattened out in the most recent one, at a level comparable to that being built in the 1980s in the United States. This corresponds to a 27% decrease (from 33% to 24%) in the fraction of urban intersections with nodal degree 4+ and a 35% increase (from 14% to 19%) in the fraction of dead ends (*SI Appendix*). While Fig. 2 shows that the node- and edge-weighted global trend in SNDi has nearly plateaued, its future

Table 2. Countries listed in order of recent urban street-network sprawl

	Sprawl (SNDi)					N (nodes)				
	<1975	1975 to 1989	1990 to 1999	2000 to 2013	Stock	<1975	1975 to 1989	1990 to 1999	2000 to 2013	Stock
Puerto Rico	4.9	7.7	8.9	9.4	6.5	54,000	47,000	12,000	8,200	120,000
Ireland	5.0	6.4	7.7	7.6	5.9	57,000	22,000	17,000	19,000	120,000
Guatemala	3.2	4.7	6.1	6.5	4.6	32,000	41,000	12,000	11,000	110,000
Thailand	4.0	4.7	4.8	6.3	4.9	140,000	470,000	74,000	120,000	920,000
Philippines	4.5	5.3	5.6	6.1	5.4	130,000	200,000	51,000	59,000	500,000
Norway	4.0	4.8	5.7	6.1	4.6	62,000	57,000	10,000	19,000	170,000
Sri Lanka	3.8	5.9	5.4	5.9	5.5	22,000	78,000	8,000	26,000	150,000
Indonesia	5.3	4.4	5.3	5.8	5.1	660,000	470,000	140,000	220,000	1.6 million
Serbia	3.0	4.3	5.3	5.8	3.8	56,000	32,000	4,100	4,700	100,000
United States	2.9	4.6	6.2	5.7	3.9	5.5 million	2.7 million	980,000	1.1 million	11 million
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
Iraq	2.1	1.8	2.0	2.2	2.0	28,000	150,000	21,000	110,000	320,000
Morocco	1.5	1.9	1.9	2.0	1.9	81,000	86,000	29,000	59,000	280,000
Sudan	0.6	1.1	1.6	1.8	1.6	64,000	52,000	12,000	92,000	320,000
Japan	1.1	1.5	2.2	1.8	1.3	2.8 million	990,000	130,000	110,000	4 million
Taiwan, China	1.1	2.1	2.0	1.8	1.3	130,000	12,000	7,900	7,500	160,000
Mozambique	2.1	1.2	1.7	1.7	1.8	16,000	33,000	16,000	38,000	130,000
Senegal	0.9	1.2	1.3	1.6	1.5	30,000	47,000	19,000	31,000	150,000
Peru	1.5	0.8	1.5	1.5	1.5	190,000	11,000	9,100	23,000	280,000
Argentina	0.2	0.5	1.1	1.5	0.6	300,000	310,000	84,000	69,000	820,000
Bolivia	1.3	1.1	1.0	1.2	1.5	42,000	34,000	26,000	36,000	170,000

Shown are the top 10 and bottom 10 countries and territories with ≥10 million population and ≥100,000 street nodes, ordered by SNDi in recent development. Countries and territories with populations >20 million are listed in boldface type. A fuller list is in *SI Appendix*.

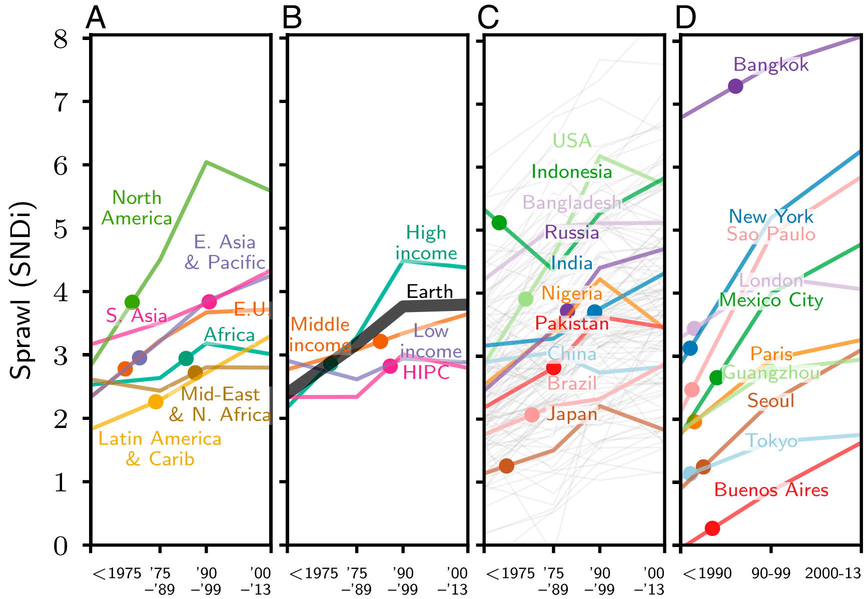

Fig. 2. Regional trends in SNDi. *A*–*C* show levels of our composite sprawl measure for the stock of streets built prior to 1975 in urban areas, followed by the SNDi of new urban construction during each successive period, 1975 to 1989, 1990 to 1999, and 2000 to 2013 (16). The vertical positions of the circles denote the SNDi of the 2017 stock of streets. (*A*) Urban region averages of SNDi for several geographic regions. (*B*) The global urban region aggregate is shown with a thick dark gray line, along with trends for 4 World Bank-defined economic and cultural country groups (17), including the HIPC. (*C*) Trends for the 10 largest countries by population in color and for the next 90 largest countries in thin gray lines. (*D*) Trends for 10 large cities, based on time series of their urban development boundaries (18). Note that cities are aggregated to a separate set of time periods (prior to 1990, 1990 to 1999, and 2000 to 2013); see *Materials and Methods* for details.

trajectory will depend on the relative rate of road expansion in areas practicing high- versus low-connectivity street construction. In *SI Appendix* we show cities and countries according to the estimated rate at which their street network is growing.

Sprawl's Growth and Decline in High-Income Countries. In 1975, the global stock of streets showed relatively little variation among income groups. Since then, however, the distribution has considerably diverged according to income levels, with higher-income countries building less-connected developments. Due to the strong reversal exhibited by North America, the recent decrease of already-low SNDi in Japan, and the leveling off in the European Union, overall the "high-income" countries have recently arrested the increasing trend of low-connectivity street construction. Despite the turnaround, recent construction in these countries remains less connected than in other country groups (Fig. 2*B*).

In fact, the leveling off in high-income countries and on Earth as a whole reflects in large part the recent decline of SNDi in North America, which accounts for 20% and 19% of mapped nodes and edges, respectively, and thus counterbalances trends elsewhere in the world. In the United States, as previously reported (10), street-network sprawl exhibited an extraordinarily steep rise until the mid-1990s, but thereafter has been in decline. Interestingly, neighboring Canada followed a similar trend to the United States, with a steep increase in SNDi followed by a turnaround in the 1990s, but it peaked at a much lower level (SNDi = 3.7; *SI Appendix*), possibly reflecting higher fuel prices and a more limited highway construction program in Canada, as well as differences in local land-use regulations (19–21).

Overall, other high-income countries and geographic regions have also seen growth in SNDi followed by a smaller, recent decline, albeit with much lower levels of sprawl compared to North America. Indeed, the high-income grouping also includes one of the least sprawling countries (Japan), with the European Union lying almost precisely midway between the United States and Japan. Nearly all European countries show increasing SNDi until the turn of the century, including the outlier Ireland (discussed in *Recent Urban Development*), which started and remained less connected than any other European country, but followed a parallel trajectory to Europe as a whole. This is consistent with the trend toward more car-oriented transportation and development in Europe over those decades (22). However, the declining connectivity of new streets in many European countries has been arrested since 2000, and the United Kingdom even shows a significant shift away from sprawl (decrease in SNDi) in this time period. By contrast, Japanese street-network sprawl has remained low and recently turned around to an improving trend. We note the correspondingly low per capita CO_2 emissions in Japan (23).

For several European countries, notably Denmark and the United Kingdom, our estimates of street connectivity are strongly affected by pedestrian and bicycle paths (see *Materials and Methods* and *SI Appendix* for details of how we include them in calculating connectivity). In Denmark, where streets are becoming steadily less connected in the most recent period, bicycle and pedestrian paths appear frequently to be integrated into new developments and significantly increase connectivity even if limited circulation is provided for cars. For example, adjacent culs-de-sac in new developments are normally connected by a foot- and cycle-way.

Mixed Trends across Low- and Middle-Income Countries. Low-income countries provide a counterpoint to the dominant pattern of increasing sprawl throughout the last quarter of the 20th century. The World Bank groupings of low-income and highly indebted poor countries (HIPC) have collectively shown nearly constant connectivity over time, with new developments exhibiting similar SNDi to the pre-1975 stock in North America. Geographically, Africa and the Middle East show relatively low and consistent levels of street-network sprawl, with SNDi rising little since 1975.

Latin America, in contrast, shows one of the sharpest increases in sprawl in recent decades. The continent, like Japan, was already considerably urbanized at the beginning of our time series and had similarly low SNDi in 1975. In Latin America, this can be partly ascribed to the Spanish colonial legacy of grid-like street patterns (24). Bolivia, Belize, Argentina, Peru, and Uruguay lie near the bottom (most connected) of a country-level ranking of SNDi in 2000 to 2013, with SNDi <2.0 and average nodal degree of $\sim$3.2. Yet, streets from earlier time periods in these countries were even better connected—particularly in Argentina and Uruguay, which in 1975 had SNDi <0.2 and nodal degree $\sim$3.5. The Latin American trend toward street-network sprawl (higher SNDi) in recent developments is among the strongest in the world and has increased monotonically on every dimension included in the SNDi.

Among more recently and rapidly urbanizing large countries, Indonesia both started (stock in 1975) and ended (development in the 2000 to 2013 period) with the most sprawling street networks of any of the most populous countries. Another remarkable feature is the divergence of India, with increasing SNDi, and China, with the opposite trend, even though the stocks in 1975 were characterized by similar levels of connectivity. This divergence reflects in particular our graph-theoretic measures of nodal degree and the fraction of edges in the cycle basis (*SI Appendix*), which remained stable in China but trended monotonically toward sprawl in India. When measuring sprawl through the geographic measures of circuity, both countries are becoming more sprawling, but India at a faster rate. Thus, all our measures suggest the same divergence of street-network development styles between Earth's 2 most populous countries. While the underlying street-network data are less complete in China (25), this finding is consistent with other evidence on Chinese urban development patterns. Indeed, many of China's new residential developments are characterized by "superblocks" or sparse grids, which are connected but less conducive to walking than a finer-grain network (26, 27).

City-Level Trends. City trends (Fig. 2*D*, tabulated more completely in *SI Appendix*) reflect the regional- and national-level patterns, with extremely high and growing SNDi in Southeast Asian cities, notably Bangkok; stable or slowly increasing SNDi in European cities along with Tokyo and Guangzhou; and rapidly increasing SNDi in initially well-connected Sao Paulo, Mexico City, and Buenos Aires. The British cities of Manchester and Sheffield, like London, have recently turned toward decreasing SNDi following a long period of broader trends toward increased sprawl (28). Seoul, and indeed South Korea as a whole, represents another example of initially high but rapidly worsening connectivity, as depicted in Fig. 3, which also shows the within-city variation at the level of individual edges and nodes. New York and Los Angeles, where recent development is less connected than in any other equally large global city in our analysis, are examples of regions with highly gridded urban cores whose suburban development in recent decades has been at the opposite extreme. Stocks and trends are tabulated and plotted for 200 cities and all countries in *SI Appendix*.

Recent development in some cities makes them stand out nationally. For instance, in São Paulo and, even more so, Florioanópolis, recent development is characterized by extremely low connectivity (SNDi >5.8, mean nodal degree = 2.6) compared with the recent country mean in Brazil (SNDi = 2.9, mean nodal degree = 3.0). Interestingly, SNDi in São Paulo has evolved nearly identically to that in New York. While the older core of São Paulo is complex, it consists largely of gridded streets like those of New York, while the outer developments are increasingly circuitous. Tijuana, Mexico is another city with unusually disconnected development since 2000 (SNDi = 6.0), compared with the rest of Mexico (SNDi = 3.9), although it is similar to the average for close-by United States (SNDi = 5.7). While Thailand as a whole is building low-connectivity streets (recent SNDi $\approx$6.3), Bangkok (recent SNDi = 8.1) stands out within Thailand as well as globally. Fewer cities are national outliers in the other direction, i.e., with lower SNDi than the national average.

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Dynamics According to Empirical Street-Network Types

Our composite measure (SNDi) analyzed in the preceding sections gauges the overall connectivity of the street network. In this section, we complement that composite measure with a categorical analysis, which classifies every urban grid cell into 1 of 8 street-network types. Such a multidimensional classification enables distinctions to be drawn between places

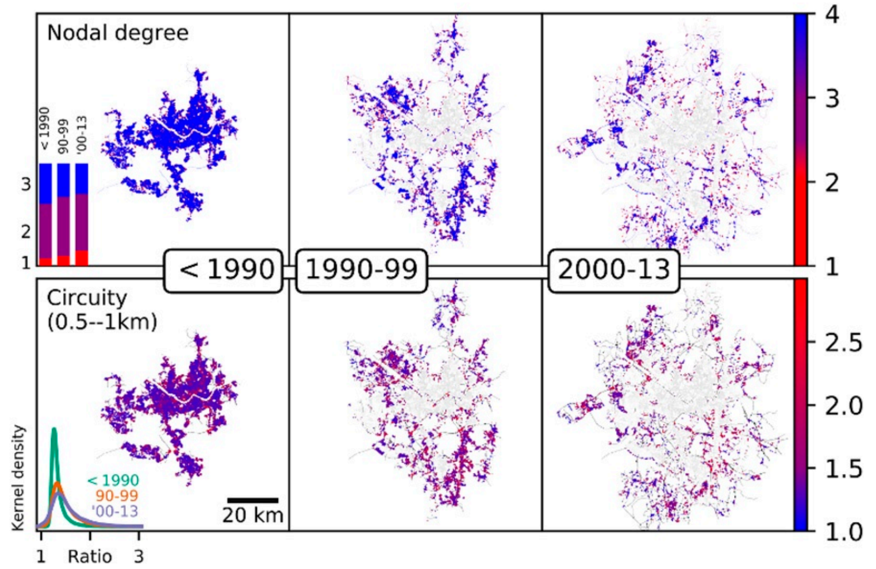

Fig. 3. Map of nodal connectivity over time, Seoul. Blue streets are the most connected. *Inset* plots show the distribution of nodal degree (*Top*) and circuity (*Bottom*) for the 3 time periods. Streets built since 1990 on the urban periphery, particularly to the southeast and northwest, have become steadily more sprawling according to both of the connectivity measures illustrated here. A high-resolution version of this is in *SI Appendix*.

with similar overall connectivity as measured by SNDi, but where that level of connectivity is achieved through different designs. Fig. 4 shows the 8 types as identified in ref. 8. Types *B* and *C*, for example, have similar levels of SNDi, but type *B* achieves this through degree-3 intersections, while type *C* has more degree-4 intersections arranged in an irregular grid. Types *E* and *F* also have similar SNDi values, as do types *G* and *H*.

The line plots in Fig. 4 show the trends in the distribution of types over time, while Fig. 5 shows the trends by world region. Overall, the message from Figs. 4 and 5 reinforces the results presented above. That is, the proportion of nodes in the most disconnected types (E–H) nearly doubled between pre-1975 development and the most recent period (2000 to 2014), with the increase particularly pronounced in Europe, Asia, and Latin America. There was also a sharp increase in the prevalence of disconnected types in North America, reaching a peak of 67% of nodes in types E, F, G, and H in 1990 to 1999. Recent additions to the street network in North America, however, show a modest shift back toward more connected types, in accordance with the fall in SNDi since 1999.

Of these disconnected types, type E (circuitous) has shown the largest increase over the period studied, rising from 9% of nodes pre-1975 to 17% in the 2000 to 2014 period. The proportion of nodes in type E has increased in every region except Africa and more than doubled in most regions. Type E often represents gated communities, as well as places with topographic barriers; some examples are shown in Fig. 6. Demand for gated communities is often driven by a fear of crime or a search for social prestige, but many analysts have raised concerns about their consequences for social segregation and for allowing a high-income elite to opt out of municipal service provision (29), as well as for their car dependence.

At the other end of the sprawl spectrum, grids (type A) are the most self-evidently connected type. In the pre-1975 period, North America and Latin America were home to the highest proportions of type A (grid), at 9% and 13%, respectively. Since then, grids have declined in importance in Latin America and almost disappeared entirely in recent North American development, with that decline only partially offset by a marked upswing in the East Asia and Pacific region (Fig. 5). However, the global reduction in street connectivity has little to do with the abandonment of grids, which even in 1975 accounted for just 6% of nodes worldwide, declining to 3% in the 2000 to 2014 period. Instead, the largest decrease, from 43% to 28% of nodes at the global level, has occurred in type C (irregular grid). The small rise in type B (degree 3), which has similar SNDi to type C, has only partially compensated for the decline in irregular grids.

Persistence

We previously found that early street-network sprawl predicts the connectivity of later construction at various geographic scales within the United States (10). In addition to a persistence of local geographic variation in prices, policy, preferences, and other drivers of development style, there are plausible path-dependent

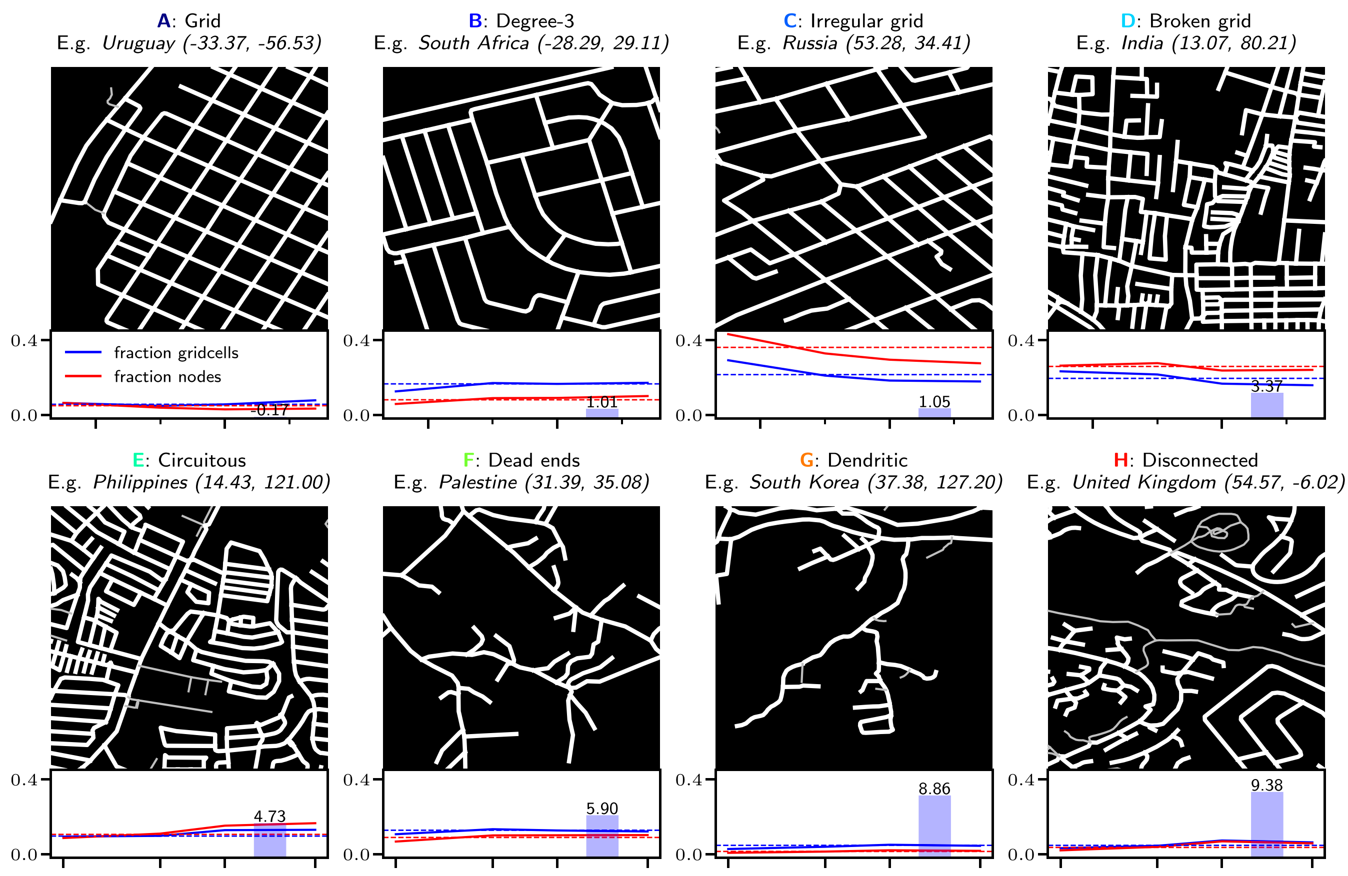

Fig. 4. Empirical street-network types. For each type, streets in a grid cell near the cluster's centroid are shown (8), along with a line plot of the proportion of grid cells (blue) and proportion of nodes (red) that fall into each type over time. Types are shown in order of decreasing SNDi, indicated by the blue bar and associated number. The caption above each plot indicates the (latitude, longitude) of each example grid cell as well as the country where it is located. The dashed line indicates the fractions of grid cells and nodes in the entire stock of urban streets.

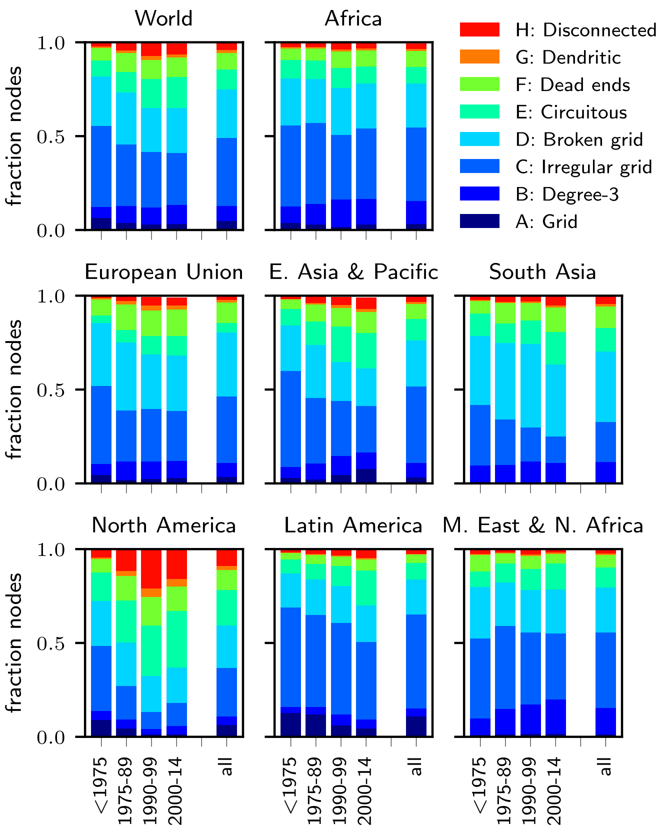

Fig. 5. Trends in empirical types by world region. The fraction of nodes that fall into each of the empirical types is given for selected World Bank-defined regions. Plots for additional regions, for both the fraction of nodes and the fraction of grid cells that fall into each type, are shown in *SI Appendix*.

processes in which urban form tends to replicate itself in new, neighboring developments (8, 10, 30). For instance, the connectivity of existing street networks is likely to influence neighboring development due to the availability, or expectation of future availability, of services and transit options accessible to pedestrians. Building a walkable neighborhood is more valuable if there are places to walk to.

Our findings show that the same persistence is observed at the scale of entire countries (Table 2) as well as cities (Table 1). Places ranking high in recent SNDi also had relatively high SNDi in our earliest time period. To quantify this persistence as well as the average shift over time, we estimate the relationship between SNDi stock at our earliest time points (1975 for countries, 1990 for cities) and the SNDi characterizing the most recent construction (Table 3). Both the average shift and the persistence are consistent across geographic scales and different measures composing the SNDi: they indicate an overall shift toward lower connectivity and a strong relationship between preexisting connectivity and recent connectivity. In fact, hardly any countries or cities are building better-connected streets than they were in our earliest time periods (i.e., lie below the dark gray line in Fig. 7), with China being a prominent exception. Other exceptions are mostly countries in the Middle East and Africa.

Policy and Conclusion

In this paper, we use a globally consistent composite measure, SNDi, to quantify trends in street-network sprawl in countries and large cities worldwide. While sprawl has increased in many of the "usual suspects" such as São Paulo, Los Angeles, and Lagos, our findings show that some of the least-connected street networks are found in places that have received less attention in the literature. The growth of large cities in China has been the subject of considerable media and academic interest, but these urban centers have moderate and relatively stable levels of street connectivity. In contrast, the most sprawling cities on the planet—and those that are trending toward even greater extremes—are found in southeast Asia and have attracted more limited attention.

We also identify the diversity of ways in which street networks can grow in a connected or less connected pattern. Gridded street networks are a primary means through which Latin American countries such as Bolivia, Argentina, and Peru have maintained their high levels of connectivity—and the move away from the grid characterizes sprawl in large Brazilian cities such as São Paulo. However, Japan has maintained low levels of sprawl via a more organic, irregular grid pattern. Northern European countries such as Germany, Denmark, and the United Kingdom, meanwhile, have maintained moderate levels of street connectivity through dedicated pedestrian and bicycle pathways, meaning that the network for nonmotorized travel is far more connected than that for cars and trucks.

Our work has some natural limitations. First, our rationale for prioritizing a street-network measure of sprawl is in part based on causal pathways which still require further empirical investigation. While SNDi and its constituent components, along with related measures of urban form such as density and housing type, are strong predictors of current car ownership and travel behavior (8, 30–33), the relationship between initial street-network connectivity and the subsequent long-run evolution of density remains a ripe subject for future work. Our global SNDi time series should facilitate such research.

Second, an important premise of our current analysis is a sufficient completeness of the underlying street-network database, which we take from OpenStreetMap (OSM). We have demonstrated elsewhere that OSM is relatively complete (25), but those estimates excluded pedestrian and bicycle paths and service roads, which we incorporate in our measure of SNDi because they are demonstrably important to connectivity in some places. This leaves our work dependent also on the sufficient completeness of OSM's pedestrian and bicycle path records. Nevertheless, our inspections suggest that where such paths are numerous, they are well mapped in OSM. Where they are prominent, but possibly incompletely recorded in OSM, we may be underestimating connectivity.

Worsening Sprawl and Its Consequences. Overall, our analysis shows that in large parts of the world, recent urban growth has increasingly resulted in inflexible and disconnected street networks. Countries with road networks that are among both the fastest growing and the most disconnected include Thailand, the Philippines, Indonesia, and the United States, while cities of the same description include Bangkok, Johannesburg, Raleigh, Los Angeles, New York, Ho Chi Minh City, and São Paulo. However, our data reveal variation in development style within countries as well as within cities.

Our network-centered approach to quantifying sprawl therefore breaks from the dominant extant emphasis on low density and land-use dispersal (21). Urban outcomes in the short term have to do with much more than the street network. However, in the long run, sidewalk and transit provision, densities, land uses, and both formal and informal rule enforcement are malleable to social, economic, and policy influences. By contrast, streets are a more permanent feature of cities; once laid down, their routes almost never change, even in the face of natural disasters such as earthquakes or fires (34). Given that many cities will continue to grow for decades, density may change and outlying regions may be subsumed into more contiguous development, but disconnected street routes will remain as a fundamental

Fig. 6. Gated community examples. These examples are from grid cells close to the centroid of type E. Images © 2019 Google.

constraint. Thus we have previously conjectured that in the long term, low-connectivity street networks lack resilience to adapt to changing pressures and resources and ultimately to densify toward a mixed-use, transit-integrated, energy-efficient urban form. In this sense, they are effectively "density proof," i.e., resistant to changing the mix of uses, modes of transportation, and density (30). In addition, in a practical policy context, the regulation of development style and infrastructure is somewhat separable from decisions about the conversion of agricultural and natural lands into urban use. Based largely on this logic, we expect our street-network measure to be a key predictor of future climate, energy, health, and social outcomes related to urban form.

The impact of today's street connectivity decisions on climate and other outcomes is amplified by the tendency of new development to mimic existing urban form (Table 3). One mechanism we have proposed for this (10, 30) is a spatial spillover from existing settlement structure onto the choices of future, neighboring land developers. A neighborhood with highly permeable streets is more likely to allow transit to access an adjacent future development, more likely to contain local services and jobs accessible to pedestrians living nearby, and so on. Building high-connectivity, pedestrian-navigable streets in the adjacent development therefore has economic complementarities with the connectivity of the existing street network. In other words, one interpretation of our findings of persistence is a long-run path dependence in urban evolution, rendering any initial design decision all the more pivotal for future human and environmental outcomes.

In our categorical analysis of street-network types, gated communities arose as a particularly illustrative instance of low-connectivity planning. While gated communities have been documented across every continent, including in Istanbul, Indonesia, the United Kingdom, and the United States, and single-country or qualitative studies have suggested their increasing prevalence (13, 29, 35), our global analysis documents the extent of their reach. In addition to their association with low walkability, car orientation, and land-use segregation, gated communities have obvious significance for other global challenges related to economic disparities and social segregation.

The Need for Policy Attention. What, then, do these widespread trends imply for policy, especially given the rapid pace of urban road construction in many parts of the world—a process that is likely to be largely completed this century? The costs of high street-network sprawl are largely externalized to neighboring developments and to future generations, so regulatory intervention is a natural approach. Several feasible policies might be sufficient to increase connectivity in new developments. The simplest would be to require that, where possible, new communities are completely gridded, given that grids do well according to all of our street-network sprawl metrics. An alternative requirement would be a "3-ways-out" rule, which requires that 3 nontouching routes exist from every new intersection to points outside a new development. Gated communities could be discouraged or outright prohibited.

Market approaches can be used in place of regulatory policies or in combination with them. For example, a tax on dead ends and 3-way intersections, which we call a "cul-de-tax," could internalize some of the external costs of street-network sprawl. Moreover, broader environmental tax policies—such as carbon taxes, motor fuel taxes, or congestion pricing—have led to increased residential densities and decreased construction on the urban periphery (6); they might reasonably be expected to encourage developers to build more connected street networks as well.

Table 3. Estimates of path dependence

Metric	Scale	Shift	Persistence
Log circuity, 0.5-1 km	Cities	0.037 ± 0.002	0.80 ± 0.14
	Countries	0.029 ± 0.002	0.91 ± 0.12
Nodal degree	Cities	-0.22 ± 0.013	0.68 ± 0.12
	Countries	-0.17 ± 0.012	0.82 ± 0.10
SNDi	Cities	1.56 ± 0.081	0.85 ± 0.13
	Countries	1.26 ± 0.081	0.89 ± 0.10

Shown are mean shift (± SE) in connectivity measures between 1975 (countries) or 1990 (cities) and post-2000 construction, and slope (± SE) of corresponding regression lines. Data and fits are displayed in Fig. 7.

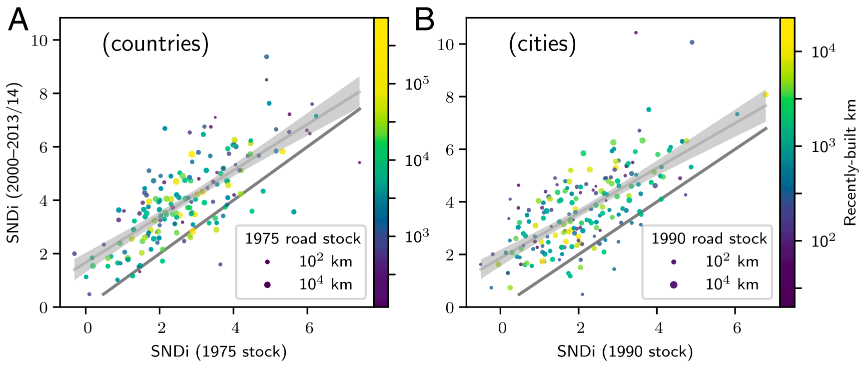

Fig. 7. Path dependence in street-network sprawl. SNDi of recent (2000 to 2013) construction is closely correlated with that of the earlier road stock in 1975 (countries, *A*) and 1990 (cities, *B*). Circle size denotes the length of original road stock, while color indicates the scale of recent construction. Only cities and countries with at least 100 km of new roads are shown. Linear fits characterizing the persistence relationship (gray shaded confidence region) are nearly parallel to the 45° line of perfect persistence (dark gray line), indicating a relatively uniform shift (on average ΔSNDi = +1.56 for cities, +1.26 for countries) (Table 3) away from earlier high connectivity. A zoomable version of this figure with labels for cities and countries is in *SI Appendix*.

Design guidance can also play a role. For example, the turnaround in the United Kingdom as a whole and in several British cities occurred in 2000, when new national planning guidance emphasized the importance of permeability for pedestrians in site design and called for the creation of well-connected streets that avoid "introverted" dead-end layouts (36). A subsequent design manual further emphasized the need to encourage walking and cycling through "networks of streets that provide permeability and connectivity to main destinations and a choice of routes" and presented a hierarchy of road users with pedestrians at the top (ref. 37, pp. 13, 28). In Ahmedabad, India, where recent development has been among the most connected of all Indian cities, boundaries of private landholdings are adjusted to allow for the creation of a regular grid as the city expands (38). In neighboring Bhuj, postearthquake planning efforts led to the interconnection of all culs-de-sac, motivated in part by the lack of access to dead-end streets that were blocked by falling rubble in the 2001 earthquake (39). In China, while much post-1949 development consists of often-gated superblocks, guidelines issued by the Chinese State Council in 2016 call for a reversal of that approach, promoting a more fine-grained network and urging a cessation of enclosed (i.e., gated) residential neighborhoods (40).

Some policies are likely to be more internationally transferable than others. Fundamentally, however, the examples of Japan and many countries in the Middle East, along with the historical street patterns in Latin America, show that street-network sprawl is far from inevitable. Their experience suggests that building connected streets can achieve not just environmental goals, but can also contribute to vibrant, economically prosperous urban centers. The world has much to learn from cities and countries that have turned the corner and are building more connected street networks—and from those that, often with little fanfare, have been doing so all along.

Materials and Methods

We calculate properties named dendricity and sinuosity for street-network edges and properties named circuity and nodal degree associated with street-network nodes. These measures address both graph-theoretic and more geographic concepts of street-network connectivity. A summary measure, derived through principal components analysis and dubbed the SNDi, best captures the global, high-resolution variance of the constituent connectivity measures. Full details are provided in the S1 file accompanying ref. 8. Also described in ref. 8 is a classification of all ∼4.1 million 30-arc second (∼1 km^2) urban grid cells into 8 empirical types using *k*-means cluster analysis.

We make use of 2 time series derived from satellite remote-sensing data, the Global Human Settlement Layer (GHSL) (16) and the Atlas of Urban Expansion (18, 41), to classify each street segment as to 1) whether it forms part of a built-up development or not and 2) the time period when it was developed. The GHSL approach yields 4 epochs (<1975, 1975 to 1989, 1990 to 1999, and 2000 to 2014), while the Atlas approach yields 3 (<1990, 1990 to 1999, and 2000 to 2013). Our method makes use of the permanence of roads, once built. However, we also validate our approach to assigning development dates using an independent method available in the United States (10) and through analyzing the consistency of the time series developed through the GHSL and the Atlas methods (*SI Appendix*).

The majority of our analysis employs the time series from GHSL, an open-data project providing global spatial information about the human presence on the planet over time (16). Data are available online (http://ghsl.jrc.ec.europa.eu). We use the built-up grid which is derived from analysis of Landsat image collections and provides built-up year classifications with approximately 38-m resolution. Pixels are classified as follows: land not built-up in any epoch, built-up from 2000 to 2014 epochs, built-up from 1990 to 1999 epochs, built-up from 1975 to 1989 epochs, and built-up before 1975 epoch. For computational reasons, we aggregate to 306-m resolution and calculate the built-up year of the aggregated grid cells as the modal built-up year of individual pixels. Each edge and node is assigned the modal epoch of the intersecting pixels.

Our city-level aggregations utilize the time series from the Atlas of Urban Expansion (18, 41), an open-data online database of city boundaries. The Atlas includes a sample of 200 of the world's metropolitan areas that had 100,000 people or more in 2010 and provides urban extents at 3 time points: circa 1990, circa 2000, and circa 2013. We calculate spatial differences between successive time points to generate boundaries for new development during the periods 1990 to 1999 and 2000 to 2013. We then aggregate our street-level metrics to these regions to characterize development over time in these cities.

SI Appendix reports results for all areas (including nonurban) and discusses our methods in detail, including extensive robustness checks. Complete open-source computer code for quantifying street-network sprawl and reproducing our results is, along with our resulting dataset, in *SI Appendix*.

Data Availability. Our results are all replicable using free and open-licensed data sources. Our complete and open-source code for server setup, data preparation, computation, and analysis is permanently available online at http://gitlab.com/cpbl/global-sprawl-2019. Therefore, we refer readers simply to the underlying source data.

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