

Heterogeneity and scale of sustainable development in cities

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Rapid worldwide urbanization is at once the main cause and, potentially, the main solution to global sustainable development challenges. The growth of cities is typically associated with increases in socioeconomic productivity, but it also creates strong inequalities. Despite a growing body of evidence characterizing these heterogeneities in developed urban areas, not much is known systematically about their most extreme forms in developing cities and their consequences for sustainability. **Here, we characterize the general patterns of income and access to services in a large number of developing cities, with an emphasis on an extensive, high-resolution analysis of the urban areas of Brazil and South Africa.** We use detailed census data to construct sustainable development indices in hundreds of thousands of neighborhoods and show that their statistics are scale-dependent and point to the critical role of large cities in creating higher average incomes and greater access to services within their national context. We then quantify the general statistical trajectory toward universal basic service provision at different scales to show that it is characterized by varying levels of inequality, with initial increases in access being typically accompanied by growing disparities over characteristic spatial scales. These results demonstrate how extensions of these methods to other goals and data can be used over time and space to produce a simple but general quantitative assessment of progress toward internationally agreed sustainable development goals.

neighborhoods | slums | urban services | spatial correlations | inequality

The current worldwide growth of cities presents at once an unprecedented historical opportunity for universal socioeconomic development and an immense challenge to global sustainability (1, 2). The mechanisms that generate improved living conditions and economic growth in cities—and that typically also increase overall energy and resource consumption—are still only partially understood (1–5) and remain hard to disentangle.

Many recent studies have emphasized the environmental and geophysical adverse consequences of an increasing proportion of the planet's population living in cities and of the acceleration of this transformation in recent decades (6–8). The type and scope of these impacts vary but include air and water pollution, land-cover change, loss of natural habitats, strain on water resources, higher demand for energy, and rising greenhouse gas emissions (1, 8, 9).

Conversely, the positive correlation between urbanization and many important dimensions of human development has also become increasingly clear. At the national level, the association between higher levels of urbanization and per capita economic productivity has been clear for some time (2). More recently, as city-scale data have become available, evidence has emerged for broader relationships between urbanization and better health, education, longer lifespans, and greater access to basic services, such as water or electricity, at lower nominal costs (2, 10).

Regardless of whether the positive or negative outcomes of urbanization are emphasized, a more systematic, empirically based understanding of processes of (sustainable) development is still missing. To fill this gap, we must focus on how and where development takes place (11): inside cities and in terms of changes experienced by households and neighborhoods (12–14). Initial steps in this direction point to a large heterogeneity and inequality

of outcomes between people or places, manifested by the unprecedented scale and growth of vast informal settlements (slums) in low- and middle-income cities (9, 11, 15–17). However, local analysis of change also reveals paths toward more sustainable human development, especially in connection to expanded access to urban services (4, 5, 9, 10, 15, 18), which improve health conditions and allow for greater energy and water consumption with much reduced adverse environmental impacts in terms of land use, contaminated effluents, or emissions.

The present paper seeks to address this critical need for connecting processes of change at their sources, by creating a simple framework for the integrated analysis of sustainable development patterns in cities with an emphasis on empirical quantitative measurements across scales—from households to nations—that track progress toward recently agreed sustainable development goals (19).

Critical to the understanding and measurement of sustainable development is the construction of empirically based indicators that capture many aspects of the process simultaneously. The Human Development Index (HDI) has been a forerunner of this methodology by emphasizing standards of health and education in addition to rising incomes (20, 21). Another example is UN-Habitat's Secure Tenure Index (STI) (9), which characterizes poor (informal) neighborhoods. In both cases, index construction is based upon a capabilities approach to development (22), where high values for indices reflect the attainment of universally desirable goals, guaranteeing minimal decent standards of living. This approach is different from and contrasts with the representation of consumption of the same quantities in terms of utility

Significance

Most nations worldwide have recently committed to solving their most severe challenges of sustainability by 2030, including eradicating extreme poverty and providing universal access to basic services. But how? Rapid urbanization is creating the conditions for widespread economic growth and human development, but its consequences are very uneven. We show how measures of sustainable development—identified by residents of poor neighborhoods—can be combined into a simple and intuitive index. Its analysis reveals that challenges of development are typically first addressed in large cities but that severe inequalities often result as patterns of spatially segregated rich and poor neighborhoods. A new systematic understanding of these processes is critical for devising policies that produce faster and more equitable universal sustainable development.

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Data deposition: All data are available at www.santafe.edu/~bettencourt/heterogeneity-scale-sustainable-development.

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Table 1. Summary of slum development priorities

Priorities	Nations									
	Total	South Africa, %	Tanzania, %	Kenya, %	Uganda, %	Malawi, %	Namibia, %	Sierra Leone, %	Nigeria, %	
All	677	26.90	26.70	22.20	13.10	4.40	2.70	1.60	1.50	
Water and drainage	36.90%	20.30	43.50	33.30	57.30	76.70	11.10	81.80	10.00	
Housing	21.30%	44.00	2.80	32.00	5.60	0	11.10	0	10.00	
Sanitation and sewage	13.90%	8.20	14.90	10.70	27.00	16.70	27.80	0	0	
Land tenure	13.70%	18.70	4.40	21.30	4.50	3.33	33.30	9.10	60.00	
Electricity	6.20%	8.20	8.30	1.30	4.50	0	16.70	0	20.00	
Others	7.80%	0.50	27.10	1.30	1.10	0	0	9.10	0.00	

There are 10 nations and 59 cities in the dataset. Four neighborhoods in the Philippines and two in Ghana are not shown but are included in the totals.

direst challenges of urban sustainable development. World-wide one in seven people is presently estimated to live in slums, but this number rises to one in two or more in parts of South Asia and Africa (2, 9). International development agencies have stressed the critical need for better understanding the nature of human and economic development in these poor neighborhoods, and of acquiring detailed empirical information on their primary needs and priorities (2, 9). However, extensive direct information on residents' priorities is still rare. Recent efforts provide us with some new insights on the most important development needs expressed by slum residents (15, 28). Table 1 and Fig. 1C show residents' priorities in 677 neighborhoods in 10 nations and 59 cities mostly in low-income nations in sub-Saharan Africa (*Materials and Methods* and *SI Appendix*, Fig. S12). Most of these data pertain to large and fast-growing urban areas, such as Lagos, Nairobi, Dar-es-Salam, Kampala, Blantyre, Freetown, Johannesburg, Cape Town, or Windhoek.

Although there is broad agreement on the most important priorities, there are also a number of differences across nations (and cities). Overall, water and drainage is the most frequent problem, mentioned 36.9% of the time, followed by issues of housing (21.3%), sanitation and sewage (13.9%), land tenure (13.7%), and electricity (6.2%). These priorities emphasize the dual role of basic services and improved housing in promoting the resilience of communities against both chronic stresses and extreme events, such as flooding and diseases associated with local environmental degradation (15, 29). Other issues, related to health access, transportation, waste collection, jobs, and education, also come up frequently but are stated as less critical. Apart from land tenure, all other issues deal with daily living challenges and are intimately connected to access to improved basic services and local environmental conditions. These findings resonate with recent definitions of sustainable development (9, 29) to which we now turn using extensive neighborhood data from two large middle-income nations: Brazil and South Africa.

City Size and Agglomeration Effects. Agglomeration effects are at the root of the advantages of larger cities at creating greater resources per capita, which historically have led to innovation and development along a broad range of human and environmental issues (2, 30, 31). **Cities are characterized by two general phenomena: agglomeration effects and high socioeconomic and spatial heterogeneity (32–35).** Both have long been understood as having a strong scale (population size) dependence (36). The strength of these scaling effects and the nature of urban heterogeneity have, however, remained poorly studied in rapidly developing cities, in large part due to the absence of systematic data for appropriate units of analysis.

Scaling effects are expressed in terms of the mean expected values for urban quantities, such as the size of the overall economy (gross domestic product, GDP), personal income, amounts of infrastructure, rates of innovation, and so on, as functions of city population size (31, 34, 35). Nonlinear scaling of all these quantities is predicted for functional cities, defined as spatially embedded

networks of socioeconomic interaction (35, 37), known as MAs. MAs are integrated labor markets circumscribing areas of work and residence for most of their inhabitants. **For other definitions of cities, whether political or resulting from density thresholds, agglomeration effects may vanish or seem inconsistent, possibly because not all heterogeneity is included (38, 39).**

To illustrate these effects, Fig. 2A shows total income for MAs in South Africa and Brazil, versus their population size (see also Table 2). In Brazil, MAs typically include many (political) municipalities, whereas in South Africa they are made up of a single large municipality, with the exception of Greater Johannesburg (*SI Appendix*, Figs. S1–S5 and Table 2).

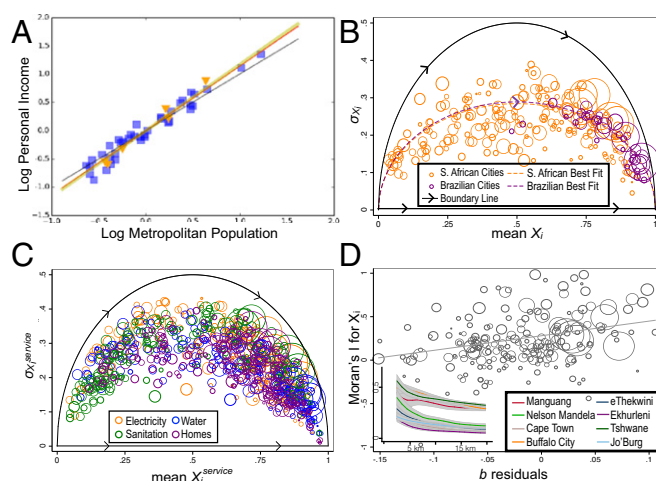


Fig. 2. Agglomeration effects and heterogeneity of sustainable development in cities of Brazil and South Africa. (A) Scaling of personal income with population for Brazil (squares) and South Africa's MAs (triangles). The yellow line shows the theoretical slope of $1 + 1/6$ (35), the red shows the best fit, and the gray line shows the 1:1 line for reference. The best fit demonstrates that larger cities have on average higher resources per capita, at least in nominal terms, which can be invested in sustainable development. (B) The relationship between the SD, σ_i , and mean, \bar{X}_i , of the Sustainable Development Index, X_i , for Brazil's 38 MAs (purple) and 207 South African municipal regions (orange), where the size of the circle is proportional to population. The two black lines bind the area in which (\bar{X}_i, σ_i) pairs can exist, with the upper curved line showing maximal inequality (Kuznets curve, $b = 1$) and the horizontal line corresponding to total equality ($b = 0$). The dashed line shows the estimated best fit for the mean heterogeneity index b . (C) The decomposition of X_i into subcomponents: $X_i^{\text{electricity}}$ (orange), X_i^{water} (blue), $X_i^{\text{sanitation}}$ (green), and X_i^{homes} (purple) for Brazil's metropolitan regions, which allows us to see the role of larger cities at providing improved services. (D) The positive association between Moran's I (distance threshold = 5km) and σ_i for South African municipalities, showing that higher spatial clustering is associated with higher inequality of access to services. (Inset) The variation of Moran's I with the distance threshold s for South Africa's major metropolitan regions.

Table 2. Agglomeration and heterogeneity of sustainable development indicators

MAs	Summary statistics			
	N_units	Estimate	95% CI	Fit
Brazil (metros)				
Income exponent β	39	1.11	[1.03, 1.20]	$R^2 = 0.90$
Heterogeneity index b	38	0.58	[0.56, 0.60]	$R^2 = 0.99$
South Africa				
Income exponent (metros) β^*	8	1.35	[1.19, 1.53]	$R^2 = 0.97$
Heterogeneity index (municipalities) b	207	0.57	[0.54, 0.60]	$R^2 = 0.96$

*The scaling fit without aggregation of the three municipalities in the Johannesburg area gives $\beta = 1.49$, with 95% CI [1.17, 1.81], $R^2 = 0.87$. The best fit for the combined dataset after centering is $\beta = 1.14$, 95% CI [1.06, 1.23], $R^2 = 0.89$, statistically indistinguishable from the simplest theoretical expectations (yellow line) in Fig. 2A. One MA in Brazil was excluded from b 's estimate because of data completeness issues.

As in many other urban systems, total personal income, Y_j , for each urban area, j , is well described statistically by a scale-free function of the form

$$Y_j = Y_0 N_j^\beta e^{\xi_j}, \quad [1]$$

where the prefactor, Y_0 , is independent of city population size, N_j , and where β is a scaling exponent (or elasticity: $\beta = d \ln Y / d \ln N$). The quantities ξ_j are (scale-independent) deviations from the mean (scaling) expectation and are characterized by a zero mean and a small variance. Fig. 2A and Table 2 show the scaling results for the two nations as well as their combined behavior (after centering the regression and pooling the data; see ref. 37). The scaling exponent $\beta = 1.11$ estimated for Brazil is very similar to that of the United States and to the GDP of Brazilian MAs (35). The relatively large number of MAs in Brazil and their size range allows us to establish with high confidence that this result is broadly consistent with theory (35), which derives quantitative expectations for scaling exponents from calculating rates of socioeconomic interactions for a population in a spatial steady state, determined by the balance of benefits and transportation costs in the tradition of urban economic geography (37). The smaller number of South African MAs show stronger scaling effects with a larger $\beta = 1.35$ but also with a wider confidence interval. The combined dataset, Fig. 2A, shows scaling that is statistically indistinguishable from the simplest prediction of urban scaling theory, $\beta = 7/6$ (35), shown as a yellow line in Fig. 2A.

A consequence of this scaling behavior is that larger cities have greater average incomes per capita and thus may exhibit greater capacity to dedicate more resources to services and infrastructure (34–36, 40). Such allocations may happen directly via local taxes or indirectly via higher receipts and reinvestments managed at the national level (30). To investigate this issue empirically, we define a sustainable development index, X_i , characterizing a population in a given spatial unit of analysis i , as

$$X_i = \sqrt[n]{\prod_{j=1}^n X_i^j}. \quad [2]$$

This index spans a number of dimensions n of sustainable development. Because much of the underlying data for assessing sustainable development goals (SDGs) remain to be collected, we illustrate here its properties in terms of access to basic services and housing (SDG goals 6, 7, 11; or 4 of the STI's components):

$$X_i = \left[X_i^{\text{water}} X_i^{\text{electricity}} X_i^{\text{sanitation}} X_i^{\text{homes}} \right]^{1/4}, \quad [3]$$

where X_i^{water} is the fraction of the population in unit i with access to an improved water source. Similarly the superscripts *electricity*,

sanitation, and *homes* refer to access to electrical power, improved sanitation, and permanent housing. Descriptions and emerging international standards for their use as indicators are given in *Materials and Methods* and *SI Appendix*.

This index is bounded between $X_i = 0$, when one or more services are totally absent, and $X_i = 1$, when there is universal access within area i . The multiplicative character of the index follows the construction of the HDI and emphasizes that all components are essential for achieving a set level of development (41) and are not substitutable. This form is also consistent with the HDI (20, 21) and UN-Habitat's definition of a "slum household" as a household that lacks access to any one of these services in the composite STI (9). For purposes of illustration, we show in *SI Appendix*, Figs. S13–S16 and section 1.5 the comparison between the multiplicative and additive forms of X and refer the reader to the relevant discussions leading to changes in the definition of the HDI to a multiplicative form, which motivate Eq. 2 (20, 21).

Fig. 2B shows the average value of X_i for urban areas of different population sizes in Brazil and South Africa. In general, the level of services increases with city size (*SI Appendix*, Figs. S17 and S18), a trend that is especially clear in South Africa. In some parts of Brazil, service provision has expanded more systematically to smaller cities and rural areas (*SI Appendix*, Fig. S8). These results answer our first question: The relative performance of larger cities in terms of access to services and thus some of the dimensions of sustainable development is consistent with advantages derived from urban agglomeration effects and points to a wide range of reasons why urbanization continues to grow in low- and middle-income nations beyond strictly economic motives. As *SI Appendix*, Figs. S17 and S18 show, living in larger cities means that, on average, residents obtain access to many dimensions of sustainable development sooner. However, these averages hide large heterogeneities, to which we now turn.

Heterogeneity of Development Across Scales. Measures of heterogeneity within MAs are especially important because at this scale residents share the same labor and real-estate markets and thus face many of the same opportunities and costs (35, 42).

Measures of heterogeneity may be spatially explicit or they may consider only variation within a population. The Gini coefficient (Fig. 1B and *SI Appendix*, Figs. S9–S11) is a well-known nonspatial measure of heterogeneity. A simpler measure of variation is the SD, σ , and its relation to the mean of any socioeconomic variable. Moran's I , by contrast, is the most widely used measure of spatial heterogeneity (43): It accounts for the level of correlation between characteristics at two spatial locations separated by a distance. The Gini coefficient (or the SD) and Moran's I are not necessarily correlated because this depends on the spatial structure of mixing between different people. Any resource within a population may be spatially distributed in a manner that is maximally clustered, meaning that Moran's I approaches $I = 1$, or perfectly anticorrelated (like a checkerboard), so that Moran's I approaches $I = -1$, or a random (well-mixed) pattern, when Moran's I approaches $I = 0$ (see *SI Appendix*, Figs. S19 and S20 for illustrations).

These quantities, taken together, characterize the heterogeneity of sustainable development indices in cities. From its definition, we see that the variance of X must be a function of the mean, and vanish when everyone in unit i has services, $X = 1$, or when they are nonexistent, $X = 0$. It typically is maximal when the mean $\bar{X} = 1/2$, because then there are more configurations possible, for example by having households with different levels of access within and across neighborhoods i . Thus, we can parameterize the SD of X_i , σ_i , as

$$\sigma_i = b_i \sqrt{\bar{X}_i (1 - \bar{X}_i)}, \quad [4]$$

where the square root corresponds to the SD of a random Bernoulli process. This relation means that $b = 1$ gives the maximal variance at each value of the average \bar{X} (Fig. 2B and C). Note also that it follows from the properties of the SD that $b \geq 0$. Thus, we can characterize two-dimensional trajectories in the space of (\bar{X}_i, σ_i) as levels of developmental change in each unit, i , and the values of $(\bar{X}_i, \sigma_i) \rightarrow (1, 0)$. Given \bar{X}_i , these trajectories are characterized by a single number: the value of b_i as a function of place and time. There are two special trajectories—of maximal and minimal heterogeneity—characterized by $b_i = 1$ and $b_i = 0$, respectively, indicated in Fig. 2B and C by solid black lines. Because of these properties we refer to b_i as a (normalized) heterogeneity index.

Although our present data are cross-sectional, we can compare different urban areas by estimating levels of heterogeneity in terms of b . Fig. 2B shows the plot of \bar{X} versus σ for Brazilian MAs and South African municipalities (see also *SI Appendix*, Figs. S21 and S22). Across different urban areas, we observe a Kuznetz-curve type behavior (24), where intermediate levels of access are associated with the greatest variance. We estimated the values of b (*SI Appendix*, Figs. S21–S23) to determine the expected value of $b = 0.58$ for Brazil and $b = 0.57$ for South Africa, which are statistically indistinguishable from each other (Table 2). The frequency of residuals (*SI Appendix*, Figs. S24 and S25) shows that the variation of b across different cities is small and slightly left-skewed so that trajectories with considerably lower inequality are possible. It is also important to realize that levels of heterogeneity are scale-dependent, as shown in Fig. 1B. Adopting smaller units of analysis, such as neighborhoods, obtains lower values of b . These results answer our second question: They suggest that there are generic trajectories of local development (Fig. 2B and C). Empirically, the variation between neighborhoods is closer to the case where access is distributed in an all-or-nothing manner ($b \rightarrow 1$) rather than when access, though limited, is provided equally to everyone ($b \rightarrow 0$). These results provide a set of specific expectations for local urban development as longitudinal data become available.

To explicitly take into account the effects of space, we now use Moran's I to measure the similarity of conditions between nearby neighborhoods (*SI Appendix*, Figs. S19 and S20 and *Materials and Methods*). We varied the distance between neighborhoods to measure the corresponding strength of spatial correlation for various quantities (Fig. 2D, *Inset*, *SI Appendix*, Fig. S26, and Table 2). In all cases, we find clear evidence of strong spatial clustering in access to services with a magnitude that is strongest at a “walkable” distance below a few kilometers (Fig. 2D, *Inset*). This spatial correlation is even higher for socioeconomic quantities, such as income and racial composition (*SI Appendix*, Fig. S26). These results suggest that assortative dynamics, which generate strong spatial economic and racial inequalities in US cities (25, 33), are likely also at play in urban areas of Brazil and South Africa. Higher levels of spatial clustering, measured by the magnitude of I , are also statistically associated with higher levels of heterogeneity in access to services, measured via the magnitude of b (Fig. 2D). These findings answer our final question: Heterogeneity between people is expressed spatially as differences between places within a city defined at about a kilometer scale, rather than differences within spatially well-mixed populations. In other words, heterogeneity is expressed in these cities systematically as spatially concentrated (dis)advantage (14, 25, 33).

Discussion and Outlook

We have shown how several central features of sustainable development are intimately connected to agglomeration and heterogeneity effects in cities and how the scale of spatial units of analyses matters to measure inequality and inform more effective assessments and policy. We expressed these connections in terms of three general questions, which we answered through empirical analysis using data from Brazil and South Africa. **First, we have demonstrated that despite environmental challenges larger cities tend to exhibit greater economic productivity and expanded access to housing and urban services (2), which nucleate solutions for sustainable development within their nations. Second, large inequality typically results as improvements are initially expanded (15).** Such patterns of inequality are scale-dependent, being larger between different neighborhoods within MAs. Nevertheless, high levels of inequality are not inevitable and several places offer counterexamples of development with low inequality. Importantly, we observe that stronger heterogeneities are associated with more spatially concentrated outcomes at characteristic scales of about a kilometer.

The indicators and statistical analyses introduced here provide a general roadmap for better understanding and assessing sustainable development in cities across scales. The construction of the sustainable development index X_i is general and should be improved and expanded to additional sustainability measures as data become available, for example relating to access to education, gender equity, health, clean energy, and environmental quality, measured within cities and globally.

To this end, it is important to emphasize several shortcomings of present data, which we expect will be gradually overcome in the near future. First, our analysis was focused on neighborhoods and cities of Brazil and South Africa, two middle-income nations with well-established urban systems and state-of-the-art census practices (*SI Appendix*). Other cities in lower-income nations may show much more incipient processes of sustainable development (9, 15, 29). It will be critical to identify and track such situations over time. Second, local sustainability indicators must be expanded to include associated quality of service. Measures associated with safety, health, environmental impacts, effort allocation, and pecuniary costs will need to be better factored in so as to promote meaningful progress (15, 29). This approach requires measurements of the several components, X_i^j , that are closer to the experience of individuals and to the spirit of each development goal and should mirror the process by which components of the HDI have been improved over time in contact with a growing availability of data and case studies (20, 21).

A third area of concern is time. We used census data for Brazil and South Africa because they are consistent and well-documented and cover every neighborhood in these large nations. However, these are decennial census data, and 10 years is too long to assess change in fast-growing MAs given the timeline to meet sustainable development goals. Two new sources of such data may come from remote sensing and citizen-generated maps and surveys. More-frequent and higher-resolution imagery may help identify the type and quality of housing and physical infrastructure and track new construction (44–46). Working collaborations between local governments, communities, and civic organizations using new data collection, mapping, and reporting technologies will be essential to create detailed evidence that is accurate, verifiable, and expressive of residents' priorities (47, 48). These collaborations also generate possibilities for supporting training and education, while providing a mechanism for local knowledge and experiences to guide change (15, 28, 47, 48).

The ultimate objective of a scientific understanding of sustainable development is to decouple improving living standards from environmental degradation. Cities play a crucial role in both processes (2, 4–6, 9, 15, 30). They create increased socioeconomic productivity and a greater intensity of environmental impacts in ways that are at once connected but also place- and scale-dependent (9, 14, 29). As emphasized by the evidence documented here, the continued improvement of theory and practices that exploit the joint dynamics created by scaling effects, heterogeneity, and spatial structure across a large number of socioeconomic and physical dimensions will be critical for harnessing the

transformative power of cities toward faster and more equitable processes of socioeconomic and environmental change.

Materials and Methods

Development Priorities Surveys. Data on informal settlement development priorities were extracted from “informal settlement profiles”—neighborhood surveys of population and services (28)—conducted during 2014–2015 by Slum/Shack Dwellers International (knowyourcity.info/) national federations in collaboration with neighborhood communities and our group. Table 1 derives from 677 neighborhood profiles in 10 nations and 59 cities, including 4 neighborhoods in the Philippines and 2 in Ghana, which are included in the total data but not as individual countries. Among other questions, communities were asked to discuss and identify their most pressing needs in ranked order. The data shown refer to their highest self-identified priority.

Small Area Statistics Data for Brazil. Data for small area statistics in Brazil were obtained from the 2010 national census, available at www.ibge.gov.br. The data are provided in a hierarchical set of spatial units (*SI Appendix*, Fig. S6). The base unit of analysis is the *setor* (average population = 695), modeled after US census tracts. The municipality and the metropolitan region are the geographic levels at which we report statistics. There are currently 39 metropolitan regions in Brazil, made of sets of municipalities ranging in population from about 1/4 to almost 20 million (São Paulo). There are 121,030 urban *setores* in Brazil, characterized in the main text and *SI Appendix*. Data contain detailed information on demographic and household characteristics in addition to construction and access to services.

Neighborhood Statistics for South Africa. South African neighborhood data are drawn from the 2001 national census, available at www.statssa.gov.za. South Africa produces universal coverage census data relevant for assessing sustainable development indicators reported in small geographical units, called “sub-places” (average population = 2,100; median population = 770). We report statistics on municipalities, defined by Statistics South Africa, which also

designates eight functional cities as metropolitan municipalities (*SI Appendix*, Figs. S1–S5). The contiguous metropolitan municipalities of Johannesburg and Ekurhuleni (East Rand) are often aggregated into a single large urban area of Greater Johannesburg, and there is discussion as to whether Tshwane (Pretoria), with a city center 35 km away, should also be included.

Sustainability Index Definition. Indices accounting for the degree of attaining each development goal were constructed for the smallest units of analysis (*setor* in Brazil, and subplace in South Africa) and composed multiplicatively (Eq. 2) to generate a composite index. Measures of access to each service category follow the definitions developed by the Joint Monitoring Program and UN-Habitat; see Satterthwaite (29) and *SI Appendix*, section 1.3 for additional details.

Scaling Analysis. Scaling parameter estimation was performed using ordinary least-squares regression of logarithmically transformed variables. Fig. 2A shows centered data, obtained by subtracting the average logarithmically transformed population and income (see ref. 39).

Heterogeneity Analysis. Estimates of the heterogeneity index b were obtained from Eq. 4, given the estimated mean and SD of X or X^{service} for each spatial unit i . Moran's I estimates were obtained using the smallest available units (*setor* or subplace). A matrix of nearest neighbors j , w_{ij} for each neighborhood i was constructed as $w_{ij} = 1/d_{ij}$, cut off at distance s , which is varied to explore the strength of I (Fig. 2D, *Inset*).

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