SPECIAL FEATURE: PERSPECTIVE

Urban sustainability in an age of enduring inequalities: Advancing theory and ecometrics for the 21st-century city

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The environmental fragility of cities under advanced urbanization has motivated extensive efforts to promote the sustainability of urban ecosystems and physical infrastructures. Less attention has been devoted to neighborhood inequalities and fissures in the civic infrastructure that potentially challenge social sustainability and the capacity of cities to collectively address environmental challenges. This article draws on a program of research in three American cities—Boston, Chicago, and Los Angeles—to develop hypotheses and methodological strategies for assessing how the multidimensional and multilevel inequalities that characterize contemporary cities bear on sustainability. In addition to standard concerns with relative inequality in income, the article reviews evidence on compounded deprivation, racial cleavages, civic engagement, institutional cynicism, and segregated patterns of urban mobility and organizational ties that differentially connect neighborhood resources. Harnessing "ecometric" measurement tools and emerging sources of urban data with a theoretically guided framework on neighborhood inequality can enhance the pursuit of sustainable cities, both in the United States and globally.

neighborhood inequality | sustainability | civic infrastructure | governance | ecometrics

Accelerating urbanization has exposed the fragile ecological future of cities and spurred extensive concerns about urban sustainability (1, 2). Efforts to confront environmental challenges are increasingly reliant on largescale data sources and rapidly changing communication technologies for solutions. The "smart cities" movement in particular aims to connect urban transportation, energy, disaster preparedness, health emergency, and other systems of urban service delivery. The explosion of "big data" and real-time monitoring devices are also major features of recent efforts to enhance ecological sustainability. Funding has followed suit: last year, the National Science Foundation allocated $40 million in funding to design smart and connected communities of the future.

Cities are highly unequal, however, a stubborn fact that both scientific and policy approaches to sustainability must increasingly address (3, 4). Consider a thought experiment: complete data with perfect technological systems of real-time coordination arrive in every city tomorrow. Even in this counterfactual scenario, we would still have vast inequalities in the physical infrastructure of cities, such as housing quality, accessible green spaces, and environmental toxicity. It follows that technological approaches to sustainability, although necessary, are not sufficient. The research reviewed in this Perspective further indicates that sharp and growing inequalities would also remain in core features of the social and institutional infrastructure. Divisions within and across cities in concentrated poverty, fragmented organizational networks, institutional mistrust, and exposure to violence, for example, are deep and surprisingly persistent (5). Inequalities in the physical health and social fabric of cities constitute a threat to urban sustainability and call into question the ability of cities to collectively respond to environmental challenges.

This article therefore argues that to be truly "smart," cities of the future—and the diverse neighborhoods therein—need fresh theoretical ideas and analytic tools for integrating environmental sustainability with the promotion of human welfare, or social sustainability. The basic premise is that whereas ecological processes have understandably taken precedence in the urban sustainability literature, the sustainability of cities entails vital social processes: human well-being

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and environmental outcomes are "intertwined" (4). This Perspective seeks to advance a more balanced consideration of these intertwined processes by making three general arguments. First, the enduring neighborhood inequality that characterizes contemporary cities influences both environmental features of sustainability (such as toxicity and pollution) and social features (such as violence and concentrated deprivation) that threaten the stability of urban populations. Second, the social inequality of cities is implicated in the governance processes that drive policy responses to the challenge of sustainability, including political decision-making and growing citizen engagement with city services. As Ramaswami et al. (4) argue, "understanding and enhancing the capacity of social, policy, and governance networks therefore holds the key to change." Third, to understand neighborhood inequality and collective capacity requires new measurement logics and procedures that go beyond standard practice.

In short, the overall argument of this Perspective is that progress in urban sustainability requires an additional theoretical focus on the social structure of cities and their neighborhoods, which in turn can guide the development of methodological tools for systematic measurement that capitalize on emerging technologies and data sources. In making this case, the article proceeds by synthesizing relevant evidence, hypothesizing specific features of urban environments that matter, and elaborating on the mechanisms and processes connecting them to sustainability. It then describes a measurement approach—what is called "ecometrics"—to advance future research. The hypotheses and methods are based on research programs largely focused on three American cities: Boston, Chicago, and Los Angeles. Although restricted to the United States in this way, the arguments can in principle be tested in cities elsewhere given the global reach of inequality and its spatial manifestations, coupled with the growing availability of big data. The article begins with a brief overview of the multidimensional nature of urban inequality.

The Landscape of Cumulative Adversity

The rise of the rich—the so-called "1 percent"—has drawn widespread attention to relative inequality at the top of the income distribution (6). Less visible are the inequalities that cut across a wide swath of everyday life, such as concentrated poverty, joblessness, family instability, violence, housing insecurity, high rates of incarceration, and infant mortality. Economic and social adversity in African American communities in the United States are especially durable and severe (7, 8), extending across long time periods and multiple generations (9). For example, nonpoor blacks are more likely to live in poor neighborhoods than are poor whites, and like the geographically concentrated nature of violence, the rapid growth in incarceration driven by government policies has had its greatest impact in poor minority communities (10). A stark indicator of the racial gap in criminal justice punishment is that the highest incarceration rate among African American communities in Chicago is over 40 times higher than that in the highest-ranked white community (5).

Inequality can literally be toxic as well. Ecological research shows that black and high-poverty communities in Chicago have been disproportionately exposed to childhood lead poisoning (11, 12), even after accounting for housing-related conditions, and recent discoveries of toxic neighborhoods in Flint, Michigan and East Chicago, Indiana point to the continuing nature of ecological threats from lead, both in the soil and water systems. In both of these cases, the neighborhoods most affected were predominantly black and poor, just as in Chicago (13, 14). Moreover, a recurrent finding in United States cities is that concentrations of pollution and other industrial hazards tend to be highest in neighborhoods with large populations of African American and Hispanic residents (15, 16). The combination of racial and economic segregation, a core social feature of the spatial foundation of inequality in American cities (8, 9), is thus directly implicated in environmental degradation, in turn undermining processes of ecological sustainability.

Although not all cities experience the same intensity of concentrated disadvantage as Chicago or smaller cities, such as Flint in the nation's Rust Belt, spatial inequality is a mainstay of the American urban landscape. Los Angeles, for example, a sprawling Sun Belt metropolis and the nation's second largest city, is very different from Chicago in both ecological and social make-up, yet it has similarly experienced durable inequality over a period of rapid social change. An overwhelming 97% of Los Angeles neighborhoods in the bottom fifth of income in 1990 remained at the bottom 10 years later (17). At the other end, 87% of the highest income neighborhoods in 2000 retained their status 10 years later, despite the disruption of the Great Recession. Downward neighborhood mobility from the top is accordingly quite rare, as is neighborhood upgrading from the bottom fifth. A 13-year follow-up of individuals in the Los Angeles Family and Neighborhood Survey also shows the rigidity of how spatial inequality is experienced over the life course. Over three-quarters of individuals who resided within the most affluent neighborhoods at baseline preserved their position 13 years later, whereas nearly 80% of adults in the lower two-fifths of neighborhood income remained there over the course of the study (17).

It is true that gentrification is upending the urban landscape in sections of cities such as New York, San Francisco, Los Angeles, and Chicago, but this too is a form of spatial inequality. And by far the bigger tendency for low-income neighborhoods is to remain "stuck in place" (9). More generally, neighborhood inequalities have persisted across long time scales and historical eras despite the transformation of political regimes and the specific layout of cities (18). Although beyond the scope of this paper, sharp and growing inequalities characterize most international cities as well (19). Spatial inequality is thus pervasive, multidimensional in nature, and persistent, even though neighborhoods constantly change, reflecting an "enduring neighborhood effect" (5).

Social Mechanisms and Processes Underlying Sustainability

The argument of this paper is that the spatial inequalities just described, both environmental and social, challenge the capacity of cities and neighborhoods to achieve sustainability. In this way, social and physical well-being are deeply intertwined. In addition to direct environmental concerns, such as pollution and lead toxicity, the premature mortality that stems from homicide, and the negative consequences of violence for communities (e.g., population loss, fear and withdrawal from public life) and individual well-being—including the impairment of cognitive development (20)—all undermine the sustainability of social systems. An alarming fact, for example, is that the leading cause of death among African American males aged 15–34 years is homicide. Neighborhoods also vary markedly in their levels of social cohesion, shared expectations, organizational density, trust in institutions, and leadership potential (5). As elaborated in this section, these resources of civic society are hypothesized to influence dimensions of urban social sustainability and governance processes that affect policies on the environment. A corollary argument is that these neighborhood processes can be reliably and validly

measured and tracked in systematic ways that can aid the pursuit of urban sustainability.

One social mechanism that is theoretically relevant to sustainability is "collective efficacy." In the Project on Human Development in Chicago Neighborhoods (PHDCN), research teams surveyed over 10,000 residents to ask about the likelihood that their neighbors could be counted on to take action in meeting various challenges (such as a fight breaking out in the street, or if the fire station closest to one's home was threatened with budget cuts). The surveyors also asked about local trust and the willingness to help one's neighbors. After accounting for a range of individual and neighborhood characteristics (such as poverty, kinship ties, and local friendships), researchers found that the higher a neighborhood's level of collective efficacy among residents—the combination of cohesion and shared expectations for informal social control—the lower its rate of violence (21). Collective efficacy was also positively linked to other-regarding behaviors, such as returning a lost letter randomly dropped in the street and the provision of aid to strangers in the form of giving CPR to heart attack victims (5).

Organizational mechanisms matter, too: the density of nonprofit organizations in Chicago communities was directly associated with higher collective efficacy and behavioral indicators of collective civic engagement (e.g., engaging in blood drives). In addition, the network connectivity among school, law enforcement, political, business, religious, and community organizations, based on a panel study of more than 1,000 leaders, was linked to community efficacy and health (5). Organizations provide more than advice and material resources: shared expectations and trust are enhanced by coordinated activities, whether by neighborhood block groups, tenant associations, or after-school centers (22). Community organizational resources enhance effective responses to natural disasters as well (23), directly underscoring their relevance for urban sustainability.

Another reason that civic engagement and community organizations are important for urban sustainability is that governance structures in the United States have seen a strong shift toward "coproduction" policies that encourage or even depend on direct constituent participation (24, 25), spurred on by the introduction of technologies that promote civic engagement with city services (26). Although growth-machine politics and the influence of wealthy corporations continue to influence economic development, episodes such as the collapse of the multibillion dollar plan for the 2024 Boston Olympics in the face of widespread public opposition—in considerable part over environmental concerns—reveal the increasing importance of civic engagement and grassroots opposition in the politics of urban planning. In addition, the devolution of federal resources in the last few decades has resulted in a sharp move away from direct transfers (e.g., welfare payments to individuals) toward nonprofit organizations serving as mediators of federal support to low-income populations (27, 28), reshaping the form of local urban governance. New research in Boston, for example, has also found that community-based organizations superseded elected politicians as the legitimate representatives of the city's economic and infrastructure development of a large corridor running through poor minority neighborhoods (29). The realignment of urban political representation and the increasing reliance on active citizen engagement in governmental services and the planning of mega-development projects, combined with governmental policies that have privatized state funding of social services in many developed countries, are thus directly relevant to planning for urban sustainability in the contemporary city.

The civic or social infrastructure of cities is fragile, however, and undermined by persistent spatial disadvantage. In Chicago, racial segregation and concentrated poverty foster lower collective efficacy and cynicism toward institutions, especially legal institutions such as the police and courts. Lower collective efficacy and legal cynicism are in turn strongly associated with violence (21, 30). Moreover, as disturbances over police shootings around the country have demonstrated, there is a growing sense among African Americans that the social contract between citizens and law enforcement has been ruptured. These ruptures have important consequences for a city's ability to maintain social order. Indeed, there is evidence that police misconduct suppresses one of the most basic forms of civic engagement: calling 911 for matters of personal and public safety (31). More specifically, a police shooting of an unarmed black male in Milwaukee was estimated to result in ∼20,000 fewer calls for police service in black communities in that city over the course of the following year than otherwise would have occurred absent the shooting. This finding is important to urban sustainability theory for at least two reasons. First, citizen requests for governmental intervention to address problems like crime, drug dealing in public, garbage overflow, or dangerous vacant properties underlie the capacity of cities to provide social order (e.g., reducing violence and maintaining physical property). Second, these requests are part of the information technology that the smart-city movement seeks to integrate with other forms of urban service delivery.

A further dimension of inequality relevant to sustainability is the social and organizational networks that differentially connect neighborhoods: what we can think of as the "higher-order" structure of the city (5). Although crosscutting social ties and processes that span the boundaries of local communities form a theoretically important resource, little corresponding empirical work at the city or neighborhood level has been accomplished because of data limitations. This gap is problematic because flows of movement and resources among the neighborhoods of a city are like rivers, with strong currents and whirlpools of activity. Like an undercurrent, they are out of sight and conscious awareness. These resource connections, or the lack thereof, are nevertheless theoretically important for the political and social order of cities, and by implication for the implementation of policies on sustainability.

Research in Chicago and Los Angeles has attempted to address the empirical nature of crosscutting neighborhood connections. PHDCN capitalized on longitudinal survey data to examine both residential mobility flows and network connections among communities that were generated by organizational leaders (e.g., in politics, business, and education). The density of nonprofit organizations within a community was a significant predictor of being connected to other communities throughout the city, whereas concentrated poverty was linked to greater isolation from citywide connections (5). The higher-order web of connections to other communities throughout the city is thus dependent on the economic resources and density of organizational life within a given community. Research based on the Los Angeles Family and Neighborhood Survey found that citywide ecological networks based on routine travel patterns across the city were also relevant to neighborhood social organization; in this case, the more residents were connected through shared visits to other neighborhoods in the city, the larger the increase in collective efficacy in home neighborhoods (32). Such chain-like movements of people and organizational ties define a core

feature of urban higher-order social organization, solidifying neighborhood advantages and disadvantages.

Although not definitive, the evidence reviewed in this section, taken as a whole, supports the hypothesis that multidimensional neighborhood inequality, patterns of civic engagement, and fissures in the social fabric influence the capacity for healthy and physically sustainable urban futures. In particular, the effects of persistent violence on individual well-being, community stability, and the broader capacity of cities to address environmental challenges; the widespread distrust of institutions like the police in minority neighborhoods; concentrated and compounded deprivations; the differential engagement of citizens with government services as a function of neighborhood characteristics; and inequality in the distribution of social ties and resources across the metropolis all deserve a place at the table in considerations of urban sustainability. The magnitude of contemporary social divisions, strains on public life, and threats to the civic infrastructure suggest that this theoretical integration of approaches is much needed.

Ecometrics in the Age of Urban Big Data

A theoretical focus on the social structure of urban areas and their interlocking neighborhoods requires the development of methodological tools of systematic measurement that capitalize on new technologies and data sources of the 21st-century city. Ecometrics, or metrics for the study of social ecology, refers to a statistical approach to reliably and validly describe characteristics of a city's particular geography, whether a building, street, or neighborhood (33). The central idea is that neighborhood phenomena demand their own measurement logic and are not stand-ins for individual-level traits. Ecometrics can be combined with smart-city technological tools to create a more balanced approach to ecological and social sustainability.

Measurement methods that feed into ecometrics and that go beyond standard census data include community surveys, systematic observations of city streets through videotaping, network analysis of community leaders and organizations, newspaper coding of collective civic events (e.g., school fundraisers, blood drives), and "lost letter" field experiments. In the Chicago PHDCN study, these data sources were combined with archival records on crime, violence, health, community organizations, and population characteristics across 40 years (5). Similarly, community surveys tapping collective efficacy and other social processes (e.g., perceived disorder, social ties) have been conducted in Los Angeles and Boston. Coding of visual images and computer vision methods exploiting Google Street View have also been used to quantify gentrification (34) and change in neighborhood physical conditions (35) in selected United States cities, with the potential for application to cities around the world given the broad and continuing coverage of Google Street View.

Surveys and audits that cover an entire city are expensive to conduct, however, and Google's images of streets limit the kinds of social and temporally refined data that we can measure. To address this gap, the Boston Area Research Initiative (BARI) capitalized on recently available data generated by citizens' requests for services through the City of Boston's "311" reporting scheme, which allows Bostonians to request city services through four channels: a telephone hotline, a self-service website, Twitter, and a smartphone app called "Citizens Connect." Citizen reports like these, along with more traditional 911 dispatches, offer an administratively based window onto the urban landscape, potentially acting as "the eyes and ears of the city," to paraphrase the great urbanist Jane Jacobs (36). Another example of new applications is the use of digitized building permits to measure changes in gentrification and neighborhood physical investments. But measurement concerns loom large in the case of administrative data that are intended to support the operations of basic city services, not scientific research. BARI researchers therefore developed an ecometric methodology for the city's output of digital data (37), working with the City of Boston's Department of Innovation and Technology to translate over one million records of calls—each one describing a discrete event or condition occurring at a particular time and place—into reliable and ecologically valid measures.

Citizen-generated reports derived from 311 and 911 technologies have been used to measure constructs theoretically relevant to sustainability, such as the physical denigration of public spaces (e.g., illegal dumping, graffiti, abandoned cars), lack of internal housing maintenance (e.g., rat infestations), medical emergencies, violence, and social disorder (e.g., public drunkenness, loud disturbances). Combining 311 and 911 data over multiple years, BARI researchers also developed a measure of private social disorder, including domestic violence and other conflict between people living together, to examine the "broken windows" theory of crime and test if physical and social disorder in a neighborhood lead to increases in crime (38). Contrary to traditional expectations, instead of disorder in public spaces inviting crime, the data instead show that private disorder escalates and spills out to the community, leading to more serious violence and visible violations. This evidence supports an internal "social escalation" model of crime and the maintenance of social order, rather than the idea that public disorder attracts crime from outside the neighborhood.

Another project in Boston aimed to distinguish civic forms of digital engagement—being aware of and willing to use call systems like 911 or 311 in the first place—and "custodianship": that is, the likelihood of someone reporting an issue in the public space (e.g., street light outages, graffiti) once a user. This latter measure provides a way to tap into the behavioral dynamics of neighborhood physical maintenance and the demand for citizen participation in obtaining city services, and by implication, the capacity for sustainability. For example, there is evidence that use of the 311 system to address issues in the public space is rooted mainly in territorial motivations for maintaining a neighborhood (39). A related field experiment found that flyers appealing to localized allegiances to specific neighborhoods or places (e.g., "Clean Dudley Square!") were more effective at eliciting reporting of public issues than more generalized messages, such as "Clean Boston!" (40). These results have implications for appeals to local sustainability efforts that involve community groups, nonprofits, and private industries.

The ability of researchers to repurpose governmental administrative data like those in Boston to measure the dynamics of both private and public spaces adds a new dimension to our understanding of neighborhood social sustainability that would be difficult to measure using traditional methodologies like surveys. Moreover, BARI's library of ecometrics is a free public resource that provides researchers and policymakers alike an increasingly nuanced measurement of physical and social conditions at multiple geographic scales (e.g., addresses, streets, blocks, neighborhoods).

Next-generation digital data from private companies will allow analysts to describe neighborhoods and their interconnections in additional ways: cell phone and transportation records capture the movement of people, purchasing data capture flows of material resources, and social media can be used to measure the higher-order structures of dynamic mobility patterns (41). Exploiting these resources, researchers have estimated sharp racial and economic

inequalities in movement flows across urban areas based on the analysis of more than 650 million geotagged Tweets over 18 months in the 50 largest United States cities (42). Focusing on segregation in terms of mobility or contact between neighborhoods rather than a static characteristic of one's estimated home residence, the data reveal that residents tend to concentrate their visits in neighborhoods with a similar racial and economic composition, a mechanism that reinforces existing inequalities. Moreover, residents of poor black neighborhoods are less likely to have contact with nonpoor or wealthy neighborhoods when they travel beyond their home residence than are residents of poor white neighborhoods, even though the average number of visited neighborhoods is similar by race and class. Racial and economic segregation thus characterizes networks of inter-neighborhood exposure in everyday movement across the city as measured by social media.

Mobility patterns based on cell phone record data can similarly be used to assess social isolation in movements throughout the city by race and class. Merging ecometric standards with next-generation digital data also opens up an opportunity to explore how dynamic patterns of segregation intersect with other networks, including organizational resource flows, raising important questions about the consequences of interlocking social dynamics for urban sustainability. For example, does mobility-based segregation in racial exposure across neighborhoods predict trajectories of urban economic development, collective efficacy, or the ability of citizens to respond to disasters and emergencies?

Conclusion

The basic premise of this article is that sustainability in the contemporary city can be more effectively realized by theorizing and systematically measuring multidimensional urban inequalities: not only economic deprivation and its correlated adversities such as violence, but variations in the social infrastructure of cities, collective civic engagement and organizational capacity, environmental toxicities, and the behavioral dynamics of citizens and leaders both within and across neighborhoods of the metropolis. Although beyond the scope of this paper, disruptions to the social fabric—especially in the form of violence—can also engulf entire societies, indirectly harming the environment and incapacitating environmental planning. A stark example of this can be seen in Colombia. As summarized in *Science*, for the past few decades, ecosystems in that country have been occupied by guerrilla fighters and other armed groups, leading to rampant deforestation in many of the conflict areas and forcing ecological scientists to stay away (43). Given the tenuous nature of cease-fire agreements between the government and guerillas, it is an open question whether Colombia can redirect its resources away from war and toward environmental sustainability. With armed conflict endemic to many other areas around the world (e.g., Syria, Afghanistan, Iraq, Nigeria, Somalia), this question takes on global importance.

Although ecometric methodologies combined with emerging data sources offer a potential tool for advancing research and informing both policymakers and engaged citizens, they are no panacea in ameliorating entrenched social inequality and the lack of trust between citizens and societal institutions. Indeed, technology or data alone cannot solve the deep-seated social cleavages that we see in contemporary American cities and, as briefly noted, in cities around the globe. Decades of interventions have likewise failed to solve problems of economic deprivation and correlated social adversities like violence. Like living in harmony with the environment, living in harmony socially is a major challenge. The frontier for urban sustainability is therefore not only to integrate environmental and social sustainability, but also to work out equitable principles and policies for urban governance in an otherwise unequal world.

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