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Article

Why large cities are more vulnerable to the COVID-19 pandemic

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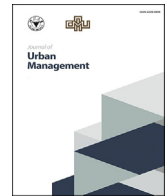
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Editorial

Why large cities are more vulnerable to the COVID-19 pandemic



1. The COVID-19 pandemic is a typical complex matter

As coronavirus disease 2019 (COVID-19) spreads worldwide, various viewpoints on or tentative countermeasures against the pandemic disseminate quickly (Nahiduzzaman & Lai, 2020; Hamidi et al., 2020). As reported by Johns Hopkins University, the global tally of COVID-19 cases passed 25 million on August 30, 2020. Because this crisis is unprecedented in scale and severity in our generation, we do not know how to deal appropriately in practice and theory with the challenges posed by the pandemic to public health and the resulting enormous waves of redundancies and industry closures worldwide. As a result, countries around the world have lost and are still losing many lives due to this deadly disease. However, we believe that the COVID-19 pandemic is a typical “complex matter,” and that we should be able to confront it by taking some concrete actions and decisions derived from complexity thinking on a scientific basis (Krakauer & West, 2020).

It is arguably true that the SARS coronavirus 2 is a relatively simple entity separate from us, while the city is precisely the opposite. When the virus and the city are intertwined, the resulting system inevitably becomes complex as well as coupled because of the dominance of complexity over simplicity (Lai, 2020); this is the dire situation the world is in at present. In simple terms, the COVID-19 pandemic could be treated as a severe outcome that has emerged from a certain degree of intensive social interactions between many cities (i.e., population agglomerations or human settlements) in the urban complex. Relying on this basic understanding, the COVID-19 crisis could be dealt with as a typical “complex matter,” according to the appropriate methods and insights derived from urban complexity thinking and complexity science.

2. Nonlinear scaling relationships between COVID-19 cases and urban scales offer useful insights

The urban allometric scaling law suggests a universal mathematical model across almost all heterogeneous urban conditions to objectively detect and quantitatively determine how various inherent substantive or non-substantive urban attributes vary with the urban scale. This law, whose essence most likely stemmed from the strong interest in and exploration of Kleiber's law and Rubner's law, has been advocated by Bettencourt et al. (2007) and West (2017) in the last 15 years (Rybski et al., 2019). The widely used general form of the urban allometric scaling law is as in equation (1):

$$Y(t) = Y_0 \cdot [N(t)]^\beta \quad (1)$$

Double-logarithmic coordinates are often applied to transform the initial exponential nonlinear form of eq. (1) to a more concise logarithmic-linear one where $Y(t)$ and $N(t)$ indicate urban attributes and urban scale at time t , respectively:

$$\ln Y(t) = \ln Y_0 + \beta \cdot \ln[N(t)] \quad (2)$$

In the above commonly used formula, the scenario of $\beta = 1$ indicates the simplest proportional relationship between attributes and scale (i.e., isometric scaling), and the scenario of $\beta < 1$ indicates negative allometric scaling relationships between attributes and scale that commonly occur in natural biological systems (Hatton et al., 2015). The final and most striking scenario of $\beta > 1$ indicates positive allometric scaling relationships between attributes and scale; it emphasizes that, on average, a doubling of the urban scale brings more than a twofold increase in the corresponding attributes. These notable and surprising average expectations, which may also be traced back to the 15% rule about the good, the bad, and the ugly, all emerge as an integrated package in predictable cities (Bettencourt & West, 2010).

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We are principally interested in understanding through urban scaling insights the influences of various urban scales on COVID-19 infection, deaths, and the most vital health care capacity because, ultimately, we would like to know whether the capacity of health care systems in realistic cities is proportional to the corresponding urban scale and adequate to fight illnesses. This rarely posed question is vital to public health and city safety (Lai, 2019), but to date, few formal or informal investigations and discussions have considered it; it is a hidden problem that should be paid more attention to and examined in depth in current urban development practice.

After adopting and merging the limited high-resolution data publicly available for the United States (e.g., the nonpartisan government data of USAFacts, the mirror archive of the United States Census Bureau, and aggregated information from the Healthcare Cost Report Information System and Definitive Healthcare, as well as the contributions of scientists on GitHub) and treating population agglomerations at the county or zip-code level as a proxy for the urban scale, we applied population-scale (PS) and population-density (PD) criteria to perform data preprocessing and filtering in advance. We then reproduced the aforementioned universal scaling laws mathematically.

The so-called PS criteria here refer to 100,000 persons as the basic unit of urban scale, which is also adopted by the OECD Metropolitan Database. The PD criterion is the density value backward-deduced by the number of cities that are filtered by the population scale mentioned above. Both these criteria are essential intrinsic properties of urbanized space (Bettencourt, 2013; Arcaute et al., 2015). It is worth noting that to avoid the observed urban scaling laws being overly dominated by a large number of small cities and to consider another perspective to calibrate our judgment and decision-making (Leitão et al., 2016), we utilized both population-scale and population-density criteria to filter relatively suitable individual cities. As shown in Fig. 1, the threshold on the left panel is 100,000 persons, and the threshold on the right panel is 100,000 persons (PRS) combined with 175 persons per square mile (PPSM). That is, we applied the number of cities filtered by the PS criterion to backward-deduce its corresponding PD criterion and then simultaneously used both these filters to achieve another balanced viewpoint.

In brief, we found that the current COVID-19 pandemic situations, including confirmed cases and deaths, demonstrate superlinear scaling relationships with the urban scale (Figs. 1 and 2). These situations revealed by urban scaling are not surprising because of the accelerating effects of socio-biological interactions on the pace of urban life (Bettencourt et al., 2007). They also correspond to the serious situation (i.e., the relative concentration of confirmed COVID-19 cases and deaths in large cities) in the United States today. Recently, a pioneering study used structural equation modeling to account for both direct and indirect impacts of density on COVID-19 infection and mortality rates of 913 metropolitan counties in the United States (Hamidi et al., 2020). It reported that larger cities indeed have higher infection and mortality rates. These analyses support the findings in this study.

3. Nonlinear scaling relationships between health care systems and urban scales offer useful insights

In addition to understanding the influences of urban scale on COVID-19 infection and deaths, we would also like to know, through insights on scaling, how the specific capacities of health care systems relate to realistic cities. This rarely investigated problem is vital to urban public health and safety, and is directly related to the resilience capabilities of cities under the severe challenges of the COVID-19 crisis. Using the same settings and steps, we treated (1) all staffed beds, (2) staffed ICU beds, and (3) all licensed beds as proxies for the capacity of health care systems of cities. “All staffed beds” refers to the number of hospital beds of all types typically set up and staffed for inpatient care, “staffed ICU beds” refers to the number of ICU beds typically set up and staffed for intensive inpatient care, and “all licensed beds” refers to the number of hospital beds of all types licensed for potential applications.

As shown in Figs. 3–5, all relevant urban health care systems demonstrate superlinear scaling relationships with the urban scale. The situations revealed by urban scaling are not surprising (i.e., all staffed beds, staffed ICU beds, and all licensed beds are relatively concentrated in large cities) because a recent study has shown similar tendencies (Meirelles et al., 2018). In addition, cities with higher density possibly possess more superior health care systems, which more effectively treat COVID-19 cases (Hamidi et al., 2020). The results of these previous studies directly or indirectly corroborate the findings of this work.

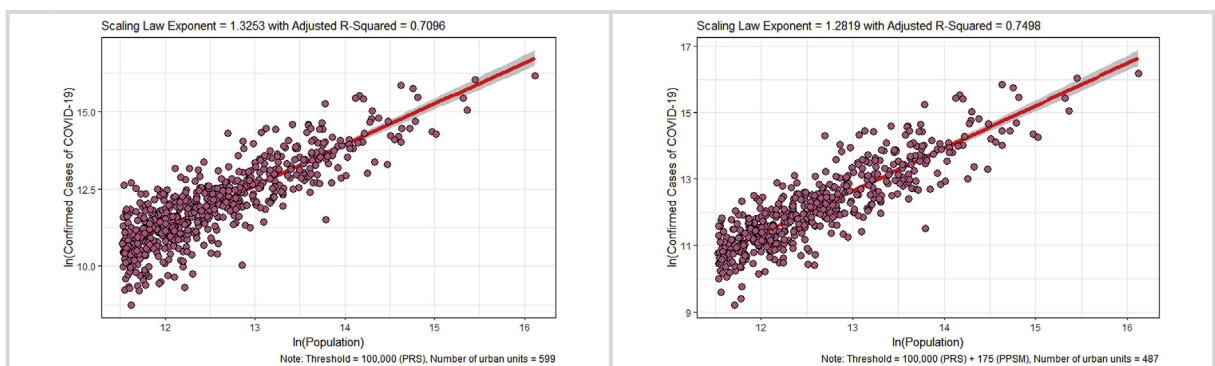


Fig. 1. Confirmed COVID-19 cases in the U.S. scale superlinearly with urban scale [August 13, 2020].

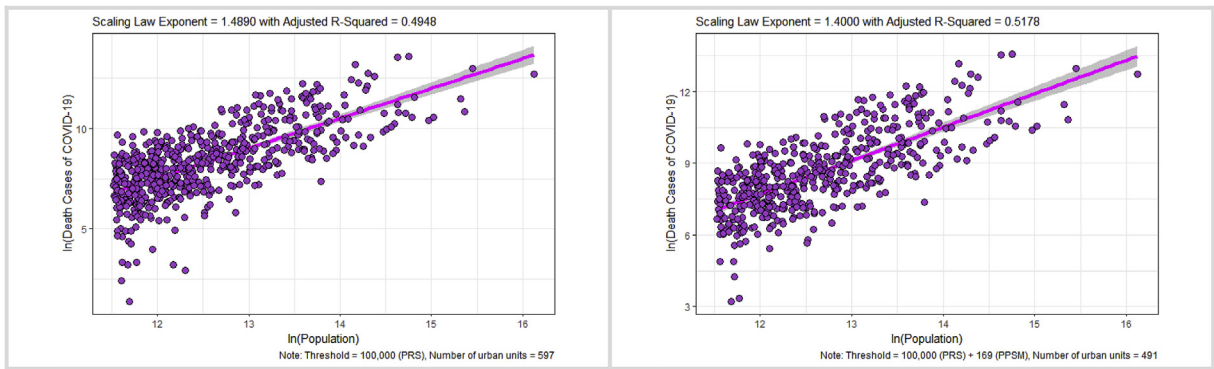


Fig. 2. Cases of COVID-19 death in the U.S. scale superlinearly with urban scale [August 13, 2020].

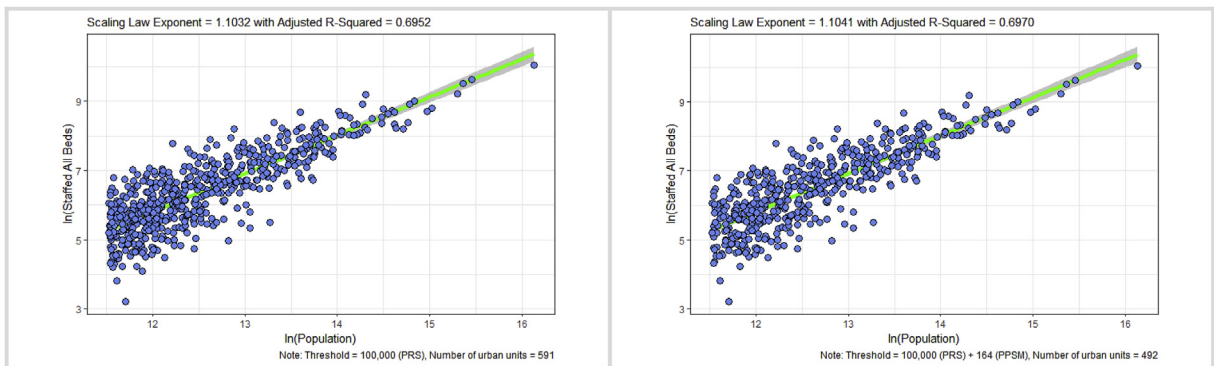


Fig. 3. All staffed beds for COVID-19 in the U.S. scale superlinearly with urban scale. [August 13, 2020].

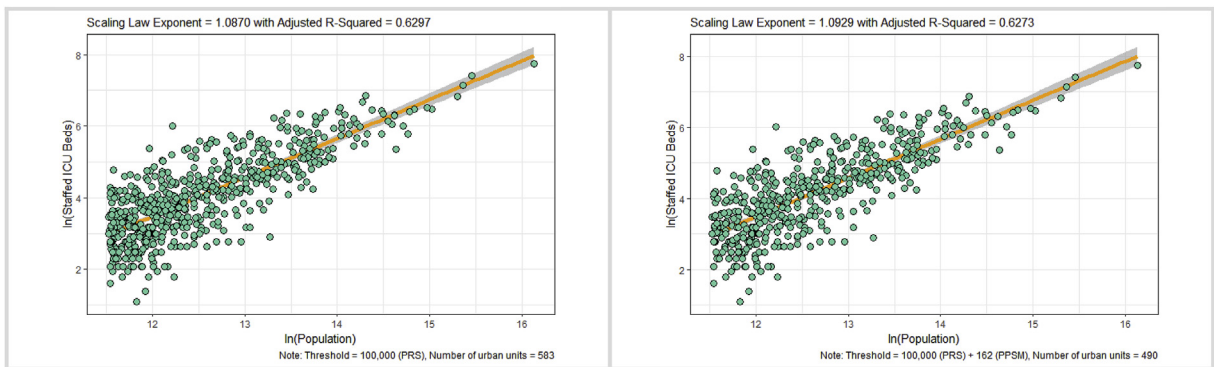


Fig. 4. Staffed ICU beds for COVID-19 in the U.S. scale superlinearly with urban scale [August 13, 2020].

4. Analyses of the relationships between the scaling regimes of COVID-19 and health care systems

In recent years, many experts have stressed that the fundamental mechanisms underlying the observed urban scaling laws are still poorly understood, and care should be taken in drawing generalizations from these aggregated characteristics (Cottineau et al., 2017; Meirelles et al., 2018; Rybski et al., 2019). In line with this understanding, we attempted to utilize sensitivity analysis (SA) to carefully draw implications from the potential changes in scaling law exponents based on various population scales, population densities, and combinations of population scale integrated with the corresponding population density, instead of adopting a single dominant scaling value as the basis for direct consideration. Consequently, we expanded the analytical scope to 10 scenarios with 100,000 persons as the axis center and 10,000 persons as the rolling positive or negative spacing. We then cautiously explored the disparities in scaling regimes between the COVID-19 dimension and the health care system dimension via the aforementioned three angles and filters.

As shown in Fig. 6, we found significant disparities in scaling regimes between confirmed COVID-19 cases and health care systems.

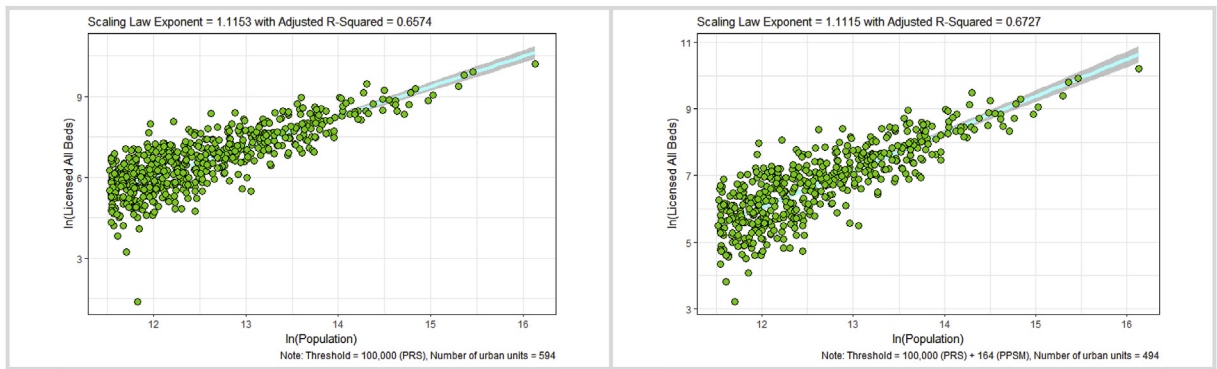


Fig. 5. All licensed beds for COVID-19 in the U.S. scale superlinearly with urban scale [August 13, 2020].

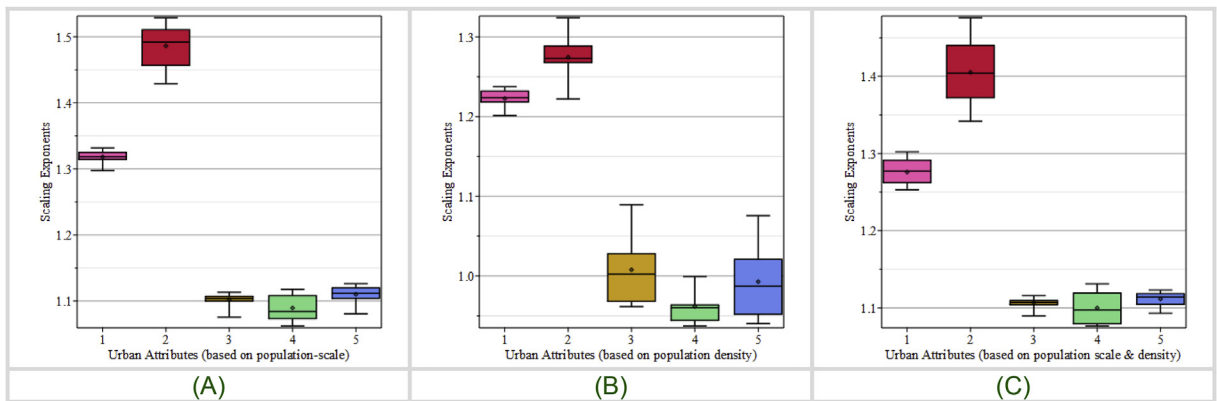


Fig. 6. Box plots of the disparities in scaling regime between confirmed COVID-19 cases (category 1), COVID-19 deaths (category 2), and health care systems (categories 3, 4, and 5 of all staffed beds, staffed ICU beds, and all licensed beds): the results of sensitivity analysis according to population scale (A), according to population density (B), and according to population scale and density (C) (August 13, 2020).

These significant differences imply that both confirmed cases and health care systems are disproportionately concentrated in large cities; however, the concentration of confirmed cases is more disproportionate than that of health care systems. Therefore, large cities are almost certainly more vulnerable than smaller ones due to the enormous pressure on health care systems. In contrast, smaller cities in the United States could probably better maintain robustness and resilience during the coronavirus outbreak at this time. We also noted that more extreme disparities in the scaling regime occur between *deaths* due to COVID-19 and health care systems. We argue that these disparities may stem from the enormous pressure on health care systems or even treatment overloads that partly reflect the concentration of health care systems that is lower than the concentration of confirmed COVID-19 cases. We conjecture that these disparities may probably be one of the main causes of the large number of COVID-19 deaths in the United States in recent months.

5. Some reflections on reasonable responses to the COVID-19 crisis via complexity science and complexity thinking

The above investigations are descriptive at best and cannot be relied on to suggest how to deal with the COVID-19 crisis. However, the findings could help inform evidence-based decisions or even develop an objective planning framework or procedure in advance (Huang & Wey, 2019), which might mitigate the rising trend in COVID-19 under some specific conditions. The key to realizing these goals is to search for the nodes or hubs in the COVID-19 web that facilitate intervention based on the aforementioned scaling of network system thinking.

To put it simply, the seemingly isolated and individual incidences of infection or death naturally converge on their own into an organized network at a macro-level (e.g., Figs. 1–5); therefore, such a self-organized network offers a potential opportunity to intervene positively through its nodes. Similar concepts can be traced back to the widely known scale-free network; that is, the structure of a network generally remains the same because most nodes have very few connections and are, in a sense, unimportant. However, if highly connected nodes, the so-called hubs, are specifically targeted, the network as a whole might not survive even the first hit (Koonin et al., 2006; Vespignani, 2009).

The Chinese Government has implemented some measures to eliminate the possible path of disease transmission with the hope of thoroughly controlling the COVID-19 pandemic, which may partly fit into network system thinking. These measures in the past year have included blocking city access, prohibiting people from gathering (i.e., social distancing), a large number of residents being forced

to quarantine at home, and suspending production activities of all society. Although these responses against all possible nodes are very radical and indiscriminate, they seem to be effective.

In summary, radical and holistic measures superficially seem to be useful; however, such indiscriminate responses are a double-edged sword. The necessary actions may not holistically intervene in the urban system because they would seriously disrupt personal livelihoods at the micro-level, urban development at the meso-level, and even long-term socio-economic robustness of the nation at the macro-level after such a historic pandemic. The alternative is to tackle the pandemic through localized intervention, that is, defining and managing specific nodes, as if targeting the highly connected nodes in a scale-free network. For example, Wuhan City, Hubei Province, China, where the COVID-19 pandemic first broke out, was a specific node. The Chinese Government promptly and decisively invested in 16 mobile cabin hospitals in Wuhan City in an attempt to intervene in and block the pandemic (Zhou et al., 2020). Considering the deadly properties of the highly contagious disease, which quickly spreads and establishes itself in the community, the localized intervention decisions and trade-offs in the urban public health care system implemented by the Chinese Government during this period seem successful. The success of these interventions in specific urban nodes should be replicable and may be functional in the subsequent second and third waves of the pandemic that are likely to occur in the future, including the current wave caused by the Omicron variant.

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