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Research Article

Learning from pandemics: Applying resilience thinking to identify priorities for planning urban settlements



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ABSTRACT

Based in an interdisciplinary review of the literature on COVID-19 and recent outbreaks, this paper uses pandemics as a lens to examine the socio-ecological resilience of human settlements. This narrative literature review applies the conceptual framework for resilience developed for complex systems to identify five planning and policy issues critical to disease emergence, transmission, and outbreak. First, since urban settlements and activities facilitate pathogen transmission between species, reducing 'shocks' like zoonotic diseases and climate change requires not just prioritizing urbanization patterns and land use in urban policies for environmental health, but also animal rearing practices and biodiversity maintenance. Second, since disease transmission is linked to not just contact rate but also host susceptibility, reducing vulnerability by improving equity in access to essential infrastructures like housing, water, sanitation, healthy food, green/public spaces, healthcare—that impact human health directly and indirectly—is critical. In its absence, curbing disease transmission requires focusing on contact rate suppression, but doing so brings human activity to a halt, decimating the economy and livelihoods. Third, the persistence of many pathogens or their vectors in environmental media suggests that built environment & public health professionals must address maintenance of environmental quality at various scales. Fourth, there is a need for redundancy, be it in commodity supply chains (like PPE, food) or data management for say, monitoring & enforcement of home quarantines during a pandemic. Fifth, while it is crucial to have a centralized response for healthcare, decentralized infrastructure management has been critical during this outbreak: including participatory governance structures to recruit civil society in data collection and self-reporting, reliance on and quick development of mutual aid groups to distribute food and other essential supplies, localized approaches to repurposing infrastructures to create safe public spaces. This application of resilience thinking also evokes the need to study cities as social-ecological systems.

1. Introduction

Novel disease emergence, transmission, and outbreak impacts—and is impacted by—planning and policy at various scales. Unsurprisingly then, the COVID-19 pandemic has spurred a plethora of predictions on long-term, radical changes—to service provision, digital infrastructure, resource and environmental health, economies, city densities, space use, communities and institutions—and prescriptions to improve the resilience of our environment and socio-economic institutions as we continue to plan urban settlements. But individual disciplines have different, overlapping conceptualizations of resilience, tuned to their examination of specific areas of concern. Given that the pandemic impacted a colossal range of actions and processes at multiple spatial scales, and cemented our

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expectation of the regularity of *systemic* disturbances, I use resilience theory as developed for the study of complex systems as my conceptual framework to identify priority areas for planning and policy transformation.

Reviewing literature from various disciplines, I specifically address: How do shocks like novel diseases disturb or destabilize systems? Why are systems vulnerable to those shocks? How do certain stresses exacerbate the impact of the shock on the system? How does reduced response diversity make systems susceptible to instability when exposed to the shock? How can social adaptive capacity compensate for the crossing of biophysical thresholds post-shock? By thus identifying the sources of shock, stress, vulnerability, susceptibility, and adaptive capacity, I develop the list of broad planning priorities needed for urban settlements in this “era of pandemics”.¹

2. Methods

2.1. Literature review

From January–June 2020, I reviewed articles being published on the COVID-19 outbreak by authoritative news outlets,² to identify planning and policy issues relevant to disease emergence, local transmission, community transmission, and outbreak, and categorized them as such. I also searched for, reviewed, and categorized planning-specific articles related to current and recent disease outbreaks in the urban context, from a range of websites³ associated with publications on planning by professionals and scholars; most collected via (non-constrained) snowball sampling. The ~500 articles reviewed included news reports, timelines, blog posts, opinion articles (by built environment professionals, journalists, or scholars), expert interviews, research reviews or preliminary research.

These articles were reviewed to identify:

1. How planning and policy for food systems, environment, natural resources, housing, community and public health, infrastructure systems, land use, and urban design, is related to disease emergence, transmission, and outbreaks.
2. Literature from various disciplines that supported, rejected, critiqued, or provided nuance or context to opinions and assessments reflected in the articles.

I also reviewed emerging medical and biological research on SARS-CoV-2 and COVID-19 by following the pandemic timeline and publications featured on *Nature*. Altogether, these steps produced a database of 237 journal articles, 132 of which are cited in this paper.

2.2. Analysis framework

A system is a set of interrelated or interacting components connected to form a unified whole, from software, to organizational structure, to physical infrastructure, to natural resources, and so on. A social-ecological system (SES) is “a bio-geo-physical unit and its associated social actors and institutions” (Glaser et al., 2008). Systems are defined—in terms of their components, boundary, environment or surroundings, functions, etc.—and understood as multi-hierarchical (system of systems). Systems can be complex: the variables defining them are dynamic, changing nonlinearly (change in output not proportional to change in input), with the collective behavior of components producing emergent properties, i.e. properties that cannot be inferred from properties of the components. Resilience is an emergent property of complex systems.

Systems are routinely exposed to disturbances or Shocks, sudden events threatening immediate well-being. They can respond by resisting change (Robustness), absorbing change without altering in function (Resilience), or reorganizing (Transformation). Stresses are chronic underlying issues that can weaken the ability to bounce back in response to a shock. Vulnerability is the propensity of systems to suffer significant transformation as a consequence to shocks. This depends on not only on the characteristics of the disturbance it was exposed to, but its Capacity to Respond. While system stability seems to be a desirable state for humans, in order to maintain a state of steady (or increasing) well-being, variability is actually inherent to a system—thus, optimizing for specific outcomes produced

under a narrow set of conditions produces efficiency at the cost of resilience.

¹ See IPBES Workshop on Biodiversity and Pandemics: https://ipbes.net/sites/default/files/2020-11/20201028%20IPBES%20Pandemics%20Workshop%20Report%20Plain%20Text%20Final_0.pdf.

² BBC, CNN, Al Jazeera, Nature, The Guardian, New York Times, NPR, Huffington Post, Wall Street Journal, WHO, UN-HABITAT, The Washington Post, Foreign Policy, The Week, The Atlantic, Time, National Geographic, Wired, The Economist, The Indian Express, The Hindu, The Times of India, Forbes, Scientific American, Brookings, The Kinder Institute, Bloomberg.

³ Including, but not limited to Planetizen, Next City, Common Edge, Medium, The Conversation.

I applied this resilience thinking⁴ conceptual framework to select and organize the literature identified for review in section 2.1.; Fig. 1 outlines this process.

3. Disease outbreaks & the resilience of urban settlements

3.1. Shocks: urbanization patterns and food systems foster disease emergence

Zoonotic viruses (transmitted from animal hosts to humans) are causing increasingly more outbreaks (Burke et al., 2012). Interspecific⁵ transmission occurs either directly from wild animals to human hosts, or from wild animal to domesticated animals to humans; both linked to a range of anthropogenic environmental disturbances.

Habitat encroachment, habitat fragmentation, and biodiversity loss resulting from human activities are implicated in wild animal to human transmission of diseases. Viruses survive as mild infections in wild animal hosts: bats teem with coronaviruses, and have antibodies for them (Drexler et al., 2014; Zheng, 2020). But stress from human disturbances to both habitats and animal hosts facilitates viral shedding (release into the environment) and pressures viruses to mutate and form new variants—including those capable of infecting humans (McMichael, 2004; Plowright et al., 2014; L. F.; Wang et al., 2006; World Economic Forum, 2019). And habitat encroachment and fragmentation creates more wildlife-urban interfaces (WUIs) where transmission occurs (Hassell et al., 2017). The SARS-CoV-2 genome links it to bats and pangolins before it jumped to humans (Boni et al., 2020; Lau et al., 2020; X.; Li, Yang, et al., 2020; Tang et al., 2020). Additionally, while not generalizable across all zoonotic diseases (Luis et al., 2018), higher biodiversity offers alternative hosts to act as reservoirs and dilute the risk of humans getting infected (Johnson & Thielges, 2010; Schmidt & Ostfeld, 2001). Biodiversity loss alters the external microbiome, which can in turn affect the human microbiome, crucial to preventing chronic inflammatory diseases (Dunn, 2018), likely countered by rewilding urban soil microbiomes through revegetation (Mills et al., 2020).

Domesticated animals serve as intermediate hosts; large farms and animal markets in rapidly urbanizing regions have increased opportunities for wildlife and domestic animals to interact, facilitating interspecific transmission (Connolly et al., 2020; Hassell et al., 2017; UNEP, 2016; Wilcox et al., 2014). Current animal rearing practices (including but not limited to live wild animal markets and factory farming) often keep animals in formerly wild animal habitats, in high density, under stress—conditions ripe for viral transmission to domesticated animals and their continued mutation, so a variant capable of infecting humans can emerge. There are multiple pathways for avian & swine-origin viruses to evolve, and enhanced replication and pathogenesis in humans has been reported (Mehle & Doudna, 2009). Peri-urban areas with high poultry density and low land use diversity, and highly urbanized centers in U.S. and Europe are hotspots of emerging infectious diseases (Kessler & Peterson, 2017; Richards, 2012). Activities like mining, commercial forestry, agriculture have produced transient human settlements equipped with few services and amenities, so wild animals are hunted for food (UNEP, 2016). These factors can explain why initial COVID-19 infections were higher in settlements with higher wild animal-human contact (Burki, 2020).

There have been efforts to construct a detailed understanding of wildlife and human movement across landscapes to predict and prevent disease spread, thereby catching the infection at the source or generating an effective early warning system. The international research NGO EcoHealth Alliance integrates the study of environmental health with the study of emerging infections across the world,⁶ in conjunction with the USAID program PREDICT (Carlson, 2020); the One Health approach is another multidisciplinary research initiative tying human and non-human health research (Gibbs, 2014). Efforts of global surveillance of viruses capable of transmission to humans are plagued by underfunding, and the challenge of accurately predicting⁷ viral evolution (Holmes et al., 2018).

Systems experience shocks that can change their state (affect some variables) or destabilize them (by changing processes and feedbacks, even impacting system robustness or resilience). Novel infectious diseases are shocks—while capable of temporarily altering human activities and institutions at local, regional or global scales, they could also have longer term impacts. For instance, while cholera outbreaks heralded the era of water and sanitation infrastructure systems in urban settlements (Rosenberg, 2009), the COVID-19 pandemic has seen a reversal in pollution trends following an initial drop from reduced industrial activity. Since human settlements and activity increase human-wildlife interfaces, produce stress-led viral shedding in wild animals, and thus facilitate interspecific pathogen transmission, reducing shocks like zoonotic diseases and climate change is important. This requires not just prioritizing urbanization patterns, peri-urban and rural land use in urban policies for environmental health, but also food systems (specifically, animal rearing practices) and biodiversity maintenance.

3.2. Vulnerability: infrastructure inequities enhance host susceptibility and can facilitate transmission

When a novel disease is introduced into the population—emergence—the disease is restricted to individuals who have traveled to the infected areas, so only a few individuals have contracted the virus and the disease is contained. However, in the next stage—local

⁴ For a detailed understanding of these concepts and their development, please refer to Brian Walker and David Salt's books, *Resilience Thinking: Sustaining Ecosystems and People in a Changing World* (2006) and *Resilience Practice: Building Capacity to Absorb Disturbance and Maintain Function* (2012).

⁵ existing or occurring between different species.

⁶ See more at: <https://www.ecohealthalliance.org/programs#/one-health>.

⁷ While the debate on the relevance of this fact is ongoing (Bengston, 2020; Burki, 2020; Y.; Li, Yang, et al., 2020), the RaTG13 virus discovered in bats two years ago (with 96% genomic similarity with SARS-CoV-2) was dismissed as low risk for human transmission.

transmission—the virus spreads through an individual who has traveled to an infected area or come into direct contact with another infected person, so virus transmission between people must be reduced by contact tracing and isolation (van Seventer & Hochberg, 2017). Understandably, most strategies—like air travel restrictions, lockdowns, social distancing—focus on reducing transmission by reducing contact rate⁸ (Ali & Keil, 2011; Bajardi et al., 2011; Cooper et al., 2006; Flahault et al., 2006; Hu et al., 2013; Liu et al., 2020; Salje et al., 2020). However, R_0 —the average number of cases that an infected person will cause during their infectious period—is not just dependent on contact rate. R_0 also increases if number of susceptible people in a population increase, if pathogen infectiousness is high, and if recovery rate of infected people is low (van Seventer & Hochberg, 2017). While countering pathogen infectiousness after it invades a population and improving recovery rates are part of a biomedical pandemic response, population susceptibility requires a planning response: universal access to critical infrastructures.

Mathematical models computing R_0 assume the whole population to be susceptible to a novel disease, but host susceptibility to infection stems from biological traits and environmental factors (van Seventer & Hochberg, 2017) like nutrition, shelter, water and sanitation. Individuals in resource-poor settings and vulnerable to malnutrition may be at increased risk of infection due to malnutrition-induced immunosuppression (Schaible & Kaufmann, 2007). Lack of housing can reduce overcrowding (and hence, contact rate), as in the case of the current pandemic with its demand for shelter-in-place (Ii et al., 2020; Ortiz & Boano, 2020). Handwashing can prevent individuals exposed to the virus from becoming infected, but a third of the world's population lacks clean water access (Satterthwaite, 2016). Just under half lack sanitation access, making open defecation rampant, and since fecal matter harbors pathogens for anywhere between a few hours to several days, fecal-oral transmission of pathogens is a persistent concern in disease transmission (Arslan et al., 2020; Gupta et al., 2020; L. Heller et al., 2020; Jefferson et al., 2020; Mohan & Deswal, 2020; Robb et al., 2017; Rusca et al., 2017; Zheng, 2020). As the “syndemic”⁹ nature of pandemics exacerbates the very inequalities that increased disease burden for the vulnerable subset of the population (Bambra et al., 2020), we can expect this positive feedback loop of higher vulnerability to continue.

Vulnerability is critical, because it could maintain threshold host density¹⁰ of people susceptible to the disease, and spatially concentrate susceptible people. To understand this, we need to clarify the relationship between transmission and density. While a study of the 1918 flu pandemic in India—the country with the most deaths—revealed that districts below a “threshold population density” experienced lower rates of population loss (Chandra et al., 2013, pp. 1–10), a World Bank analysis found that population density is not a key determinant of COVID-19 caseload for 284 Chinese cities (Fang & Wahba, 2020). In fact, contact rates tend to increase with density, saturate at higher density, and decrease at “extremely high density, when it becomes difficult for people to move and make contact with others” (Hu et al., 2013). The only clear relationship between transmission and density is at the scale at which pathogens are transmitted: SARS-CoV-2 is released into the air by activities ranging from coughing or sneezing to even breathing (Morawska & Cao, 2020; Stadnytskyi et al., 2020; Y.; Wang et al., 2020)—carried in large Flüge droplets or fine aerosols—these particles and pathogens can linger in air or land on surfaces, surviving on inanimate surfaces for up to 9 days (Kampf et al., 2020; Van Doremalen et al., 2020). Understandably then, contact tracing and genomic studies for COVID-19 transmission have traced majority transmission events to SSEs or “superspreading events”, and secondary infections (and attack rates) have been found to be high (Fan et al., 2020; Hamner et al., 2020; Y. Liu et al., 2020; Lu et al., 2020; Miller, Martin, Harel, Tirosh, et al., 2020). Thus, high density of people at smaller spatial scales facilitates transmission, and overcrowded spaces are a product of stark socioeconomic inequities in housing. Moreover, these spatially concentrated populations likely also face other factors increasing their susceptibility to disease—lack of water, sanitation, nutrition, affordable healthcare (Corburn et al., 2020). This could effectively sustain the disease within the population.

In the absence of reduced vulnerability through pointed interventions for equitable housing, infrastructure and healthcare access, curbing disease transmission will require contact rate suppression. While lockdowns are successful in greatly reducing community transmission (Miller, Martin, Harel, Tirosh, et al., 2020; Zhang et al., 2020), doing so brings human activity to a halt, decimating the economy and livelihoods, in turn increasing short or long term vulnerability.

3.3. Stresses: poor environmental quality increases disease incidence, severity, lethality, and can facilitate transmission

Since infectious diseases result from a combination of pathogen, host, and environmental factors (epidemiological triad model),

⁸ In the simplest mathematical disease model, the population is compartmentalized into three mutually exclusive groups (*susceptible, infected, recovered*), people transition between these “compartments” at different rates, and using some basic calculus, R_0 is calculated. If $R_0 > 1$, the infection will be able to start spreading in a population, and the higher the R_0 , the more challenging it is to control the spread of the disease in the population. The models are meant to show how different public health interventions may affect the outcome of the epidemic, by addressing factors impacting the value of R_0 . This model gains complexity with the inclusion of various other parameters (Britton & Ouédraogo, 2018; Campbell, 2017; Chowell et al., 2007; De la Sen et al., 2019; Inaba, 2014; Leung et al., 2018)). One source of complexity comes from factoring in natural birth and death rates of a population, which is required when an epidemic persists over time. A second source of complexity comes from factoring in the spatial movement of populations. A third major source of complexity stems from the compartmentalization of the population: the simple model has just susceptible, infected and recovered people, but scholars have identified other compartments in past epidemics and pandemics: for seasonal flu and the 1918 and 2009 pandemics, the *exposed*; for Ebola, the *dead* could be infectious. For COVID-19, susceptible people can also get the disease from *asymptomatic* people (Peng Shao, 2020). Many such model variants exist. However, mathematicians conclude that contact rate is crucial to determining if there will be an epidemic or not, and how many people will be infected.

⁹ “A syndemic exists when risk factors or comorbidities are intertwined, interactive and cumulative—adversely exacerbating the disease burden and additively increasing its negative effects” (Bambra et al., 2020).

¹⁰ minimum concentration of individuals necessary to sustain a density-dependent disease within a population.

strategies to reduce infections include reducing reservoirs and vectors harboring pathogens. Curtailing human movement and animal populations reduces exposure to human, domesticated and wild animal host reservoirs, not environmental reservoirs.¹¹ Given the aforementioned stability of SARS-CoV-2 on surfaces and in environmental media (water, particulate matter, dust, and sewage) under various conditions, people can have higher risk of being infected because of higher exposure to environmental reservoirs of pathogens. For instance, *Anopheles* mosquitoes—that spread malaria—breed in clean standing water, a fixture in ‘informal’ settlements lacking consistent water supply.

Polluted environments harbor pathogens, or the vectors and vehicles¹² that transmit the pathogens to human hosts. Given such varied modes of infectious disease transmission, it is clear that transmission is not just a result of proximity between humans but the persistence of several pathogens in the environment, sometimes for extended periods of time. Dengue is spread by *Aedes* mosquitoes that breed well in poor water and sanitation conditions in various polluted urban microhabitats (Braack et al., 2018; Getachew et al., 2015), and *Anopheles* mosquitoes are beginning to adapt to polluted city water (De Silva & Marshall, 2012; Mattah et al., 2017). The role of polluted water in producing higher disease burden is well-documented (Stewart et al., 2008), even quantified (Katukiza et al., 2014). Mortality during the 1918 flu pandemic has been linked to air pollution related to coal burning (Clay et al., 2018, 2019). Research from multiple countries, using methods ranging from inferential and descriptive statistics to bioinformatic analyses of DNA sequences, show that air pollutants—notably, particulate matter, ozone, nitrogen and sulfur dioxides—significantly increase COVID-19 incidence, severity, death, or length of recovery (Bilal et al., 2020; Borro et al., 2020; Domingo et al., 2020; Isphording & Pestel, 2020, p. 13418; Lolli et al., 2020; Mele & Magazzino, 2020). While the role of particulate matter is undebated, there is lesser agreement on whether its impact stems from weakening biological barriers to infection (i.e. increasing host vulnerability) or because it acts as a vector for SARS-CoV-2 (Barakat et al., 2020). This distinction is relevant because particulate matter acting as a vector implicates poor environmental quality in having a *direct* role in COVID-19 transmission.

Stresses impact system capacity to respond to shocks. The persistence of many pathogens or vectors in soil, water, and pollutants suggests the need to maintain environmental quality at multiple scales. Integrated Pest Management—a WHO effort to contain vectors and vehicles of pathogen transmission—illustrates the multi-sectoral, multi-scalar activities undertaken: besides direct measures like routine spraying of various -cides and provision of bednets, they work with agriculturalists to conserve the natural enemies or competitors of vectors and maintain food hygiene, and with water, sanitation, and hygiene (WASH) experts to reduce fecal–oral flow of diarrheal pathogens (World Health Organization, 2012).

3.4. Redundancy: the need for response diversity, from supply chains to data management

A major challenge during this pandemic has been healthcare product shortage, even in many high-income nations. In the U.S., healthcare products have “distinct supply chains”, resulting in multiple challenges: suppliers are limited (for Personal Protective Equipment or PPE, commodities like swabs), imports are high and majority shortages occur due to facility quality concerns or capacity issues (pharmaceuticals); stockpiles are low (pharmaceuticals, PPE); lack of component interchangeability or standardized interfaces makes ramping up production difficult (devices) (Dill & Ahn, 2014; Mirchandani, 2020). Commodity chains have been global for decades, focusing on low cost, “just-in-time” inventory, and specialized divisions of labor, making them dependent on few, specific producer countries, and thus prone to severe shortfalls following export restrictions in response to the global spread of COVID-19 (Anukoonwattaka & Mikic, 2020, pp. 1–23; Gereffi, 2020). Not planning redundancies in supply chains resulted in trading off of robustness and resilience for efficiency (Bryce et al., 2020; Golan et al., 2020).

Some infrastructure systems are developing these redundancies in physical or IT assets, and organizational processes—be it a regional electric transmission operator adding an extra control room (Clark-Ginsberg et al., 2020), building distributed water management infrastructures (Allison et al., 2018; Guo et al., 2014; Leigh & Lee, 2019), physical infrastructure and institutional redundancies for earthquake surveillance and tsunami monitoring (Kawaguchi, Kaneda, Baba, & Takahashi, 2012; Ranghieri & Ishiwatari, 2014), and so on. Some enterprises have also built redundant capacity, like Boston Scientific's redundant production lines for crucial products, FedEx's “shadow flights”, or Helix's reliance on its suppliers' capacities to manufacture its products (Sheffi, 2007). Redundancy also seems characteristic of some nations' approach to data gathering for COVID-19: in India, data is being collected and shared by both government and crowdsourcing efforts, and COVID-19 hotspots are being monitored using various sources, including CCTV Surveillance of public places, GPS tracking of healthcare workers and those in home quarantine, GIS mapping of positive cases and spatiotemporal

¹¹ Roundworms in soil cause infections in children; the *Clostridium* bacteria, that causes tetanus and botulism, survives for years within soil; *Legionella pneumophila*, that causes Legionnaires' disease, occurs naturally in freshwater and thrives in engineered aquatic reservoirs; parasites causing cryptosporidiosis and giardiasis flourish in varied aquatic environments; TB is often spread by airborne transmission.

¹² Vectors & vehicles transmit pathogens from a reservoir or infected host to a susceptible host. Vectors include biological ones (crucial for pathogen development/multiplication) like mosquitos, or mechanical ones, like flies. Vehicles are inanimate objects like food, water, fomites, surgical instruments, used needles.

flow maps of route movements, generation of heat maps and buffer zones.¹³ Even as shortages and hoarding behavior laid bare the problems resulting from lack of redundancies in food supply chains in the UK and US, online farmers markets, community-supported agriculture systems (CSAs), and individual and community gardening were being heralded as important to enhancing redundancies in food systems (Garnett et al., 2020; Worstell, 2020). And there has been a range of innovative examples of repurposing urban infrastructures during the pandemic,¹⁴ building on an emerging trend of urban adaptive reuse (Burnham, 2018).

Systems optimized for efficient production of specific products and services under a narrow set of conditions lack the functional redundancies required to support this production when those conditions (inevitably) change (Walker & Salt, 2006). Be it functional redundancies from genetic to ecosystem-scale, or in engineered constructs and governance systems, the question isn't whether redundancy is critical or not, but how much redundancy is optimal (Low et al., 2003).

3.5. Social adaptive capacity: the need to cultivate social capital, cohesion, and adaptive governance

U.S. civil defense planning used to involve volunteer mobilization to gather home and medical supplies in decentralized emergency shelters, but as disasters grew to require expert responses, disaster response became more centralized and seems to have left people less prepared to respond to a crisis, as reflected in the panic buying behavior or the reluctance of large businesses to focus on manufacturing critically needed supplies (Hess & Bitterman, 2020). Some organizations, groups, businesses quickly, innovatively made useful behavioral switches, be it the breweries effectively transitioning to sanitizer manufacturing (Thomson & Bullied, 2020), or mutual aid groups providing essential services (Mao et al., 2020; Springer, 2020).

Such actions are part of a panoply of traits essential to building adaptive capacity, to respond to the instability wrought by shocks. Originally stemming from theoretical ecology, adaptive capacity encompasses both ecological capacities like biodiversity and ecosystem heterogeneity to buffer environmental change, and social-institutional capacities to improve human well-being when the environment changes nevertheless (Adger, 2003; Armitage, 2005; Gallopín, 2006; Gunderson, 2000; Walker & Salt, 2006, 2012). The state of Kerala in India—lauded worldwide for plateauing cases, slowing infection peak, and lowering mortality rate—demonstrated several traits indicative of social adaptive capacity (SAC) in its handling of the COVID-19 pandemic. One trait is adaptive governance, that—among other things—requires multi-level organization, legislations and governmental policies enabling self-organization and adaptive co-management, and key persons providing trust, leadership, vision and meaning in the face of crisis situations (Folke et al., 2005). Kerala's Health Minister prominently shepherded its success (Chandrashekhar, 2020; Spinney, 2020), relying on the strength of its local institutions—be it the expanded healthcare systems, the panoply of health workers, officials and volunteers that descended to conduct aggressive contact tracing in the first and second waves of infection, or the participatory governance organizations that nurtured the urban development and healthcare programs that delivered affordable, accessible healthcare during the pandemic (Chathukulam & Tharamangalam, 2021; C. M.; Kurian, 2020). These successes are linked to the state's success in truly operationalizing the principles of decentralization enshrined in the Indian constitution since 1993: in delivering control to local organizations, in giving them a third of the state healthcare budget, and in mandating representative committees to approve and audit budgets, and design innovative programs (Chathukulam & Tharamangalam, 2021; Elamon et al., 2004; P.; Heller et al., 2007; Williams et al., 2011). A second trait crucial to building SAC is social capital, the informal networked bonding, bridging, and linking relationships built on norms of trust and reciprocity that help collectives and individuals build capacity (Adger, 2003; Pelling et al., 2005). A range of attributes contribute to building social capital, like a strong ethnic identity, education, and information sharing behavior (Barnes-Mauthe et al., 2014), organizations that create bridging relationships (Rathwell & Peterson, 2012), trust and cooperation that can be culturally transmitted (Carpenter et al., 2004). These are hallmarks of Kerala's social capital: residents and Non-Resident Keralites unite not around caste or religion but their identity as Keralites, the state heavily invested in education and health, and civic organizations have proliferated under Kerala's political legacy of social mobilization and struggles against class difference (Chathukulam & Tharamangalam, 2021). Daily media briefings by the state government created a reliable source of information for all residents, and became an important tool for the state's contact tracing efforts for its second wave of infections by a family of super spreaders (C. M. Kurian, 2020; O. C. Kurian, 2020; Varma, 2020). This relationship with their polity has helped nurture a third trait of SAC—social cohesion—that relies on accumulated social capital (Dayton-Johnson, 2003) to engage *all* members of a community to assist, and has been found critical to disaster risk resilience worldwide (Fabinyi et al., 2014; Ludin et al., 2019; Patel & Gleason, 2018; Townshend et al., 2015). Not only did several civic organizations mobilize in response to this and recent disasters in Kerala (floods, Nipah virus outbreaks), but the state relied on a stream of community volunteers to help with a range of programs: phone-based monitoring of those in home quarantine, home delivery of supplies to support those under quarantine, ~1500 community kitchens to disburse food to midday meal program recipients (despite school shutdowns) and migrant camps, counselling call centers, and organizing geo-surveillance and geofencing (Arnimesh, 2020; Faleiro, 2020; C. M.; Kurian, 2020; O. C.; Kurian, 2020; Varma, 2020). That some of the critiques to Kerala's handling of the third wave of infections—transferring contact tracing and quarantine enforcement to the police, confusion over Central government repatriation policies, and transferring surveillance data management to a U.S. consultancy—are linked to a reversal of the policies responsible for the achievements of the “Kerala model”, perhaps hints at the need for social adaptive capacity in disaster response.

Adaptive capacity is the ability of systems, institutions, individuals to respond to the instability wrought by shocks; in social-ecological systems, adaptive capacity includes environmental contingencies, and social capacities to improve human well-being

¹³ See more at: <https://www.hindustantimes.com/india-news/how-centre-s-smart-cities-command-centres-are-monitoring-covid-19-hotspots/story-HWui8G3q5mmuMHldKuvFK.html>.

¹⁴ For reference, see these anthologies by Urban Land Institute, *Reprogramming The City* initiative, Stantec.

when the environment changes nevertheless. As laid out using the case of the “Kerala model”, human capital metrics like education and health, bonding relationships between groups with shared interests, and bridging relationships across groups with different interests contribute to building social capital. These state and non-state actors can conglomerate into social networks when supported by trust and clear communication, reciprocal and repetitive interactions. This, coupled with a cohesive identity, can help mobilize communities for effective responses to shocks.

4. Planning foci: reduce SHOCKS, stresses, vulnerability, and enhance redundancy, social adaptive capacity

This paper presents a first attempt to consolidate the unprecedented swath of causes and impacts of the COVID-19 pandemic to identify priority areas for planning. Given that goal, I applied the conceptual framework of resilience for systems study to research on disease emergence, transmission, and outbreaks. Framing urban settlements as systems, I examined the sources of shocks, stresses, vulnerability, redundancy, and adaptive capacity for this system. This revealed five priority areas:

1. Reduce wildlife urban interfaces (WUIs), improve food systems planning to reduce zoonotic disease emergence and interspecific disease transmission.

Urban expansion encroaches on wildlife habitat, creating WUIs. Human activities in these ‘buffer zones’ create stress for wild animals, facilitating viral shedding. Reduced biodiversity depletes the possibility of alternate hosts for disease transmission. These provide opportunities for disease emergence and pathogen transmission to humans. Planners must work with ecologists to better envision urbanization patterns that do not create WUIs, and regulate activities in the buffer. Animal rearing is particularly risky since domesticated animals can act as intermediate hosts for the virus to evolve until a mutant capable of infecting humans manifests.

2. Universal access to critical infrastructures reduces the need for contact rate suppression in the disease transmission stage.

Disease transmission decreases if the number of people susceptible to the disease decrease. Many people lacked access to two basic deterrents to the spread of COVID-19—water and shelter. In the absence of reduced system vulnerability (i.e. less number of susceptible people) through pointed interventions for equitable housing, infrastructure and healthcare access, curbing disease transmission requires contact rate suppression, which severely challenges economic activity, and is thus unsustainable in the long run. Equity is thus not just critical to social, economic, or environmental justice, but human health itself.

3. Centralize environmental quality improvement via better site design and regional planning, to reduce stresses that exacerbate the impact of shocks.

Polluted environments harbor pathogens, or the vectors and vehicles that transmit pathogens to human hosts. Better urban design for human health thus cannot be extricated from better environmental quality. Here again, disproportionately subjecting a certain strata of society to environmental pollution will not only create a cycle of environmental injustice, but serve to sustain the disease in the population.

4. Facilitate response diversity by bringing redundancy into operations, not optimization for specific products and services under a narrow set of conditions.

Economic and public service institutions promote efficiency at the cost of redundancy. This grimly manifested as critical shortages in household supplies, certain foods, and worse, PPE and masks for frontline healthcare workers. Management and engineering systems research offers several examples of supply chain redundancies that should be researched further in the context of local and regional planning for—among other things—food systems.

5. Prioritize participatory governance structures that provide agency, facilitates social cohesion and network formation, i.e. build social capital.

Despite reducing shocks (zoonotic disease emergence), vulnerability (threshold density of hosts susceptible to disease), stresses (environmental reservoirs harboring pathogens), and enhancing redundancies (buffering critical supply chains), we will invariably face disturbances that will jolt our system out of its stable state. At that point, relying on our social adaptive capacity to respond to the shock will be critical. As explained using the case of the successes of the “Kerala model” in handling the COVID-19 pandemic, adaptive capacity is built by investing in human capital, cultivating formal and informal networked relationships built on norms of trust and reciprocity (social capital), and institutionalizing multi-level governance, which *over time* can mobilize whole communities to respond in disaster scenarios (social cohesion).

5. Complex systems and resilience theory in public health and planning

Fifteen years ago, Jason Corburn discussed how the field of public health had gradually become more distant from the field of urban planning: on the one hand, public health became focused on the micro, molecular-level pathogenesis, rather than the unequal

distribution of disease in society; and on the other hand, urban planning went macro—shifting focus onto environmental health. But the macro and micro are intertwined: our biology reflects the “physical, social, economic, and psychosocial environments in which we live” (Corburn, 2004). Neighborhood-scale inequities in access to social resources are biophysically “embodied” at household and individual scales, and not only expressed as health inequalities across populations but creates a “social disruption cycle”¹⁵ that reinforces these disparities (Corburn, 2005). The focus on “one disease, one risk factor, one hazardous exposure, one population group, or one suspected ‘cause’ of poor health” (Corburn, 2015) is unable to untangle the complexities of the multi-factorial pathways through which planning impacts urban health. This paper offers a further integration of environmental and human health factors given the added spatiotemporal complexity of zoonotic disease emergence, transmission, and outbreak. The previous section identified several planning activities that do not necessarily fall with the ambit of public health planning, yet have clear implications for it: urbanization/land use patterns and the creation of WUIs, food systems planning and lack of regulation of animal rearing in WUIs, infrastructure access and vulnerability to disease, environmental quality and exposure to pathogens.

A review of the impact of urbanization on zoonoses in the Global South (Ahmed et al., 2019) noted that the dominance of techno-scientific concepts over politico-economic factors in delineating the causal factors for zoonotic disease emergence and transmission results in ill-conceived interventions aimed at isolating the urban poor or decimating informal spaces of interaction. The objective application of concepts from complex systems study and resilience thinking helped link some of these techno-scientific concepts to politico-economic factors. First, by explaining that contact rate suppression is not the only means to reduce disease transmission; that a system continues to be vulnerable to the disease if a threshold density of susceptible hosts is maintained in the population, which can be linked to inequity in access to basic infrastructure or inequitable exposure to environmental contamination. And second, in explaining that adaptive capacity—even in a framework emerging from theoretical ecology—is not merely ecological, but social. The research presented highlights the dire consequences of inequity for ‘pandemic planning’: inadequate infrastructure—like healthcare, water, nutrition, housing—can create vulnerable hosts (allowing the pathogen to infect), designations of “informality” produce overcrowding (which increases host density, and hence, disease transmission), and spatial segregation of different socioeconomic groups disproportionately exposes a part of the population to environmental toxins and pollutants (which can enhance their exposure to disease vectors and pathogens). All these factors play a key role in maintaining a disease in a population by sustaining a threshold density of susceptible hosts, which can give the pathogen time to evolve into a more virulent strain¹⁶ capable of infecting even previously non/less susceptible people.

There are critical North/South differences with respect to both the unprecedented nature of the challenges that the rapidly urbanizing Global South faces, and their position on the trajectory of institutional development, that could have otherwise given them the ‘tools’ necessary to tackle these unprecedented challenges. This review highlighted several concerns applicable to the Global South: the peri-urbanization of industrial agriculture, the higher incidence of interspecific pathogen transmission in spaces of livestock rearing, and that specific subsets of urban populations have a higher disease burden due to higher exposure to pathogens and reservoirs, lower access to healthcare, little to no access to shelter or basic infrastructure, and higher comorbidities/susceptibilities like malnutrition-induced immunosuppression. But the analysis does not uncover factors specific to the developmental trajectory of Global South cities: (1) changing dietary preferences in the Global South that intensified animal rearing and the complex commodity ‘webs’ for sale of animal products, (2) how back-and-forth human and animal movement between rural and urban areas has resulted in migrants acting as carrier, host and transporter/facilitator of pathogens, and (3) gender roles differences in zoonotic disease exposure and tackling (Ahmed et al., 2019).

The United Nations has recorded an 80-fold increase in pandemics over the 20th century. Framing human settlements as systems and a novel disease as a shock to the system helped identify sources of stress, vulnerability, redundancy, and adaptive capacity, but this review is only a *first* step in the application of this framework. Several key studies over the last two decades have established a link between climate change and infectious diseases, be it through increased vector populations due to wildly fluctuating weather patterns or shifting climate, or increased host vulnerability to infection stemming from crop failures and famine, or enhanced transmission due to scarce and contaminated water sources, etcetera (Bartlow et al., 2019; Haines et al., 2006; Hunter, 2003; Metcalf et al., 2017; Semenza et al., 2012; Semenza & Menne, 2009). This adds yet another layer of spatiotemporal complexity, requiring a more thorough conceptualization of a *system* and its *boundary* and *variables*, its *stable states* and scenarios of *regime change*, and the factors impacting the system at higher spatiotemporal scales (*panarchy*) (Allen et al., 2014; Holling & Gunderson, 2002; Walker & Salt, 2006), but that is beyond the scope of this paper. What this review reveals however, is a clear value to undertaking such an exercise, since the complex systems conceptual framework lends itself to multi-scalar, cross-sectoral analysis with ease.

Declaration of competing interest

The author declares that there is no known competing financial interests or personal relationships that could have appeared to

¹⁵ Taking the example of asthma, Corburn explained that geographic morbidity patterns “cannot be explained by socioeconomic factors alone”. The lack of “neighborhood social capital” limits a family’s ability to obtain information, access healthcare, avoid environmental triggers, and organize to demand improvements and services. This contributes to deterioration in infrastructure and further disinvestment at household and higher scales, in turn triggering not only the causal factors of the disease but also the stresses that exacerbate an individual’s capability to deal with the disease. This perpetuates the “social disruption cycle” wherein the illness demands more time off and reduced to no income leading to further stress and reduced resources to treat the disease.

¹⁶ For reference, see these recent updates by Johns Hopkins and the Association of American Medical Colleges.

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