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Advancing equitable health and well-being across urban–rural sustainable infrastructure systems

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Infrastructure systems have direct implications for how health and well-being evolve across urban–rural systems. Scientists, practitioners, and policy-makers use domain-specific methods and tools to characterize sectors of infrastructure, but these approaches do not capture the cascading effects across interrelated infrastructure and governance domains. We argue that the development and management of sustainable urban infrastructure must focus on interactions across urban and rural places to advance equitable health and well-being. We call for a research agenda that focuses on urban–rural infrastructure systems, addressing trade-offs and synergies, decision-making, institutional arrangements, and effective co-production of knowledge across the diverse places connected by infrastructure.

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INTRODUCTION

The development and management of sustainable urban infrastructure systems constitute one of the greatest political, scientific, and technological challenges of this century¹. Infrastructure systems include hard infrastructure that interacts with natural infrastructure to deliver energy, water, transport, recreation, and telecommunications², as well as soft infrastructure that includes the institutional arrangements that enable the provision of services³. Urban infrastructure is sometimes further broken down into gray (built systems), green (ecological systems), and blue (hydrological systems) components⁴. Urban infrastructure develops through formal and informal activities, practices, and processes⁵ and may proceed through large-scale metropolitan planning initiatives or incremental expansions, often unplanned and opportunistic⁶. There are distinctly different patterns and intensities of infrastructural development in cities in the Global North and Global South, with considerable intra-regional variation⁷. Infrastructure systems around the world determine the types of services and goods and their flows to, from and within cities and shape health burdens and inequities across urban–rural systems. Infrastructure systems must be understood as integral to urban–rural connectivity, and thus have diverse constituencies across urban–rural spectrums. Because infrastructure systems span and connect both proximal and telecoupled urban, suburban, periurban, exurban, and rural places, they also must be managed at different levels of organization^{8,9}.

Infrastructure systems have substantial and unequal impacts on different populations through mechanisms such as displacement, exposure to environmental risk, and access to essential services like water or health care, and as a result are central to the question of social and environmental equity. The spatial context, including the built and natural environments, in which people live

directly impacts the health status of individuals and creates health disparities across regions. Urban infrastructure can have negative and positive impacts on health through processes like physical exposure to pollutants, as well as access to green space and their associated psychological, affective benefits, positive, and pro-social health behaviors. Because large-scale infrastructure, such as highways or waterways, link proximate and distal urban and rural places, infrastructure can serve intentionally or unintentionally to transfer risks without necessarily transferring (or building) capacity to address risks across these systems¹⁰. Subsequently, infrastructure systems have direct implications for how health and well-being evolve over time within cities and across urban–rural systems¹¹.

Decisions on how to build infrastructure are made on the basis of technical and engineering considerations. While these decisions involve mostly policymakers and professionals, they in turn reflect existing economic and political structures and interests and can shape or exacerbate social and racial inequities and historical biases, which can contribute to health disparities^{12–15}. By political, we are referring to “the contestations, collaborations, and negotiations through which collectives govern their everyday affairs”¹⁶ (p 527). Such a blend of political and technical considerations influences who benefits from or bears the costs of infrastructural development, who participates in decision-making, and how stakeholder participation affects the short- and long-term trade-offs of infrastructure.

We argue that the development and management of sustainable urban infrastructure must focus on interactions across urban–rural systems to ensure that the benefits and burdens of different types of infrastructure are equitably distributed, including across distant constituencies and environments. For this purpose, it is necessary to understand how decisions about

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infrastructure systems are made at different levels, who participates and in what position, as well as the extent to which normative decisions consider trade-offs and disparities in health and well-being across as well as within urban and rural places. We call for a transdisciplinary research agenda that addresses the following four points, with an explicit focus on urban-rural systems: (1) How trade-offs and synergies between services that are provided by infrastructure impact health and well-being, (2) How decisions are made about the short- and long-term trade-offs created by infrastructure, (3) How different institutional arrangements that govern the appropriation and provisioning of infrastructure systems interact, either aligning or conflicting across jurisdictions, and (4) How governance, including planning, development, and management, can facilitate or constrain effective co-production of knowledge for sustainable infrastructure across diverse places and communities.

TRADE-OFFS AND SYNERGIES ACROSS URBAN-RURAL SYSTEMS

Infrastructure critically impacts health and well-being and how equitably these benefits are distributed across urban-rural systems. Transportation infrastructure that connects urban and rural areas can enhance access to health services across urban-rural and socioeconomic divides^{17,18} and acts to reduce urban-rural and socioeconomic health disparities. Community-organized infrastructure can effectively provide public services, such as water, across diverse urban and rural communities that are disconnected from government-controlled systems^{19,20}. Despite the potential of infrastructure systems to promote health and well-being and reduce health disparities in certain communities, the benefits of infrastructure are inequitably distributed. Along the continuum of urban and rural places, cities are prioritized over rural areas for health care²¹, water provision²², and electrification via hydropower²³. In certain cities in the Global South, where legacies of colonial-era exclusionary zoning, poor governance, limited public finance, and rapid and unplanned urban growth create infrastructural disparities, informal settlements are denied formal infrastructure and are forced to develop informal infrastructure systems²⁴. Environmental justice studies document how poor communities, communities of color, and rural and indigenous populations experience the brunt of environmental inequities and are consistently excluded from opportunities in both the Global South and North^{10,25–27}. Economically and politically marginal communities are more vulnerable to infrastructure failures because their influence in governance and decision-making is limited²⁸.

Given the intricate trade-offs between services provided by different types of infrastructure and the critical role of infrastructure in reinforcing and ameliorating social inequities, an integrated, dynamic systems perspective that accounts for trade-offs across sectors and communities in urban-rural systems is needed^{29,30}. We argue that an integrative understanding is essential to account for the social, economic, environmental, and health outcomes deriving from complex and often inconspicuous interactions between different types of infrastructure. This approach is relevant in urban regions where there are dense networks of infrastructure systems that serve urban and rural areas and where urban growth is expanding over sparsely populated places and ecosystems, particularly in the Global South. These systems are particularly vulnerable to extreme weather events and climate change and have considerable implications for health and well-being³¹. For example, wildfires along the urban-rural interface reveal these interconnections and impacts on health and well-being and potentially devastating impacts on local economies. Downed power lines due to poor maintenance of energy infrastructure along with the construction of housing infrastructure in fire-prone wildlands can constitute ignition

sources that increase the incidence of climate-induced wildfires³². Wildfires increase respiratory illnesses caused by air pollution, disrupt ecosystem services, damage property, and displace residents from fire-damaged housing infrastructure. Cascading effects of wildfires may include impacts on food and water, as well as secondary landslides and additional flood hazards.

Engineers and scientists use domain-specific methods and tools to characterize specific sectors of urban infrastructure (transportation, public transit, buildings, stormwater control, energy supply, water, and sewer, and public works). But these methods neither easily factor in the complexity of cascading effects across interrelated infrastructure and governance domains^{31,33}, nor do they explicitly quantify the impacts of discrete infrastructure decisions on different demographic groups. Although there are numerous examples of urban infrastructure projects that embody sustainability principles (e.g., LEED-certified buildings, green stormwater management, bike/pedestrian pathways), there is a gap in knowledge and methods for assessing the sustainability of infrastructure systems across different sectors^{34,35} and how these systems impact health and well-being across interconnected urban and rural places.

Understanding infrastructure as interconnected and cross-sectoral systems reveals how the provision of services to urban places has implications for health and well-being across urban-rural systems. It also opens space for consideration of the various equity dimensions of infrastructure decision-making processes, such as recognition, procedural, and distributive equity³⁶. Such a conceptualization can highlight trade-offs and synergies among ecological, social, economic, technical, and health goals across urban and rural places³. The concept of urban ecological infrastructure is one way of conceiving infrastructure as integrated systems by explicitly accounting for trade-offs and synergies between blue, gray, and green infrastructure in the provision of ecological services^{29,37}. For example, although urban trees can shade buildings to reduce energy use and provide thermal comfort, the same trees can also damage overhead utilities and buildings during storm events, meaning that gray and green infrastructure can sometimes be in conflict with each other³⁸. Intentional urban design can facilitate sustainable urban development to improve the synergies between these forms of infrastructure. Understanding how to advance urban design that enhances synergies across diverse geographic places requires new approaches and methods that center decision-making to make it more robust and equitable.

DECISIONS ABOUT SHORT- AND LONG-TERM TRADE-OFFS

Decisions regarding the design and management of infrastructure along and across urban-rural gradients are particularly critical to sustainability planning and directly determine the ability of land- and waterscapes to provide a wide range of benefits to urban and rural inhabitants in both the short- and long-term. From an engineering perspective, infrastructure decision-making and management is a multi-criteria, multi-objective problem³⁹. Interdependencies among infrastructure systems are touchpoints of vulnerability, impacting system performance and resilience. These complex interdependencies require the articulation of multi-dimensional perspectives on sustainable urban infrastructure that include conceptualizations of the economy, society, and the environment. However, the lack of integration and methodological approaches across engineering, social and natural sciences, and public participation at various hierarchical levels constitute persisting challenges⁴⁰. The lack of integration in the planning process results, for instance, in highways sited without consideration of their impacts on natural or social systems and automobile-oriented patterns of development causing pollution, and associated losses in health and economic productivity⁴¹.

Infrastructure policy-making is embedded within broader political and economic structures, and therefore the decision-making process is rarely motivated by technical maximizations of equity and social justice. Instead, decisions about infrastructure systems are the consequence of various interactions between groups and individuals with different and often conflicting vested interests and varying degrees of influence^{11,42}. Rapid urbanization can challenge municipal authorities' ability to expand infrastructure systems that deliver basic services, such as drinking water or sewage systems, to a growing population across a larger metropolitan area⁴³. Informal settlements often develop without adequate infrastructure or access to formal decision-making about infrastructure and typically cannot meaningfully influence formal planning processes. The siloed nature of decision-making within and among communities means policy-makers are not addressing policy problems in an integrated manner. Policy decisions about urban sustainable buildings, for example, are focused on managing and designing programs for environmental conservation and energy efficiency. These policies are rarely acknowledged in decision-making in water or transportation departments; much less include stakeholders such as engineers, builders, developers, and owners of these buildings⁴⁴.

There are numerous forums for public participation in regulatory decision-making, yet not all stakeholders have equal access or influence across forums, and not all forms of participation result in the empowerment of stakeholders⁴⁵. Lack of representation may be particularly significant for rural populations that are affected by urban decision-making but do not have the political standing to participate in urban regulatory processes. In studies examining participatory processes for hydraulic fracturing regulation in the US, researchers have found that forums, such as public comments and public meetings, have more diverse stakeholder participation compared to government hearings, where participation is by invitation⁴⁶. Importantly, the research has also found that wider participation does not necessarily translate into more equitable outcomes as elite stakeholders, such as industry representatives and lobbying groups, can often craft public statements that have more influence on decision-making processes.

The social, ecological, and technological systems (SETS) framework may provide one way to make decision-making processes more explicit and equitable in infrastructure development and management^{4,47,48}. SETS includes the social system, defined as people's roles, activities, values, and decisions, alongside the ecological system (e.g., climate, as well as ecosystems and their functions), and technological systems (e.g., physical and cyber-infrastructure and knowledge systems)⁴⁸. Building upon Ostrom's Institutional Analysis and Development framework (IAD), Anderies et al. propose a Coupled Infrastructure Systems approach in which interactions among different types of infrastructure—hard, human-made, natural, human and social, and soft—dynamically interact within action arenas where participants with different positions, power, and worldviews make decisions that produce outcomes over time³. This approach may allow for a more intentional examination of trade-offs across sectors and diverse geographic places than traditional methods⁴⁹ and can address issues of social equity⁴⁸.

INSTITUTIONAL ARRANGEMENTS ACROSS URBAN AND RURAL PLACES

The role of infrastructure in urban-rural interactions has been conceptualized from multiple perspectives. It can be according to types of interdependencies, networks, and intensities of interactions^{50,51}, or in terms of fluxes of resources, pollutants, and other materials within and across city boundaries⁵², including those resulting from regional and global telecoupling^{8,53}. Operationalizing these concepts in a policy framework is a challenge.

Governance for sustainability at the regional scale is fragmented across both jurisdictional lines and sectoral lines⁵⁴. The jurisdictional fragmentation of regions leads to communities competing for investments and prevents comprehensive planning that can promote an equitable distribution of services and amenities across the urban-rural gradient^{54,55}. The sectoral fragmentation of planning means that land use, housing, schools, transportation, energy, and water (both drinking and stormwater) are not typically planned or coordinated at the regional level. There are also different forms of arrangements among formal and informal actors and decision-making processes, where techno-managerial systems of government administration interact with urban residents living in conditions of informality to produce different qualities of infrastructure and service provision⁵⁶. The boundaries between urban and rural areas are often where there are institutional vacuums—poorly defined mandates and rules between metropolitan boundaries and county boundaries. It is at these ambiguous boundaries that injustices are often exacerbated^{54,57,58}. From an ecological planning perspective, it is difficult to plan across watersheds, airsheds, foodsheds, and ecological units, and to coordinate critical infrastructure investments when multiple jurisdictions have the authority and where funding is local, and metropolitan planning is primarily advisory.

Marginalized populations in both rural and urban areas across the world are exposed disproportionately to environmental burdens, including air and water pollution, flooding, and resource degradation^{59–61}. Yet, attention to the equity implications of infrastructure across the urban-rural gradient has been limited at best. Representation of the interests of specific communities is often inadequate. Affected constituencies are typically not neatly divided into administrative jurisdictions that can advocate for their interests. Instead, they are identified by the distributional implications of infrastructure, which often correlate with socioeconomic status^{13,62}. Environmental justice scholars have highlighted the importance of extending environmental justice frameworks to the urban-rural interface to better account for the role it plays in the distribution of benefits, such as water, energy, or aesthetics, and burdens, such as pollution and displacement^{10,63}.

KNOWLEDGE CO-PRODUCTION ACROSS SECTORS AND CONSTITUENCIES

Recent work on sustainable policies and resilience planning for infrastructure systems has begun to address the concept of inclusive arrangements to integrate the design, construction, and maintenance stages of an infrastructure project's lifecycle⁶⁴. An inclusive decision-making mechanism for sustainable infrastructure systems would not only focus on the reduction of greenhouse gas emissions and non-renewable resource use, but also on the production of socially equitable outcomes⁶⁵. Sustainable infrastructure systems and knowledge co-production are possible through multi-stakeholder engagement, public participation, cross-sectoral data sharing and analysis, hybrid organization, and communities of practice, enabled by communication technologies and computational efficiency⁶⁶. There is a robust body of research on knowledge co-production in the context of sustainability⁶⁷, yet there is a need to better understand how multiple and diverse communities connected by infrastructure in urban-rural systems meet these challenges in different yet potentially complementary ways.

Co-producing knowledge with diverse groups in different geographic locations can be difficult due to power asymmetries and different or competing goals in urban and rural places. Reed describes the challenges that participatory processes face and highlights the importance of institutionalizing stakeholder participation based on a philosophy of empowerment, equity, trust, and learning⁶⁸. Synergistic outcomes can emerge by engaging diverse stakeholders, and when government institutions provide

ongoing resources to organize and sustain such collaborations, though there may not be such regional institutions that adequately represent all constituencies. The co-production of knowledge and infrastructure occurs in different geographic locations and formal and informal urban contexts, such as sanitation infrastructure in informal settlements in African cities⁶⁹ or tree planting and monitoring campaigns in North American cities⁶⁶. These contexts suggest that such an approach provides a way towards inclusive governance. While these studies serve as promising responses to recent calls for improved approaches to create policy-relevant knowledge for sustainable transitions that include participation from a broader group of stakeholders⁷⁰, there is little research that directly addresses knowledge co-production across urban-rural systems⁹. Further, there is a need for boundary institutions that capture the diversity of constituencies across urban-rural continuums.

Efforts in knowledge co-production in much of sustainability science have missed potential power differentials and political conflicts among researchers and other groups^{67,71}. These power differentials may be exacerbated across urban-rural systems with divergent and competing interests, yet these dynamics have implications for who is an appropriate partner and how the partnership should work to produce ethical, relevant, and translational science. Brandt and colleagues identify a significant challenge in that while practitioner knowledge is often incorporated or exchanged with researchers, practitioner empowerment in decision-making is rare⁷². There needs to be explicit attention and analysis of knowledge systems in order for effective co-production to take place⁷³. Knowledge systems analysis evaluates people and the social practices that make knowledge⁷³. This approach reveals how different forms of knowledge can be systematically excluded from incorporation in planning and others are unquestioned, yet continue to guide policy and practice⁷⁴. Enabling a context for co-production requires upfront recognition that diverse populations with valuable and highly differentiated perspectives exist and that governance procedures often unintentionally (or deliberately) marginalize these important constituencies⁷⁵.

Facilitating knowledge co-production for sustainable urban infrastructure may need to grapple with the construct of the “urban” in infrastructure decision-making: the infrastructure that provides critical services to urban areas is intricately embedded in and connected to surrounding and distal, more rural areas. As such, rural constituencies are essential voices to recognize and include in the decision-making process and in sustainable urban systems research, as illustrated in regional natural resource management and co-managed conservation practices⁷⁶. It is critical that we understand highly differentiated marginalized communities in terms of their frameworks for experiencing, understanding, and evaluating infrastructure⁷⁵. This process may require addressing deeper historical distrust that prevents some populations from wanting to engage in planning, design, or governance processes⁷⁷. Engaging with broader theories of power and inequality that reveal how infrastructure decisions are embedded in and reinforce prevailing social and political processes can potentially open up governance processes to incorporate these issues and provide different avenues for promoting urban-rural knowledge co-production⁷⁸.

SUMMARY

Infrastructure shapes health and well-being across urban-rural systems. Therefore, decisions about infrastructure should consider how to equitably convey these benefits across the urban and rural places that infrastructure systems connect. This endeavor requires the identification of interdependencies among different types of infrastructure, a broader understanding of economic, social, environmental, and health implications of infrastructure decisions,

and how both burdens and benefits from such decisions are distributed across different populations. There is a clear need to develop a framework to consistently reveal the potential benefits and costs of infrastructure^{79,80}. In addition, the implementation of governance structures that transcend territorial and sectoral boundaries and that ensure the involvement of multiple stakeholders in knowledge production can help remove political and institutional barriers and enable the effective consideration of health and well-being in decisions aiming for the sustainability of urban infrastructure systems.

DATA AVAILABILITY

No datasets were generated or analyzed during the current study.

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AUTHOR CONTRIBUTIONS

H.P., V.H.G.V. and M.R.G. led the development of the manuscript; H.P., V.H.G.V., M.R.G., S.H., H.E., E.B., W.S., L.T., J.E.B., J.E.B., K.B., C.H., K.H., J.M., L.A.R., C.R., E.C.S. and R.D.V. contributed to the analytical framing of the paper; H.P., V.H.G.V., M.R.G., S.H., H.E. and E.B. drafted initial sections of the manuscript; W.S., L.T., J.E.B., J.E.B., K.B., C.H., K.H., J.M., L.A.R., C.R., E.C.S. and R.D.V. edited those sections and contributed additional text. H.P., V.H.G.V., M.R.G., S.H., H.E., E.B., W.S., L.T., J.E.B., J.E.B., K.B., C.H., K.H., J.M., L.A.R., C.R., E.C.S. and R.D.V. reviewed and approved the final manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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