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Multi-Sector Dynamics: Advancing Complex Adaptive Human-Earth Systems Science in a World of Interconnected Risks

**Key Points:**

- Cities are concentrators of complex, multi-sectoral interactions
- In order to address climate risks, people need transformative solutions tailored to their problems and at decision-relevant scales
- A richer understanding of human and natural interactions in urban environments can support our transition to a more climate secure future

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# Cities Are Concentrators of Complex, MultiSectoral Interactions Within the Human-Earth System

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**Abstract** Cities are concentrators of complex, multi-sectoral interactions. As keystones in the interconnected human-Earth system, cities have an outsized impact on the Earth system. We describe a multi-lens framework for organizing our understanding of the complexity of urban systems and scientific research on urban systems, which may be useful for natural system scientists exploring the ways their work can be made more actionable. We then describe four critical dimensions along which improvements are needed to advance the urban research that addresses urgent climate challenges: (a) solutions-oriented research, (b) equity-centered assessments which rely on fine-scale human and ecological data, (c) co-production of knowledge, and (d) better integration of human and natural systems occurring through theory, observation, and modeling.

**Plain Language Summary** Cities can be seen as concentrators of complex, multi-sectoral interactions: ripples of influence across different systems travel faster, through more systems, and have greater consequences within cities than in other contexts. We describe a multi-lens framework for organizing our understanding of the complexity of urban systems and of scientific research on urban systems. We then describe four important improvements to urban research so we can better address urgent climate challenges in cities and globally.

## 1. Introduction

Cities are concentrators of complex, multi-sectoral interactions. As keystones in the interconnected human-Earth system, activities in cities have an outsized impact on the Earth system. Cities' influence on global socio-economic and environmental processes also means that research about cities provides a critical opportunity to shape insights for solution-oriented action to address the climate crisis. Climate change is increasing the frequency and magnitude of urban exposure to climate-driven hazards, which has compounding effects on the stability of interconnected urban systems and sectors. Cities face challenges in transitioning to clean energy systems through the large-scale decarbonization of major energy use sectors, including buildings, transportation, and industry, which are interconnected and interact with the urban environment (Perera et al., 2023). Our opportunities to produce the scientific insights needed to address the paired challenges of urbanization and climate change are thus both urgent and time-limited (Cologna & Oreskes, 2022; Gadgil et al., 2022; Glavovic et al., 2022; Keith et al., 2023; Lee et al., 2023; Lobo et al., 2023).

We describe a framework of multiple lenses for organizing our understanding of the complexity of urban systems and scientific research on urban systems (Figure 1). Cities are vulnerable to accelerating and interacting stresses from climate change, population growth, resource scarcity, and land-use pressure as they simultaneously

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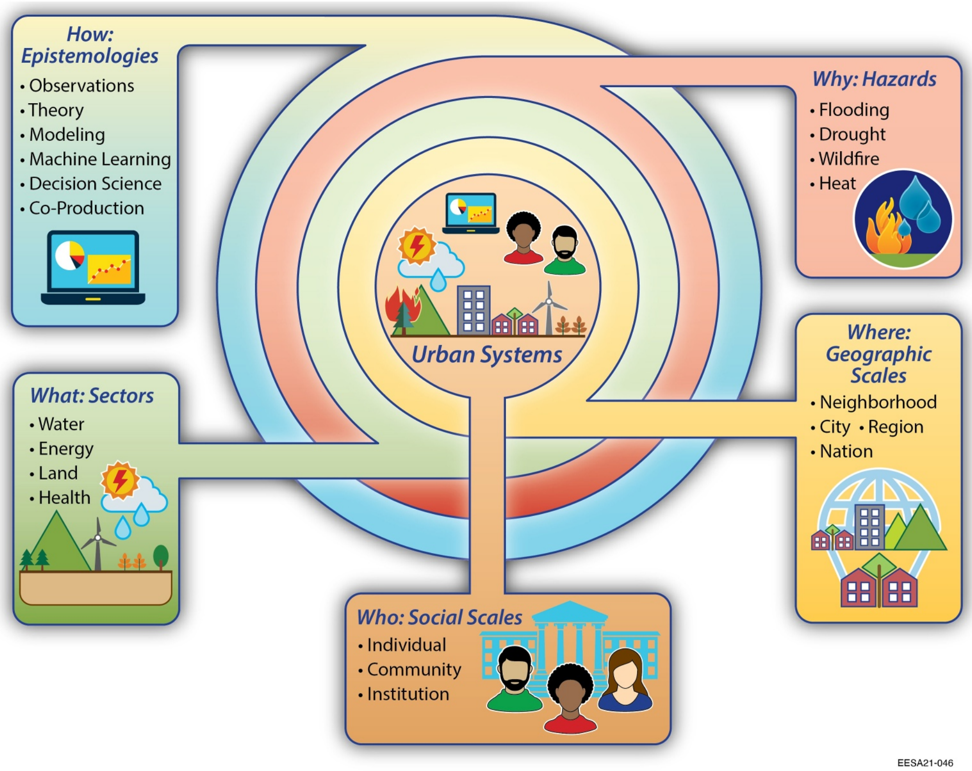


**Figure 1.** A conceptual diagram demonstrating multiple lenses that can be used for organizing the complexity of urban systems and scientific research within the human-Earth system. In the center, environmental, social, and built systems processes interact to produce outcomes of relevance to resilience, equity, and sustainable use of resources. Moving outward, lived experiences and decision-making take place on a continuum of social scales impacting the "Who" from individual to institutional. Key process interactions and heterogeneities "Where" multisectoral dynamics intersect differ across spatial scales from neighborhoods to nations. Sectors, the "What", connect people and resources across urban landscapes and act as behavioral aggregators from smaller to larger scales through infrastructure networks and management institutions. Urban systems are embedded within larger environmental systems and are vulnerable to changing hazards, which motivates "Why" questions regarding resilience and adaptation and provides a lens through which to understand differential outcomes and interactions across sectors and scales. The outer circle highlights "How" we create knowledge about urban systems. Scientific insight and data, which in turn feedback to inform decision-making and behavior across the social scales highlighted in the center. Each of these lenses provides a valuable perspective on urban systems, and each is incomplete on its own.

influence regional and global socio-economic and environmental systems (Grimm et al., 2008; Seto et al., 2012). The outcomes of actions that originate in cities are shaped by the interconnections between urban sectors, nested geographic scales of action and influence, climate and non-climate-related hazards, and our own mechanisms for observing and understanding the system. For example, cities consume a large share of global energy and water, and so urban activities play a significant role in overall production & distribution. Energy conservation innovations in urban environments are shaped by the systems and sectors that use and produce energy and are influenced by regional, national, and global patterns in energy production and cost (Kennedy, 2011; Perera & Hong, 2023; Ramaswami et al., 2016). This framework highlights the need for integrative, solutions-oriented, and human-centric research to address urgent urban climate response challenges.

Human processes — increasingly determined within urban environments — are significant drivers of environmental change and a key agent of solutions and uncertainty for the future of the Earth system. Framed another way, the outcomes of these human processes define our opportunity space to avoid the most catastrophic consequences of the climate crisis. However, to explore these intertwined uncertainties and opportunities, we need to improve fine-scaled and multi-sectoral representations of coupled human-natural system processes that move beyond simple conceptual coupling (Müller-Hansen et al., 2017). Causal understanding of coupled human-natural systems are strengthened by integrating empirical and modeling approaches, and by robustly incorporating human processes into analyses of natural systems (Schlüter et al., 2023). Uncertainties and opportunities that are driven by the coupling of urban and Earth System processes exist across geographic scopes and scales, motivating the need for diverse approaches, quantitative models, and research in this space.

As analyses of urban systems in an Earth systems context are developed, they need to support communities, scientists, and policymakers as they explore "what, who, where, why, and how" questions about the implications of particular courses of action and support identification of pathways that offer co-benefits across human, built infrastructure, and environmental systems (Hamstead et al., 2021). Cities offer an opportunity to make these advances and the incorporation of cities into Earth system analysis will improve our predictive capabilities and highlight opportunities for climate solutions.

To advance a human-Earth systems urban research agenda that addresses salient and relevant climate challenges, improvements in four key dimensions are needed: (a) solutions-oriented research, (b) equity-centered assessments that rely on fine-scale human and ecological data, (c) co-production of knowledge, and (d) better integration of human and natural systems through theory, observation, and modeling.

## 2. Solutions-Oriented Research

In order to address climate risks, people need transformative solutions tailored to their problems and at decision-relevant scales. Although the nature of solutions-oriented research is changing, most Earth System research has not been organized around usability of the ultimate science outcomes (cf. use-inspired research) (Coen, 2021; Morrison et al., 2022). That is, research in the context of urban climate responses must be human-centric — action and actor-oriented and center equity and justice from the perspective of both the research and governance processes and their potential outcomes. Human-centric, solutions-oriented research can take many forms and should encompass a broad range of potential interventions and theories of change, including institutional, technical, behavioral, and nature-based solutions. The critical organizing principle is that transformative research, if successful, will improve our ability to address root drivers of climate change and mitigate the consequences of the climate crisis (Morrison et al., 2022).

Within cities and across urban sectors, examples of solutions-oriented research are growing (Jagannathan, Emmanuel, et al., 2023). For example, the Grid Modernization Lab Consortium brings together leading experts, technologies, and resources to collaborate on the goal of modernizing the nation's grid (U.S. Department of Energy, 2014). The US Department of Energy's Urban Integrated Field Laboratories aim to provide the knowledge and information necessary to inform equitable climate and energy solutions that can strengthen community-scale resilience across urban landscapes (U.S. Department of Energy ESS, 2022). Basic science research, such as through the Urban Resilience to Extremes Sustainability Research Network, used knowledge co-production to learn how cities can develop urban social-ecological-technological systems that is resilient to future extreme weather events and benefits diverse urban populations equitably (Hamstead et al., 2021).

There are a range of critical literature which articulate the importance of more diverse epistemologies, ways of knowing, and cultural and geographic foci in developing and evaluating solutions-oriented research (Orlove et al., 2023). The "northern bias" in research is well documented across disciplines (Abimbola, 2019; Asase et al., 2022; North et al., 2020), but has particularly dramatic consequences in urban contexts because the vast majority of foreseeable urban growth will occur in the global South (Auerbach et al., 2018; Roy, 2005; Watson, 2016). Indigenous knowledge systems and ways of knowing have the capacity to lead toward fundamentally different understandings of climate action opportunities, but their inclusion in climate research has been uneven (David-Chavez & Gavin, 2018; Latulippe & Klenk, 2020; Smith & Sharp, 2012). Urban Governance systems have the capacity to reinforce or alleviate the systemic obstacles to sustainable urban development (Pieterse, 2019); solutions-oriented research must address insights from these diverse knowledges to achieve its most fundamental objective.

## 3. Fine-Scale Data

The recent explosion in digital trace data available about human behavior, mobility, and social processes is a transformative opportunity (Watts, 2012) for understanding fundamental characteristics of anthropogenic processes; for measuring and understanding inequality and its determinants; and for policymakers to understand what cities can do to mitigate and adapt to climate change on decision-relevant scales. For example, digital traces of social interactions and human movement patterns provide insight into behavioral patterns with complexity and richness that has not previously been possible (Alessandretti et al., 2020; Brelsford et al., 2022; Pappalardo et al., 2015; Schläpfer et al., 2021; Sparks et al., 2019). Fundamental patterns in human behavior like those described by (Alessandretti et al., 2020; Pappalardo et al., 2015; Schläpfer et al., 2021) and others can quantify human behavioral processes, providing an empirical mechanism for modeling or predicting sectoral interactions, and can thus help support empirical predictions of system behaviors. This can contribute systematic insight into cities and their function as concentrators of interactions across the sectors that connect earth system risks and hazards to their impacts on societies.

This high-resolution human information is complemented by recent advances in crowd-sourced observational data sets, such as backyard weather monitors, and high-resolution urban climate modeling enabled by increases in both computational power (Almgren et al., 2023) and detailed data sets that characterize the heterogeneity of urban environments for example, (Aslam & Rana, 2022). In both cases, we need investment in data verification, validation, and comparison. For human data, these investments are needed to infer representative real-world metrics from digital traces of anthropogenic processes. For climate data, these investments ensure that estimates, their moments, and their spatial heterogeneity are represented with sufficient fidelity. This can be supported by rich computational methods–that is, Bayesian data assimilation, anomaly detection, and statistical and machine learning. Machine learning models are a powerful strategy both for arriving at complex decisions with the help of massive and heterogeneous data sets and for generating forecasts of decision-relevant urban features. However, more efforts are still needed to make machine learning models trustworthy, tractable, and capable of adequately capturing realistic, mechanistic precursors of modeled phenomena. These high-resolution data, in addition to bringing about new opportunities for insight, also bring new concerns. Digital trace data also lacks context and social depth, and often excludes the most vulnerable (people who lives are not digitized). The comfort that natural scientists have with empirical data of this sort risks obscuring the validity of other forms of narrative, which remain closer to the actual lived experiences of communities and individuals (Simone & Rao, 2021). Furthermore, high resolution data create new concerns about data privacy, access, and ethical interactions with individuals and communities that is, (Anhalt-Depies et al., 2019; Seidl, 2022; Zipper et al., 2019). If the data management infrastructure is streamlined, scaled, and progress is made on the new methodological, contextual, and ethical challenges, we believe that there will be significant new opportunities for insights into urban climate response, prediction, and opportunities. Fine scale data, models, and analysis present significant unrealized opportunities for systematic understanding of multi sectoral urban processes, but alone they are insufficient.

## 4. Knowledge Co-Production

Fine-scale assessment of urban systems is both necessary and insufficient to comprehensively and realistically characterize the myriad of places, settings, and scales where these challenges and opportunities play out. Mechanisms of human harm from climate stressors are likely to be highly contextual. Correspondingly, assessing the critical mechanisms through which earth system hazards and stressors cause human harm requires the co-production of knowledge with stakeholders–the people at risk (Chester et al., 2023; Lemos et al., 2018; Norström et al., 2020; Ostrom, 2007). Opportunities can also be highly contextual, so assessing the key systems and sectors through which climate opportunities exist also requires co-production with the people who can develop and implement solutions in each context.

Co-production refers to collaboratively developing new knowledge, understanding, and sensemaking (Cook et al., 2021). Co-production goes beyond just sharing knowledge or extractive forms of eliciting information from a particular community; it often involves reconciling differences and building understanding through iterative collaboration. Co-production increases stakeholder agency and power in the research process, enables the research community to benefit from local perspectives on issues of critical local concern, formalizes knowledge of community-based solutions, and enhances the legitimacy and credibility of collaborative solutions that can be identified by both stakeholders and researchers. Finally, co-production allows the invention of locally specific, contextually informed opportunities for mitigation and adaptation, which are more likely to be successfully implemented because they are conceived with an understanding of the particular context. Despite the necessity and benefits of knowledge co-production, there are significant structural impediments in how this mode of science is funded, performed, and evaluated that impede implementation and success (Acuto et al., 2018). Research that aims to advance equity and environmental justice goals in urban contexts must invest in developing strategies and appropriate research scope to cope with these structural impediments.

Including human-centric approaches requires understanding the determinants of localized outcomes, experiences, and their dependencies on numerous interacting sectors. Some questions might include: What mechanisms and co-evolving sectoral processes in cities lead to differential impacts across social groups and changes in urban resilience and vulnerability? Are downscaled global or regional climate estimates reliable enough at urban scales for assessing changes in climate impacts, hazards, and adverse event probabilities? What are the primary mechanisms through which climate events (chronic and acute) cause harm? Are those critical processes well represented in high-resolution climate information? What opportunities are already used to mitigate and adapt to meteorological extremes? What are the failure mechanisms in those adaptive strategies for a range of social groups? What are the differential burdens of various adaptive strategies? How does the solution space change under different potential social, economic, and demographic futures? How much are people willing to change behavior, infrastructure, and institutions in order to move toward Net Zero carbon futures?

## 5. Risks and Best Practices

There are substantial risks and ethical concerns inherent in the transition from Earth system research as a discipline focused almost exclusively on natural systems to a more expansive vision which also recognizes social processes as central to determining the future of the Earth system. Beyond concerns associated with individual scale data privacy, knowledge co-production and co-design can be extractive (Lemos et al., 2018). This process can benefit the careers and goals of scientists but fail to provide tangible benefits to stakeholders, interlocutors, and co-designers. Researchers who are not active members of the communities they work in may be unaware of distinct factions and power dynamics within communities, and so inadvertently influence existing power struggles, sometimes exacerbating existing inequalities (Turnhout et al., 2020). When solution-oriented research is not directly actionable, the challenges of ethical community engaged research become more substantial because the community benefits are more abstract. Some scholars propose that incrementalist research is also an impediment to the kinds of transformational change that is necessary to address the climate crisis (Cologna & Oreskes, 2022; Glavovic et al., 2022). There is no single formula for best practices for human-centric research, but we argue that all scientists with an interest in policy relevant work should educate themselves in the state of the literature (Bixler et al., 2022; Chambers et al., 2021; Jagannathan, Buddhavarapu, et al., 2023; Mach et al., 2020; Norström et al., 2020).

## 6. Interconnected Assessments of Human and Natural Systems

Fundamentally, understanding urban resilience to climate change requires new theory, observations, and modeling that integrates human and natural systems. Hazard-related risk is a function of environmental conditions as well as system-level interactions among infrastructural, behavioral, and institutional factors. Understanding how these factors interact to mitigate or enhance risk is a critical area of research requiring new theoretical frameworks, observations, and modeling (Chester et al., 2023; McPhearson et al., 2021; Schlosser et al., 2023). Beyond vulnerability assessment, decision-makers need insight into the multi-objective trade-offs among alternative adaptation strategies (Ramaswami et al., 2023; Ürge-Vorsatz et al., 2018). This requires scientific foresight regarding the implications of hypothetical investment decisions, management changes, and/or environmental changes that may be out-of-sample with respect to past observed experience. In particular, green infrastructure and nature-based solutions can complement engineered infrastructure to enhance resilience and provide a multitude of co-benefits including reducing urban emissions and mitigating hydrologic or temperature extremes (Newcomer et al., 2014; Passalacqua et al., 2021; Ulpiani & Sailor, 2023). Research is needed to understand how these investments function and at what scale they can be implemented. The physical characteristics of environmental extremes can be modified by the built environment within urban areas. This highlights the importance of two-way coupling among natural and human processes in urban areas.

The insights we need are feasible. They may change our scientific understanding of the human-Earth system. Collaborative, interdisciplinary analyses at the city scale can highlight uncertainties in the future outcomes of these coupled systems, and therefore demonstrate our opportunity space for positive change. With a richer understanding of human and natural interactions in urban environments, the science we produce will be better positioned to inform decisions and policy addressing the climate crisis from a multi-sectoral perspective: supporting a transition to a more climate secure future for cities around the world.

## Data Availability Statement

This commentary article does not use any new data.

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