SUSTAINABLE URBAN SYSTEMS: ARTICULATING A LONG-TERM CONVERGENCE RESEARCH AGENDA

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EXECUTIVE SUMMARY

This report articulates a vision and a compelling research agenda for developing the next generation of sustainable urban systems science. It identifies fundamental research questions that need to be answered so that the transformative social and technological changes forecasted in urban areas may be harnessed to benefit society at all scales-local, national, and global.

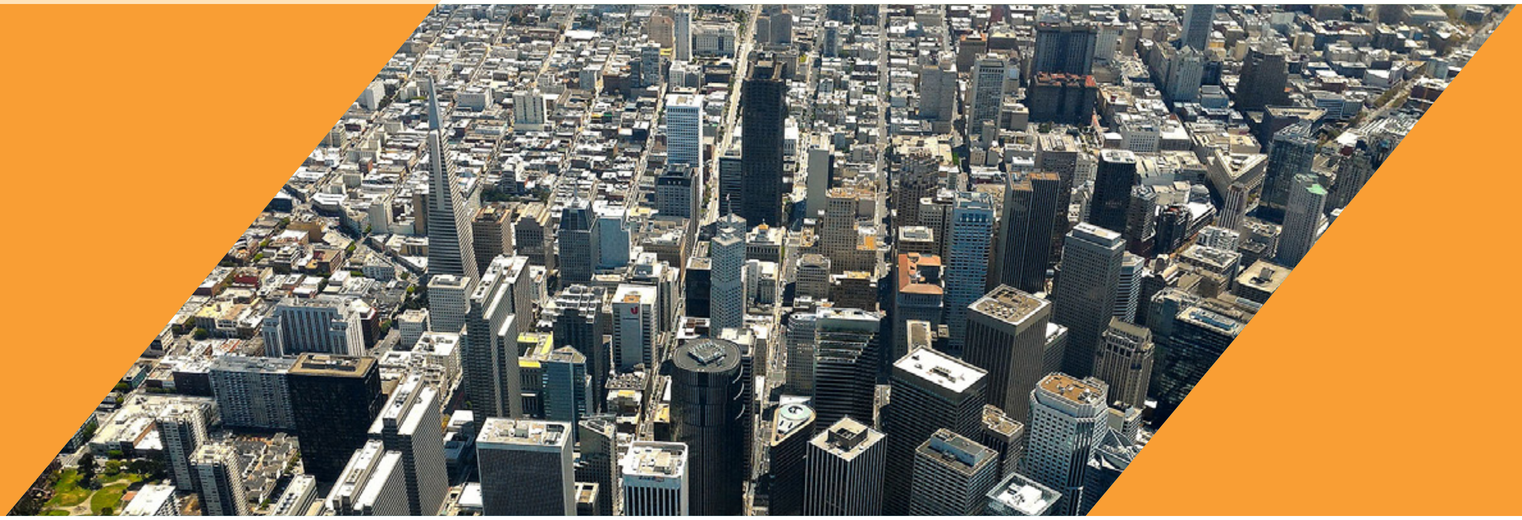
These complex transboundary interactions and teleconnections yield a new conceptualization of urban systems as multiscale, interdependent social, natural and engineered systems that impact human and planetary well-being across spatial (local to global) and temporal scales.

THE IMPORTANCE OF URBAN AREAS

Urban areas are centers of innovation that generate more than 80% of the global Gross Domestic Product (GDP), and will house nearly 66% of the world's population by the year 2050, almost doubling our current urban population in a very short time. This scale and pace of urbanization has never before been seen in human history. Several recent high-level reports have identified that we now live on an urban planet — where urban areas, although occupying only 3% to 4% of the land surface, are impacting human and environmental well-being from local to global scales at unprecedented levels in complex ways that are poorly understood. In the United States (US), urban areas are home to approximately 80% of the population and generate 85% of the national GDP, making these locales critical for local and national prosperity, security, and well-being.

A NEW CONCEPTUALIZATION OF TRANSBOUNDARY URBAN SYSTEMS

While engines of innovation, urban areas face challenges of: aging/inadequate infrastructure; health risks from pollution, poor diets, and sedentary lifestyles; vulnerability to disasters and extreme events; and inequities in economic opportunity, risk-exposure, and human well-being. Furthermore, the high concentration of human activities in urban areas creates large transboundary flows of people, natural resources, goods and services (including multiple essential infrastructures and food supply), information, innovation, waste, and pollution — through networks of trade, migration, infrastructure, and information — the impacts of which extend well beyond urban administrative boundaries. For example: energy use in urban areas



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contributes to more than 70% of global greenhouse gas emissions; water supply to just 50 of the world's largest cities draws upon watersheds covering 41% of the world's land surface; social and technological innovations in cities have reverberating impacts on surrounding rural areas, as well as across networks of cities connected via trade, nationally and internationally. Urban areas, in turn, are impacted by regional and global processes, with social, economic, environmental, and health consequences. These complex interactions and teleconnections yield a new conceptualization of urban systems as transboundary, multiscale, interdependent social, natural and engineered systems that impact human and planetary well-being across spatial (local-to-global) and temporal scales.

OPPORTUNITY FOR MULTIPLE CONVERGENT URBAN TRANSITIONS

Multiple transitions are converging in urban areas over the next decade that present a historic opportunity to improve human and environmental well-being, locally and globally, thereby advancing sustainability. Examples include: demographic transitions (e.g., aging populations in US cities versus exploding urbanization and the youth bulge in India and parts of Africa); socioeconomic transitions (e.g., the new sharing economy and alternate future modalities of work); and infrastructure transitions in multiple sectors (e.g., green infrastructure, distributed renewable energy systems, urban vertical farming, and driverless vehicles). Many of these innovations (e.g., driverless vehicles and shared mobility) are incubated in cities by businesses, are inter-dependent across sectors, require a deep understanding of the human-technology interface, and need carefully crafted policies and multi-level governance to ensure the public good. However, the science is yet nascent on how to guide these emerging social, technological, and infrastructural innovations occurring in urban areas, such that they advance multiple sustainability outcomes, locally and globally. Researchers, industry leaders, and policymakers are recognizing a historic, time-sensitive opportunity to develop a new convergence science of sustainable urban systems (SUS) that is multiscale, trans-disciplinary, and actively advances science-policy-community partnerships to identify and inform pathways toward a more sustainable urban future.

LANDSCAPE OF CURRENT RESEARCH

Early investments by the US National Science Foundation (NSF) have laid the groundwork for interdisciplinary urban systems thinking and have helped create a pool of researchers and policy/practitioner partners who demonstrate capacity and readiness for convergence science. However, current urban sustainability research efforts typically focus on individual cities and communities, often addressing transitions within single infrastructure sectors (e.g., water or energy) and individual sustainability outcomes (e.g., low-carbon development or resilience) in a limited number of case study cities. To develop the next generation of convergent SUS research, a much broader and longer-term research agenda is needed with specific elements and three essential perspectives that must be integrated together.

Urban Systems and Sustainable Urban Systems

Urban systems are geographical areas with a high concentration of human activity and interactions, embedded within multiscale interdependent social, engineered, and natural systems that impact human and planetary well-being across spatial (local to global) and temporal scales.

Sustainable urban systems (SUS) are those that are transforming their structures and processes with the goal of measurably advancing the well-being of people and the planet.

A VISION FOR NEXT-GENERATION SUS SCIENCE

Advancing the next generation of SUS science requires intentional integration across three perspectives:

i. The study of single urban areas/metropolitan regions where multiple sustainability outcomes are addressed from a multiscale systems perspective that connects homes, businesses, and communities to regional and global scales.

ii. The study of multiple cities and communities, exploring inter-relationships among networks of cities and communities, and identifying city typologies for the study of cohort groups and comparison groups.

iii. The study of supra-aggregations of cities and urban areas, e.g., of all urban areas in an electrical grid region, a nation, a world region, or the world, to assess the collective impact of urban transformation on people and the planet.

Within each of these perspectives (i-iii), integration of the following six key elements (A-F) is expected to significantly advance SUS science.

A. Developing new data and methods to understand current drivers and interactions among natural, human-built, and social systems in urban areas as they impact multiple sustainability outcomes across scales.

B. Developing the science to assess the sustainability outcomes nexus in urban systems, i.e., the co-benefits and trade-offs among multiple human and planetary well-being outcomes across spatial (local to global) and temporal scales.

C. Understanding the levers for change in diverse urban systems ("theories of change"), combining:
    1. A focus on integrative design, technology innovation, and sociotechnical transitions.
    2. A focus on multi-level actors and governance.

D. Advancing comparative studies, typology studies, and scalability studies to develop a generalizable science of theories of change across diverse city types.

E. Developing the science to model the future of SUS across the three perspectives.

F. Developing the science of knowledge co-production among researchers, communities, industry groups, practitioner groups, and governments at multiple levels, leveraging real-world experimentation ongoing in urban areas.

The three perspectives (i-iii) noted above are envisioned to enable a holistic study of local to global SUS, while the six key elements (A-F) fill critical research gaps and work to provide a strategic pathway to advance SUS, starting from understanding the system, to designing change from a social-ecological-infrastructural perspective, and finally, to informing action to change the forecast (AC ERE, 2015).

QUESTIONS ADDRESSED BY NEXT-GENERATION SUS SCIENCE

Next-generation SUS science is expected to address both fundamental science questions, as well as inform key questions about societal transitions. Fundamental science questions include:

- How can we systematically understand the functioning of cities and urban areas as multiscale, interdependent, adaptive systems, with interactions among social, natural, and engineered systems shaping multiple sustainability outcomes across scales?
- What is the impact of changes arising in urban areas on local well-being, on the transboundary distribution of benefits and burdens across communities (urban and rural), and on planetary boundaries?
- What shapes human well-being in diverse urban areas, including city cores, and along urban-rural gradients?
- What are the processes for adaptation, disruption, and change, and the timescales for such changes in urban systems?
- What are the linkages and inter-relationships among action taken by individual actors within cities, by policymakers in individual cities and metro areas, and by national and international policy actors?
- What are the different modalities for co-producing actionable science at the different scales?
- What theories best describe how new technologies and infrastructure configurations impact and are impacted by multiscale socio-technical processes in urban systems?
- Is there a fundamental science to identify city typologies and model their futures?

Practically, SUS science is expected to help inform questions and actions around key societal transitions. The questions listed below, while not comprehensive, exemplify some of the critical societal transitions that the next generation of SUS science could help inform:

- What is the role of distributed infrastructure and disruptive technologies in achieving multiple local and global sustainability outcomes?
- What is the future of urban systems and their sustainability implications in the new shared economy? What is the future of work in cities and associated implications for human and planetary well-being?
- How can sustainable economic development be achieved across cohorts and clusters of cities, and across urban-rural linkages? What are key urban-rural linkages in pursuing sustainability, equity, and well-being goals?
- How can global urban systems contribute to deep de-carbonization, while maximizing local human well-being benefits?
- What are pathways for developing secure, disaster-resilient, healthy, and sustainable cities?

A ROADMAP

A broad roadmap is proposed to stimulate, support, and sustain next-generation SUS science through NSF investments. A two-pronged approach is proposed that supports: a) large multi-investigator cross-directorate projects that integrate most of the key elements of a convergent SUS science across two or more of the three perspectives, and b) smaller projects that enable focused exploration within the key elements. The conceptualizations of the larger and smaller projects are summarized in Table 1 (p. 23) and Table 2 (p. 25) and provide a road map for implementing a long-term research agenda on next-generation SUS science in the US and globally.

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I. RATIONALE

Urban areas are geographical locations with a high concentration of human activity that collectively contribute to more than 80% of the world's gross domestic product (GDP) (McKinsey Global Institute, 2011). They are centers of social and technological innovation, offering pathways to prosperity and human development (Bettencourt, et.al. 2007; UNDP, 2010). Today, more than half the world's population lives in urban areas and this proportion is expected to increase to 66% by the year 2050, nearly doubling the world's current urban population in a very short time (UN Habitat, 2016). Many scholars (e.g., see commentary in Seto, et.al. 2017; Wigginton et al., 2016; Bettencourt & West, 2010) note that we are now living on an urban planet, in which urban areas are focal points of some of the world's most complex challenges, and hence also offer the promise of transformative solutions.

The urban sustainability challenge impacts both people and the planet at unprecedented levels, and from local to global scales. Although occupying only about 3% of the land, the massive scale and pace of urbanization is now affecting the well-being of people and the environment both within and far beyond urban administrative boundaries. These boundaries can be conceptualized at different organizational levels ranging from neighborhoods and business districts, to municipalities and metropolitan planning organizations, to emerging supra-metropolitan urban governance structures such as the Beijing-Tianjin-Hebei (JingJinJi) national capital region in China, the proposed Delhi-Mumbai industrial corridor in India, and the United States (US) equivalent — the Boston-Washington DC corridor. Transcending these boundaries the collective global urban demand for energy contributes more than 70% of the world's greenhouse gas emissions (Seto et al., 2014). Urban land expansion and massive draws of resources to support urban activities are impacting global carbon and nitrogen cycles and contributing to biodiversity loss (D'Amour et al. 2017; Grimm et al., 2008). Water supply to just 50 of the world's largest cities draws upon watersheds covering 41% of the world's land surface (McDonald et al., 2014). Regional

Scientists, as well as public and private sector actors, recognize that the science is yet nascent to address some of the most fundamental questions that can ensure that urban innovations yield the intended sustainability outcomes, both locally and globally.

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air pollution arising from multiple infrastructures that converge in cities — e.g., energy supply, transportation, building construction, and waste management — contributes to more than 6.5 million premature deaths per year in the world (greater than 100,000 in the US), a majority of which occur in cities due to the high concentration of people exposed to pollution-risk (Ramaswami et al., 2016; IHME, 2017). Water-stress and climate change related extremes — such as extreme heat, cold, and flooding — are impacting both the economy and human lives in cities (World Bank, 2010), as seen in recent examples of flooding in Bangkok and New York City and heat stress in Phoenix and Chicago. There is also significant inequity within cities and across urban-rural trade and migration networks that profoundly affects human well-being at both locales (World Bank, 2009a; 2009b; 2011; Grant, 2010). Urban sustainability challenges are thus global sustainability challenges and vice versa. This present trajectory is unsustainable.

Several high-level scientific journals (e.g., Science[1], Global Environmental Change, Environmental Research Letters[2,3], Proceedings of the U.S. National Academy of Sciences[4], and Nature[5]) have recently published special issues that document the challenges of our urbanizing planet, highlighting the scale, complexity, and transboundary aspects of the urban era as an emerging area of inquiry where scientific advancement is urgently needed.

A CONVERGENCE OF INTERESTS IN A NEW SCIENCE

In tandem with the scientific community, many cities, nations, and international organizations around the world are recognizing the urgency to act (e.g., C40 Cities[6], World Bank[7] , UN[8]). City managers and mayors are recognizing a unique window of opportunity to act in the coming decade. Many US cities are presently engaged in rebuilding or replacing their aging infrastructure, while globally, about 60% of urban land areas and infrastructure have yet to be built, presenting a strategic opportunity to get it right from the start (UNEP, 2013). With long lifetimes for the physical infrastructures, as well as, 'lock-in' effects embodied in social and cultural norms, the risks of inaction are large.

Illustrating the imperative to act, more than 1,000 US cities have signed on to the US Conference of Mayors Climate Protection Agreement[9] and more than 150 cities are signatories to the Milan Urban Food Policy Pact.[10] These initiatives exemplify a new action arena for city governments; one that seeks to address impacts well outside city administrative boundaries, engages diverse stakeholders across geographic scales (from households to international decision makers), and seeks systems-level transformation toward a more sustainable future.

National and international agencies are also recognizing that technological and social innovations incubated in urban areas can invigorate the economy and advance quality of life. Several countries, including the United Kingdom (UK), India, and the US, have initiated national Smart Cities programs. The World Bank's efforts (2016) and the United Nation's New Urban Agenda (UN Habitat, 2017) illustrate efforts at the international level. Most importantly, many private sector innovations in infrastructure, technology, and business, often originate and are pilot-tested in cities. Innovations, such as driverless vehicles, shared mobility, the sharing economy, and smart buildings and energy grids, are transforming the way we live, and can potentially offer new pathways to creating a sustainable urban future.

However, scientists, as well as public and private sector actors, recognize that the science is yet nascent to address some of the most fundamental questions that can ensure that urban innovations yield the intended sustainability outcomes, both locally and globally.

For example, scientists, professionals, and policymakers find that:

- They lack the knowledge and the data to identify key levers of change in urban sociotechnical systems (behavioral, technological, urban design, or policy) and their impact on the multiple and interrelated sustainability outcomes of economy, environment, health, well-being, and equity, also called the sustainability outcomes nexus.
- There is yet a burgeoning understanding of natural resource flows, and associated impacts, in cities of different typologies, by population size, wealth, economic structure, age, urban form, and other attributes.

1 (2016). Urban Planet [Special Issue]. *Science*, 352(6288).
2 (2018). Focus on Resource Requirements of Future Urbanization [Special Issue]. *Environmental Research Letters*, Forthcoming.
3 (2017). Focus on Urban Food–Energy–Water Systems: Interdisciplinary, Multi-Scalar and Cross-Sectoral Perspectives [Special Issue]. *Environmental Research Letters*, 12(7).
4 (2016). Sustainability in an Urbanizing Planet [Special Feature]. *Proceedings of the National Academy of Sciences*. 114(34).
5 (2010). Science and the City [Special Issue]. *Nature*, 467(2010).
6 See C40 Cities Climate Leadership Group, http://www.c40.org
7 See Urban Development at the World Bank, http://www.worldbank.org/en/topic/urbandevelopment
8 See UN Habitat, https://unhabitat.org; See also UN Environment- Cities, https://www.unenvironment.org/explore-topics/resource-efficiency/what-we-do/cities
9 See Mayor's Climate Protection Center, US Conference of Mayors, https://www.usmayors.org/mayors-climate-protection-center
10 See Signatory Cities, Milan Food Pact, https://www.milanurbanfoodpolicypact.org/signatory-cities

- The science is yet nascent to frame and model urban sociotechnical futures incorporating interactions among socioeconomic, urban design, technological, and environmental sub-systems that interact at multiple scales and impact multiple sustainability outcomes related to human and environmental well-being.
- The interactions among sustainability outcomes across scales are complex and require insights on trade-offs and co-benefits to better inform policies and actions.
- Understanding is yet limited on how different actors – individuals, the private sector, and governments – can coordinate effectively toward sustainability transitions at the local level, leveraging policy environments at larger levels, including city-regional, state, national, and global levels of governance.
- At the same time, actors and agencies at higher organizational levels, such as national governments and international organizations, are also grappling with how to address the urban sustainability challenge from a national and/or global perspective.
- There are few professional education programs and curricula that train urban sustainability professionals (at all levels) to navigate the above scale, boundary, nexus, and governance issues.

Hence, there is high interest and engagement in co-developing knowledge, science, action, and education networks that help inform action, employing a cross-scale systems perspective on urban sustainability.

However, traditionally urban-focused disciplines such as urban planning, urban design, and infrastructure engineering do not have the tools or the scope to address this multiscale complexity because their foci have traditionally been within city or metropolitan region boundaries and/or within the confines of single applied sectors such as water supply or transportation planning. Other fields such as environmental science, climate science, and ecology have typically focused on larger spatial scales, such as watersheds, oceans, and forests, resulting in the urban and intra-urban scales being comparatively less well-understood and highly data-sparse. There is an urgent need for a transdisciplinary science that generates new knowledge, methods, and theories to advance fundamental understanding of the urban sustainability challenge and inform potential solutions.

While the science is not yet fully developed, given the urgency to act, there is a high level of experimentation already underway in urban areas with businesses and cities pilot-testing new technologies, infrastructure designs, behavioral campaigns, policy innovations, and multi-stakeholder partnerships. These rich and ongoing experiments provide the ideal landscape for knowledge co-production among practitioners and the science community. First, these experiments present as yet untapped opportunities to develop generalizable theories of change through comparative sociotechnical analyses across multiple cities and urban areas — i.e., theories that identify how advancement toward sustainability outcomes is achieved. Second, they present opportunities to advance translational science, i.e., unpacking the process and modalities of knowledge co-production among researchers in diverse, multiscale, multi-actor urban systems. Ethical considerations and training in participatory research are particularly important in knowledge co-production with diverse stakeholders.

The current landscape of urban sustainability research and education does not address the multi-faceted aspects described above. Thus, there is an urgent need, as well as a historic, time-sensitive opportunity, to develop a new convergence science of sustainable urban systems (SUS) that is multiscale, trans-disciplinary, and actively links science and action to identify and inform pathways to a more sustainable urban future. The new science that is needed must be both transdisciplinary and convergent (See Box 1), because a) it requires deep integration across disciplines that results in new methods, theories, and models that transcend individual disciplines, and b) it is driven by specific and compelling problems that are ripe for collaboration among scientists, professionals, policymakers, and the public. This new science aligns broadly with the goals identified in the Advisory Committee for Environmental Research and Education's (AC ERE) America's Future report that highlights the importance of "supporting science that can be used to design resilient landscapes, productive managed and natural ecosystems, sustainable urban spaces, and a healthy planet" (AC ERE, 2015, p. 2).

Following a rich discussion at its September 2016 meeting, the AC ERE recognized a need to fill a critical knowledge gap by advancing scientific understanding of SUS that can inform actions in communities and advance human and planetary well-being. A SUS subcommittee was convened to develop a report that articulates a compelling research agenda for transforming our understanding of SUS. This report presents a synopsis of the subcommittee's deliberations, its rationale, and its vision for a research agenda focused on SUS.

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BOX 1: DEFINING MULTI-, INTER-, AND TRANSDISCIPLINARY RESEARCH AND CONVERGENCE SCIENCE

Multidisciplinary: Knowledge, theories, and methods from multiple fields are brought to bear on a particular challenge, i.e., a group of experts work to address a common challenge, but from within the confines of each expert's core discipline.

Interdisciplinary: Knowledge, theories, and methods from multiple fields are intersected and synthesized in a way that allows for novel consideration of and work on a particular challenge, i.e., an expert applies knowledge from more than one field simultaneously to address a challenge in a new way.

Transdisciplinary: Transdisciplinary research is represented by two distinct strands of thought: (1) Enhanced interdisciplinary research practice to the point that a fundamentally new science emerges that transcends the disciplines being intersected and synthesized (Gray, 2008; Vasbinder et al., 2010); (2) Research practice that is explicitly concerned with drawing on and engaging with the expertise of actors outside of academic and research communities, with an emphasis on the co-production of knowledge with practitioners and social actors (Brandt et al., 2013; Toomey et al., 2015). This perspective intersects with what is sometimes referred to as translational research, i.e., research that has as its goal the deployment of research findings in actual practice and for "real-world" applications in communities of practice.*

Convergence Science: This type of science relates to both definitions of trans-disciplinary research, in which new science and methods are generated as a function of deep integration across disciplines and the explicit consideration of how to transition from basic scientific discovery to practitioner application (NRC, 2014). The National Science Foundation (NSF) identifies convergence as exhibiting two primary characteristics: 1) deep integration across disciplines, and 2) driven by a specific and compelling problem. The convergence paradigm augments a more traditional transdisciplinary approach to research by framing challenging research questions at inception and fostering the collaborations needed for successful inquiry (NSF, n.d.). Convergence science integrates both representations of transdisciplinary highlighted above.

* The NSF Engineering Directorate defines translational research as research that moves beyond basic scientific discovery through to "proof-of-concept" for real-world application, often in collaboration with relevant industry, government, or other practitioners. Public health and medical fields consider translational research as being rooted in efforts to translate science into practice, premised on "brought-to-market" or "bench-to-bedside" efforts that link basic science with clinically and commercially applicable interventions. Some take the concept further, connecting basic science to changes in fundamental health decision making and systems of care (Woolf, 2008).

II. SUSTAINABLE URBAN SYSTEMS

The AC ERE subcommittee defines urban systems and sustainable urban systems (SUS) as follows: *Urban systems are geographical areas with a high concentration of human activity and interactions, embedded within multiscale interdependent social, engineered, and natural systems that impact human and planetary well-being across spatial (local to global) and temporal scales. Sustainable urban systems (SUS) are those that are transforming their structures and processes with the goal of measurably advancing the well-being of people and the planet.*[11] See other definitions drawn from the literature in Box 2.

The subcommittee notes that the study of multiscale urban systems in the context of multiple sustainability goals is essential to developing the next generation of SUS science. To achieve this vision, the portfolio of next-generation SUS research must integrate three perspectives:

- The study of single urban/metropolitan regions, where multiple sustainability outcomes are addressed from a multiscale systems perspective that connects homes, businesses, and communities to regional and global scales.
- The identification and study of city/urban typologies, i.e., where the differences or similarities in geography, governance structure, economic activity, urban form, or technological innovation help develop a generalizable science of SUS.
- The study of supra-aggregations of cities and urban areas, e.g., assessing the collective impact of all urban areas in an eletrical grid region, nation, world region, or the world on people and the planet.

Bridging and linking across these three perspectives is essential to advance this science. The complexities of urban systems require new ways of conceptualizing, processing, and thinking about data and models of SUS. While social scientists, natural scientists, and engineers have developed theories and models for studying individual components of urban systems (e.g., ecological processes, physical climate, governance, social justice, engineered systems) a new class of research that approaches cities from a convergent systems-level perspective is emerging and is of critical importance. The next generation of SUS projects must develop their own methods, research questions, and broader impacts activities that transcend the conventional disciplines in NSF's Directorates.

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BOX 2: OTHER DEFINITIONS HIGHLIGHTING THE MULTISCALE AND COMPLEX NATURE OF SUS

"Urban sustainability is the process by which the measurable improvement of near- and long-term human well-being can be achieved through actions across environmental (resource consumption with environmental impact), economic (resource use efficiency and economic return), and social (social well-being and health) dimensions."
(NASEM, 2016, p. 11)

"A higher-order understanding of cities as trans-boundary, multi-sectoral, multi-scalar, social-eco-logical-infrastructural systems with diverse actors, priorities, and solutions.... transitioning toward a sustainable and healthy future."
(Ramaswami et al., 2016, p. 940)

"Evolving conceptual frameworks for urban ecology view cities as heterogeneous, dynamic landscapes and as complex, adaptive, socioecological systems, in which the delivery of ecosystem services links society and ecosystems at multiple scales"
(Grimm et al., 2008, p. 756)

"Many urban systems display key properties of complex adaptive systems, meaning that they can be highly interconnected and unpredictable while having modular subsystems that confer redundancy and are capable of resiliency."
(MacPhearson et al. 2016, p. 205)

III. THE CURRENT LANDSCAPE

NSF's earlier investments in interdisciplinary environmental research[12] provide a strong foundation to advance the next generation of SUS science. These investments conceptualize interdisciplinary frameworks that consider urban systems as multiscale, complex adaptive systems with non-linear dynamics, and emergent behavior (e.g., See Box 2). These early investments by NSF have also helped create a pool of researchers and policy/practitioner partners who demonstrate capacity and readiness for convergence. The next generation of SUS science will enable such convergence to fully mature.

However, current urban sustainability research efforts focus on individual cities and communities, often addressing transitions within single infrastructure sectors (e.g., water or energy) and a few individual sustainability outcomes (e.g., low-carbon development or resilience) in a limited number of case study cities. To enable the next generation of convergent SUS research, a much broader and longer-term research agenda is needed: to develop, operationalize, compare, and contrast emerging interdisciplinary frameworks; to assess competing theories, compare alternative modeling approaches; to identify key hypotheses that

11 Advancing human and planetary well-being is the overarching goal of sustainable development (including as articulated in the United Nations' Sustainable Development Goals and the "New Urban Agenda"). However, there is a significant gap in the science and methods needed to define and measure human and planetary well-being from an urban systems perspective. This critical area of research is described further in Section III.

12 For example: the Biocomplexity in the Environment initiative, the Science, Engineering, and Education for Sustainability (SEES) initiative, the Smart and Connected Communities (S&CC) initiative, the Innovations at the Nexus of Food, Energy, and Water Systems (INFEWS) initiative, the Urban Long-Term Ecological Research (LTER) sites, the Sustainability Research Network program, and the Dynamics of Coupled Natural Human Systems (CNH) program.

advance the science; and to develop convergence science that informs effective actions toward sustainability. It is also important to align US SUS research efforts with international efforts and global sustainability agendas — including those articulated in the UN's Sustainable Development Goals, UN Habitat's New Urban Agenda, the UN's Sendai Framework for Disaster Risk Reduction — that are presenting a vision for transformation by 2030 and 2050. Similar agendas are being advanced by most large American cities, and require scientific frameworks and assessment methods to effectively inform action. Aligning fundamental research with these practical, transformative agendas provides the most compelling and transformative scientific program for the next few decades.

Specifically, areas that next-generation SUS science must address are noted below:

- New data and methods are needed to understand current drivers and interactions among natural, human-built and social systems within urban areas, as they impact multiple sustainability outcomes. Urban areas are complex assemblages of natural, built, and social sub-systems that have been under- measured and monitored relative to other ecosystems and land systems. NSF's current investments are just beginning to develop the large datasets and associated cyberinfrastructure needed for study of SUS. A sustained effort on data, data science, and cyberinfrastructure is needed across scales, from intra-city to planetary. More critically, data and methods are needed that bridge the three foci of: a) individual cities/urban areas, b) networks and cohorts of cities/communities, and c) national or global systems of cities.
- First-generation SUS research projects typically focus on single sectors and a few sustainability outcomes, often in a few case study cities. Next-generation SUS science must address the sustainability outcomes nexus, i.e., the interactions among multiple human and planetary well-being outcomes in multiscale urban systems, incorporating the emerging science of human well-being and planetary boundaries. The United Nation's Sustainable Development Goals framework presents an opportunity to align with international efforts to assess interactions, co-benefits, and trade-offs among multiple sustainability outcomes.
- Current projects do not have a large enough sample size of cities to compare and contrast alternative interdisciplinary theories of change toward SUS, integrating multiple levers of change, including technological changes, urban spatial design, and infrastructure innovations as well as social and policy innovations. Indeed, while a few interdisciplinary systems-frameworks have been articulated, large time frames (10 to 20 years) are needed to fully populate the frameworks with the requisite theories, data, and models. Furthermore, issues of multi-level governance are also poorly understood in terms of which actors (business, households, and governments) acting at what spatial scale and level of governance can best coordinate a transition toward SUS.
- It is also critically important to identify city typologies, cohort groups, and comparison groups to test the underlying hypotheses in the theories of change. Examples include comparing across central cities, suburbs, and rural areas and/or contrasting economic or governance structures across similar or contrasting city types.
- There is an urgent need and a high impact opportunity to leverage the many real-time and real-world policy experiments already on-going in communities across large numbers of cities and across different city typologies. Such large-N studies of cities will be a key aspect of developing the science for identifying key levers of change and for studying effective knowledge co-production in the urban arena.
- While the field of urban simulation has advanced significantly, particularly in areas of spatial modeling of individual cities or neighborhoods, few studies examine the evolution of urban system futures across scales, including from the perspective of cohorts of cities and collectives of urban areas in a national or global region, and considering their aggregate effects on people and on the Earth system or planetary-scale sustainability.

- To advance convergence science, researchers must collaborate with cities, multi-city networks and citizens in knowledge co-production, drawing upon the large number of real-world policy experiments already underway in cities. Partnering with multi-city organizations such as the Urban Sustainability Directors Network (USDN), ICLEI and the International City/County Management Association (ICMA) may also offer an opportunity to leverage the rich policy experimentation occurring across large numbers of cities. Little is known today about the best modalities of such knowledge co-production in urban systems, ways to assess the effectiveness of such co-production in informing and catalyzing action, and ways to advance ethical practice of participatory research in new public-private-community-research partnerships.

The above topics are beyond the scope of a majority of current urban sustainability research projects. The size and scope of the urban challenge requires large-scale investments to develop the next generation of SUS science that addresses the key knowledge gaps noted above. The next section identifies elements of SUS Science as envisioned by the sub-committee, to address the gaps noted above.

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IV. KEY FEATURES OF NEXT-GENERATION SUS SCIENCE

The next generation of SUS science is expected to address the key research needs identified above, in an integrated manner, across three perspectives (noted at the beginning of section II) that, together, contribute to a holistic understanding of SUS:

i. Single urban/metropolitan regions where multiple sustainability outcomes are addressed from a multiscale systems perspective that connects homes, businesses, and communities to regional and global scales.

ii. Multiple cities and communities, exploring relationships among networks of communities, and identifying city/urban typologies for the study of cohort groups and comparison groups.

iii. Supra-aggregations of cities and urban areas, e.g., all urban areas in an electrical grid region, nation, world-region, or the world, to study the collective impact of urban transformation on people and the planet.

For each perspective (i-iii), the following key elements are identified (based upon the needs and gaps noted in Section III) that must be integrated to advance the science of SUS.

A. Developing new data and methods to assess current drivers and interactions among natural, human-built, and social systems in urban areas as they impact multiple sustainability outcomes across scales.

B. Developing the science to understand the sustainability outcomes nexus in urban systems, i.e., the co-benefits and trade-offs among multiple human and planetary well-being outcomes across spatial (local to global) and temporal scales.

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C. Understanding the levers for change in diverse urban systems ("theories of change"), combining :

   1. A focus on integrative design, technology innovation, and sociotechnical transitions.

   2. A Focus on multi-level actors and governance.

D. Advancing comparative studies, typology studies, and scalability studies to develop a generalizable science of theories of change across diverse city types.

E. Developing the science to model the future of SUS across the three perspectives.

F. Developing the science of knowledge co-production among researchers, communities, industry groups, practitioner groups, and governments at multiple levels, leveraging real-world experimentation ongoing in urban areas.

Illustrative examples of research foci within each of the key elements are provided in Section V. The three perspectives noted above are envisioned to enable holistic study of local to global SUS, while the six key elements (A-F) fill critical research gaps and work to provide a strategic pathway to advance SUS, starting from understanding the system, to designing change from a social-ecological-infrastructural perspective, and finally, to informing action to change the forecast (AC ERE, 2015).

QUESTIONS ADDRESSED BY NEXT-GENERATION SUS SCIENCE

Next-generation SUS science is expected to address both fundamental science questions, as well as inform key questions around societal transitions. Fundamental science questions include:

- How can we systematically understand the functioning of cities and urban areas as multiscale, interdependent, adaptive systems, with interactions among social, natural, and engineered systems shaping multiple sustainability outcomes?

- What is the impact of change in urban areas on local well-being, on the distribution of benefits and burdens across communities (urban and rural), and on planetary boundaries?

- What shapes human well-being in diverse urban areas, including city cores, and along urban-rural gradients?

- What are the processes for adaptation, disruption, and change, and the timescales for such changes in urban systems?

- What are the linkages and inter-relationships among action taken by individual actors within cities, by policymakers in individual cities and metro areas, and by national and international policy actors?

- What are the different modalities for co-producing actionable science at the different scales?

- What theories best describe how new technologies and infrastructure configurations impact and are impacted by multiscale socio-technical processes in urban systems?

- Is there a fundamental science to identify city typologies and model their futures?

Practically, SUS science is expected to help inform questions and actions around key societal transitions. The questions listed below, while not comprehensive, exemplify some of the critical societal transitions that the next generation of SUS science could help inform:

- What is the role of distributed infrastructure and disruptive technologies in achieving multiple local and global sustainability outcomes?

- What is the future of urban systems and their sustainability implications in the new shared economy? What is the future of work in cities, and associated implications for human and planetary wellbeing?

- How can sustainable economic development be achieved across cohorts and clusters of cities, and across urban-rural linkages? What are key urban-rural linkages in pursuing sustainability, equity and well-being goals?

- How can global urban systems contribute to deep de-carbonization, while maximizing local human well-being benefits?

- What are pathways for developing secure, disaster-resilient, healthy and sustainable cities?

V. ILLUSTRATIVE EXAMPLES

To illustrate the six key elements that must be integrated for holistic research on SUS, this section provides a brief overview of each of the elements (A-F), along with a few select examples of smaller-scale, focused research projects within each element.

A — DEVELOPING NEW DATA AND METHODS TO UNDERSTAND CURRENT DRIVERS AND INTERACTIONS AMONG NATURAL, HUMAN-BUILT, AND SOCIAL SYSTEMS IN URBAN AREAS AS THEY IMPACT MULTIPLE SUSTAINABILITY OUTCOMES ACROSS SCALES.

Data and theoretical frameworks are lacking that advance understanding of how physical processes, social dynamics, the design process, and biological 'rules of life' interact in urban areas to determine their form and function (MacPhearson et al. 2016, Pataki et al. 2015) and their resulting impact on multiple sustainability outcomes across scales. Interactions between human activity, built environments, and ecological systems rely on dynamic processes of co-evolution and co-adaptation. Understanding these interactions requires detailed data within urban areas at fine spatial scales, where data are critically lacking. Assessing multi-scale outcomes also requires accounting for the fundamental openness of cities and regions to understand, for example, how innovations in one city are influencing economic, social, and environmental outcomes in other cities, or, in aggregate, across larger regions, through interdependent flows of people, money, resources, goods, and services. Likewise, ecosystems and environmental processes interact across multiple scales, implying interdependencies in ecosystem stocks, resource scarcities, and environmental impacts across cities and regions. A better understanding of these dynamics requires new data and methods. Furthermore, participatory research with decision-makers is needed to identify the most relevant data, data sources and quality considerations, cyberinfrastructure design, and how data can be used in visualizations and the development of indicators to track progress toward various sustainability outcomes. Example projects in this topic area include:

- Coordinated empirically-based efforts to leverage citizen science for big data approaches.

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- Complexity science modeling approaches based on an expanded understanding of evolutionary dynamics in ecosystems and of growth in human urbanizing societies.
- Understanding the biological 'rules of life' in urban areas.
- Understanding the role of urban form in shaping multiple sustainability outcomes.

B — DEVELOPING THE SCIENCE TO ASSESS THE SUSTAINABILITY OUTCOMES NEXUS IN URBAN SYSTEMS, I.E., THE CO-BENEFITS AND TRADE-OFFS AMONG MULTIPLE HUMAN AND PLANETARY WELL-BEING OUTCOMES ACROSS SPATIAL (LOCAL TO GLOBAL) AND TEMPORAL SCALES.

How do we measure multiple desired attributes of human and planetary well-being from a multiscale and dynamic urban systems perspective, recognizing correlates, transboundary (local to regional) linkages, co-benefits, and trade-offs? Measures of human well-being have now advanced beyond measures of economic growth (e.g., income and GDP) to include human development, human capabilities, assessments of inequality, health status, health risks and subjective well-being, including cognitive and emotional aspects of well-being. Methods are emerging to measure human well-being in real time, in different urban environments, and to identify the different factors that may shape such well-being; including the physical environment, physical infrastructure, social networks, physical health, and economic opportunity. The relationship between human well-being and the natural system is complex and mediated by human-built engineered infrastructure and social arrangements in cities, as well as transboundary economic and trade linkages. For example, providing urban services and economic opportunity in cities can enhance the quality of life of urban residents. At the same time, large inequalities exist within cities by race, gender, and socioeconomic class, as well as inequalities arising outside the city (e.g., in the context of rural-urban linkages and trade relationships). These inequalities range from income, access to key services and opportunities, exposure to pollution, and health disparities within cities, as well as a shifting of burdens and benefits across city boundaries. Environmental impacts likewise range from local to regional to global and cover multiple nexus attributes. Overall, this research area seeks to develop methods to measure progress toward improvement of the environment, equity, health and well-being within cities, and along rural-urban gradients, with assessments of global planetary impacts. Examples of specific projects within this topic areas include:

- Science of well-being and equity in cities and across rural-urban gradients.
- Science and methods to link cities to planetary boundaries.
- Assessing and communicating co-benefits and tradeoffs to the public and to policymakers.

C — UNDERSTANDING THE LEVERS FOR CHANGE IN DIVERSE URBAN SYSTEMS ("THEORIES OF CHANGE"):

Focusing on integrative design, technology innovation, and sociotechnical transitions. Urban environments are dominated by designed and engineered infrastructures and ecosystems spatial design and evolution that are poorly understood in terms of impacts on sustainability outcomes. This is specifically manifested in the clash of perspectives between bottom-up evolved designs – typical of informality in cities, as well as of evolutionary dynamics in ecosystems and markets – and top-down design, typical of human interventions, via infrastructure, institutions and policy. Furthermore, new technologies are being introduced at an unprecedented rate into urban systems, including self-driving electric vehicles, smart meters and sensors, new materials for buildings and infrastructure, and energy and information technologies. These technologies disrupt existing social dynamics, challenge institutions, and transform economic models, with unforeseeable consequences, negative and positive. How do these technologies impact diverse outcomes in different cities and metropolitan areas in various parts of the US? How will these innovations transform nations and global regions? Example projects in this topic area include:

- Urban organic bio-design of green infrastructure.
- Studies of emerging technologies and sustainable urban transitions in US metropolitan areas.
- Studies of human technological interface in urban systems.

Focusing on multi-level actors and governance. Multiple actors, acting across spatial scale, shape sustainability outcomes in urban systems. Theories of change among the actor groups — citizens, government, community groups, knowledge partners, and industries — are critically important to advance SUS science. Effective citizen mobilization can take root in cities due to the collective responses of individual citizens as seen in the case of the Japanese energy crisis after the Fukushima disaster. In other cases, communities may rally around neighborhood associations and/or organize non-profit or for-profit enterprises that leverage new technologies and ways of service provisioning, such as community supported agriculture. At the policy level, multi-level governance in urban systems can range from neighborhood associations, city offices, metropolitan regions, nation states, and international governmental and non-governmental organizations. Important questions arise in sociotechnical transitions, as to what are the key levers of change, who or which actors will lead the transitions, what are the stimuli (i.e., the various sustainability outcomes) that stimulate change, and what are barriers or enabling environments for such change. Traditional approaches to study multi-level governance and policy processes, such as Ostrom's (1990) institutional analysis and design framework or advocacy coalition framework, have not typically addressed governance with multiple objectives, and do not traditionally address transitions and futures; scholarship in the transitions literature is also often focused on historical transitions. A few studies are emerging to explore modalities and key levers for future transitions, e.g., in the UK energy grid (Bolton & Foxon, 2015); but applications to the multiscale urban systems are rare. New methods are needed to identify key pathways and actors for change, and the motivations, barriers, and enablers. Key questions include: What are the theories of change that shape how different actors shape transitions toward SUS, including different stakeholders acting across scale? What are the well-being outcomes that stimulate change, and how are they linked to social, environmental, and technological aspects of urban systems change? How do heterogeneous actors interact and influence each other, in different city and country contexts? How does learning occur across similar or different city types, facilitated by governmental and non-governmental organizations, ranging from neighborhood associations to international organizations? Examples of specific projects within this topic area include:

- Pathways analysis for sustainable futures in different cities, city types, and world regions, incorporating multilevel governance.
- Theories on citizen engagement and multi-level governance approaches in different city types and sociotechnical context.

D — ADVANCING COMPARATIVE STUDIES, TYPOLOGY STUDIES, AND SCALABILITY STUDIES TO DEVELOP A GENERALIZABLE SCIENCE OF THEORIES OF CHANGE ACROSS DIVERSE CITY TYPES.

Next-generation SUS science is expected to leverage data, models, and natural experiments occurring across large numbers of cities and urban areas as they evolve in and from different contexts. This provides an avenue both to test hypotheses about SUS theories of change and to generalize these theories across different typologies of cities. In processes that involve growth and evolution, absolute measures e.g., of environmental performance, economic performance or equity, are often problematic because there is no absolute measure of performance or well-being. As a result, comparative analysis becomes key. This involves at once identifying what is common and what is different among cities (as well as neighborhoods and urban systems), and organizing differences in classes or typologies that allow for careful and controlled assessment of divergent performance and of causal effects related to different histories and interventions. In this sense, empirical evidence is needed that is both functional, related to measures of performance or well-being (such as wealth creation, environmental impacts, health) and of size and form (including population, density, infrastructure and other characteristics of the built environment). Environmental, economic, and social data over long time periods and across multiple cities at similar scales are needed to enable such comparative analyses. This will require novel approaches to data creation that can yield comparable evidence across units of analyses, including neighborhoods, cities, metropolitan areas and urban systems and alignment of these measurements with international emerging standards, such as the sustainable development goals (Brelsford et al, 2017). Examples of specific topics include:

- Comparative studies of divergent trajectories of urban growth and decline across cities.
- Typology studies to understand how environmental and social heterogeneities across cities influence sustainability outcomes.
- Comparative studies to assess key heterogeneities in the resilience of cities to natural hazards, including differences in the recovery and adaptability of cities to these events.

E — DEVELOPING THE SCIENCE TO MODEL THE FUTURE OF SUS ACROSS THE THREE PERSPECTIVES.

Modeling the future with social, technological, infrastructural, and environmental change, and consequent impacts on multiple sustainability nexus outcomes is challenging. It is impossible to presage the innovations in energy, transportation, water services, and other sectors that will restructure our current systems and fundamentally change future trajectories and sustainability outcomes. Nonetheless, it is possible to construct scenarios of plausible future technological, environmental, and social conditions, and to project futures on this basis. The science of modeling futures has evolved, particularly with integrated assessment models at global scales that seek to understand the environmental and economic impacts of climate change under baseline and alternative scenarios by combining environmental process models of the climate system with global economic and energy models. However, many challenges remain in developing models of futures that ultimately can be applied to inform actions and policies, including: downscaling models to regional scales, which raises questions of system boundaries and how to account for the openness of cities and regions and multi-scalar interdependencies; and incorporating multiple types of uncertainty, including inherent uncertainty of the systems, incompleteness or misspecification of models, data quality, and data resolution. What are the different approaches to develop such futures' models? How can they best be evaluated and applied to inform actions and policies? How can futures modeling incorporate scaling effects, including path dependency (history) and other contextual issues of cities, and account for the influence of key heterogeneities that influence human decisions and responses at more aggregate (city, region, nation) scales? Addressing these challenges will require the integration of more dynamic representations of growth and development processes into present theory of cities from complex systems, geography and economics and developing context-sensitive models of general dynamics that can help scientists and policy makers assess different sustainability futures. A key goal is to distinguish different futures in terms of actionable variables in the present that can deliver integrated and sustainable urban growth and human development. Examples of specific topics include:

- Modeling future transitions that integrate trends in technologies, infrastructure, and environmental systems of the future with our knowledge of current governance systems.
- Projecting sustainability outcomes under a range of plausible adaptations at household, firm, and community scales to changes in environmental, social, economic, and technological conditions.
- Developing multiscale integrated models of natural, engineered, and social systems that account for the many inherent uncertainties in future environmental, economic, and social conditions.

F — DEVELOPING THE SCIENCE OF KNOWLEDGE CO-PRODUCTION AMONG RESEARCHERS, COMMUNITIES, INDUSTRY GROUPS, PRACTITIONER GROUPS AND GOVERNMENTS AT MULTIPLE LEVELS, LEVERAGING REAL-WORLD EXPERIMENTATION ONGOING IN URBAN AREAS.

It will be necessary to develop new ways of learning from rich experiments ongoing in many cities in the US and across the world. This requires comparing and evaluating various modalities of co-producing science with stakeholders at different scales — in communities, individual cities, and metropolitan areas, across cohorts of cities, and at national and international platforms. How are cities learning from each other? What are the most effective modes for knowledge co-production and exchange (e.g., open science, open data, citizen science, and participatory visioning/planning) and how is effectiveness measured? What are different modalities for knowledge co-production, shared socio-technical pathways visioning, and participatory planning in SUS, and how can we evaluate successful/effective models across a range of contexts? How can discussion of values and ethics be integrated in the co-production of SUS science? Ethical considerations and training are important in translational research to avoid perverse outcomes from knowledge co-production with diverse stakeholders. Examples of projects in this area include:

- Comparing modalities for citizen science in urban systems.
- Studying knowledge co-production strategies at different levels of governance.
- Understanding values and ethics in co-produced SUS science.

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VI. RECOMMENDATIONS FOR DEVELOPING A SUS RESEARCH AGENDA

The AC ERE's SUS subcommittee recommends that the NSF nurture interdisciplinary teams to advance the convergent science of SUS, recognizing:

- Long term research is needed to advance SUS,
- Significant investment in time is needed to build transdisciplinary convergent teams and partnerships with cities and policymakers,
- Projects often end in 4-5 years, when teams are in a rhythm, so mechanisms to extend or support projects for the longer term (i.e., beyond 4-5 years) can help effective teams achieve results,
- At the same time, smaller projects, including those led by a single investigator with requisite interdisciplinary expertise, can also be powerful.

Hence, the subcommittee recommends a two-pronged approach that supports: a) large multi-investigator cross-directorate projects that integrate most of the key elements of a convergent SUS science, similar in scale and time frame to NSF Engineering Research Centers, and b) smaller projects that enable focused exploration within the key elements. Both are described next.

LARGE CROSS-DIRECTORATE NEXT-GENERATION SUS PROJECTS

We recommend that all large inter-disciplinary SUS projects address a majority of the key elements of SUS science across two or more of the three perspectives described in Section IV. See Table 1. These large SUS projects must address multiple dimensions of human and planetary well-being, integrating economy, equity, environment, health, and risks. They must address transitions and connect fundamental science questions to action. These projects are envisioned to be of 4 to 10 years in duration, and may be applied to address SUS elements in individual cities and metropolitan regions, examine cohorts of cities, or to evaluate the collective impact of urban systems on SUS outcomes. Bridging between two or more of these perspectives is expected to be very valuable.

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TABLE 1: CONCEPTUALIZATION OF LARGE CROSS-DIRECTORATE NEXT-GENERATION SUS PROJECTS IN A LONG-TERM CONVERGENCE RESEARCH AGENDA

KEY ELEMENTS OF CONVERGENCE SUS SCIENCE	APPLICATION TO THREE PERSPECTIVES
A. Developing new data and methods to understand current drivers and interactions among natural, human-built, and social systems in urban areas as they impact multiple sustainability outcomes across scales. B. Developing the science to assess the sustainability outcomes nexus in urban systems, i.e., the co-benefits and trade-offs among multiple human and planetary well-being outcomes across spatial (local to global) and temporal scales. C. Understanding the levers for change in diverse urban systems ("theories of change"), combining: 1. A focus on integrative design, technology innovation, and sociotechnical transitions. 2. A focus on multi-level actors and governance. D. Advancing comparative studies, typology studies, and scalability studies to develop a generalizable science of theories of change across diverse city types. E. Developing the science to model the future of SUS across the three perspectives. F. Developing the science of knowledge co-production among researchers, communities, industry groups, practitioner groups and governments at multiple levels, leveraging real-world experimentation ongoing in urban areas.	i. Individual cities and metropolitan regions from a multiscale systems perspective. or ii. Multiple cities and communities. Comparative or cohort studies of diverse city/urban typologies, or studies of networks of cities. or iii. Assessing the collective impacts of all urban areas in a nation, region, or the world.

Examples of thematic topics that illustrate the large cross-directorate model presented above:

- What is the role of distributed infrastructure and disruptive technologies in achieving multiple local and global sustainability outcomes?
- What are pathways for developing secure and sustainable cities?
- How can global urban systems contribute to deep de-carbonization?
- What are key urban-rural linkages in pursuing sustainability, equity and well-being goals?
- What is the future of urban systems and their sustainability implications in the new shared economy?

The proposed cross-directorate program format for next-generation SUS science research efforts fits well with NSF's convergence paradigm focusing on the merging of ideas, approaches, and technologies from widely diverse fields of knowledge to stimulate innovation and discovery. Examples of thematic topics that demonstrate integration of the key elements are noted in Table 1.

SMALLER PROJECTS IN AN SUS RESEARCH AGENDA THAT ENABLE FOCUSED EXPLORATION WITHIN THE KEY ELEMENTS

Table 2 describes smaller projects that enable deeper dives into addressing knowledge or methodological gaps within the key elements of SUS noted in Table 1. These smaller focus areas may be led by one or two directorates, with projects led by fewer investigators (1 to 3) and smaller budgets. These projects could address key knowledge gaps by specifying a narrow focus within the overarching priority topics (A-F) noted above. Examples of topic areas are noted below.

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TABLE 2: CONCEPTUALIZATION OF SMALLER PROJECTS IN AN SUS RESEARCH AGENDA THAT ENABLE FOCUSED EXPLORATION WITHIN THE KEY ELEMENTS

KEY ELEMENTS OF SUS SCIENCE	EXAMPLES OF NARROW FOCUS TOPICS WITHIN EACH KEY ELEMENT
A. Developing new data and methods to understand current drivers and interactions among natural, human-built, and social systems in urban areas as they impact multiple sustainability outcomes across scales.	• Specific data science advancement for study of SUS • Development of novel cyberinfrastructure for urban system studies
B. Developing the science to assess the sustainability outcomes nexus in urban systems, i.e., the co-benefits and trade-offs among multiple human and planetary well-being outcomes across spatial (local to global) and temporal scales.	• Focused exploration of the science of measuring subjective well-being in urban systems • Method development to measure and model urban to planetary linkages • Methods to study economy, environment, and well-being across the urban-rural continuum
C. Understanding the levers for change in diverse urban systems ("theories of change"), combining : 1. A focus on integrative design, technology innovation, and sociotechnical transitions. 2. A focus on multi-level actors and governance.	• Exploration of the nexus of ecological and engineering design • Evaluating infrastructure / technology transitions in select sectors • Deeper exploration of specific frameworks representing multi-level governance of SUS • Deeper exploration of theories describing individual behavior change in the context of human technological interface
D. Advancing comparative studies, typology studies, and scalability studies to develop a generalizable science of theories of change across diverse city types.	• Advancing the science of identifying urban typologies • Approaches for scaling up from single urban areas to larger scales
E. Developing the science to model the future of SUS across the three perspectives.	• Comparative study of different modeling approaches
F. Developing the science of knowledge co-production among researchers, communities, industry groups, practitioner groups and governments at multiple levels, leveraging real-world experimentation ongoing in urban areas.	• Developing the science of conducting and evaluating citizen science in cities • Science of engaging and evaluating knowledge co-production networks in urban systems • Focused studies of ethics in knowledge co-production networks

REFERENCES

Advisory Committee for Environmental Research and Education (AC ERE). (2015). *America's Future: Environmental Research and Education for a Thriving Century*. A Report by the NSF Advisory Committee for Environmental Research and Education. Retrieved from https://www.nsf.gov/ere/ereweb/ac-ere/ac-ere_thriving_century.pdf

Bettencourt, L., Lobo, J., Helbing, D., Kühnert, C., and G.B. West. (2007). Growth, innovation, scaling, and the pace of life in cities. *Proceedings of the National Academy of Sciences*, 104(17), 7301-7306.

Bettencourt, L., & G. West. (2010). A unified theory of urban living. *Nature*, 467(2010), 912-913.

Bolton, R., & T.J. Foxon. (2015). Infrastructure transformation as a socio-technical process — Implications for the governance of energy distribution networks in the UK. *Technological Forecasting and Social Change*, 90(2015), 538-550.

Brandt, P., Ernst, A., Gralla, F., Luederitz, C., Lang, D.J., Newig, J., Reinert, F., Abson, D.J., H Wehrd. (2013). A review of transdisciplinary research in sustainability science. *Ecological Economics,* 92(1), 1-15.

Brelsford, C., Lobo, J., Hand, J., & L.M.A. Bettencourt. (2017). Heterogeneity and scale of sustainable development in cities. *Proceedings of the National Academy of Sciences*, 114(34), 8963-8968.

D'Amour, C.B., Reitsma, F., Baiocchi, G., Barthel, S., Guneralp, B., Erb, C.H., Haberl, H., Creutzig, F., & K. Seto. (2017). Future urban land expansion and implications for global croplands. Proceedings of the National Academy of Sciences, 114(34), 8939-8944.

Grant, U. (2010). *Spatial inequality and urban poverty traps*. Overseas Development Institute and Chronic Poverty Research Center. Retrieved from https://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/5502.pdf

Gray, B. (2008). Enhancing Transdisciplinary Research through Collaborative Leadership. *American Journal of Preventative Medicine*, 35(2), S124-S132.

Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., & J.M. Briggs. (2008). Global Change and the Ecology of Cities. *Science*. 319(5864), 756-760.

Institute for Health Metrics and Evaluation (IHME). (2017). GBD Results Tool. University of Washington. Accessed December 2017. http://ghdx.healthdata.org/gbd-results-tool

McDonald, R., Weber, K., Padowski, J., Flörke, M., Schneider, C., Green, P.A., Gleeson, T., Eckman, S., Lehner, B., Balk, D., Boucher, T., Grill, G., & Montgomery, M. (2014). Water on an urban planet: Urbanization and the reach of urban water infrastructure. *Global Environmental Change*, 27, 96-105.

MacPhearson, T., Pickett, S.T.A., Grimm, N.B., Niemelä, J., Alberti, M., Elmqvist, T., Weber, C., Haase, D., Breuste, J., & S. Qureshi. (2016). Advancing Urban Ecology toward a Science of Cities. *BioScience*, 66(3), 198-212.

McKinsey Global Institute. (2011). *Urban World: Mapping the economic power of cities*. Retrieved from https://www.mckinsey.com/global-themes/urbanization/urban-world-mapping-the-economic-power-of-cities

National Academies of Sciences, Engineering, and Medicine (NASEM). (2016). *Pathways to Urban Sustainability: Challenges and Opportunities*. Washington, DC: The National Academies Press.

National Research Council (NRC). (2014). *Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond*. Washington, DC: The National Academies Press.

National Science Foundation (NSF). (n.d.) "Characteristics of Convergence Projects," U.S. National Science Foundation Website. Accessed October 2017. https://www.nsf.gov/od/oia/convergence/characteristics.jsp

Ostrom, E. (1990). *Governing the commons: the evolution of collective action*. Cambridge: Cambridge University Press.

Pataki, D.E. (2015). Grand challenges in urban ecology. *Frontiers in Ecology and Evolution*, 3(57).

Ramaswami, A., Russell, A.G., Culligan, P.J., Sharma, K.R., and E. Kumar. (2016). "Meta-principles for developing smart, sustainable, and healthy cities," *Science*. 352(6288), 940-943.

Seto, K.C., Golden, J.S., Alberti, M., & B.L. Turner. (2017). Sustainability in an urbanizing planet. *Proceedings of the National Academy of Sciences,* 114(34), 8935-8938.

Seto K.C., S. Dhakal, A. Bigio, H. Blanco, G.C. Delgado, D. Dewar, L. Huang, A. Inaba, A. Kansal, S. Lwasa, J.E. McMahon, D.B. Müller, J. Murakami, H. Nagendra, and A. Ramaswami. (2014). "Human Settlements, Infrastructure and Spatial Planning." In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Toomey, A.H., Markusson, N., Adams, E., and B. Brockett. (2015). *Inter- and Trans-disciplinary Research: A Critical Perspective.* Global Sustainable Development Report Brief 2015. Retrieved from https://sustainabledevelopment.un.org/content/documents/612558-Inter-%20and%20Trans-disciplinary%20Research%20-%20A%20Critical%20Perspective.pdf

United Nations Development Programme. (2010). *Divergences and Convergences in Human Development. UNDP Human Development Report.* Retrieved from http://hdr.undp.org/en/content/divergences-and-convergences-human-development

United Nations Environment Programme. (2013). *City Level Decoupling: Urban Resource Flows and the Governance of Infrastructure Transitions*. Retrieved from http://wedocs.unep.org/handle/20.500.11822/8488

United Nations Habitat (2016). *World Cities Report 2016*. Retrieved from http://wcr.unhabitat.org

United Nations Habitat. (2017). *New Urban Agenda*. Retrieved from http://habitat3.org/wp-content/uploads/NUA-English.pdf

Vasbinder, J.W., Andersson, B., Maarten Boasson, W.B.A, de Boer, R., Changeux, J.P., Domingo, E., Eigen, M., Fersht, A., Frenkel, D., Rees, M., Groen, T., Huber, R., Hunt, T., Holland, J., May, R., Norrby, E., Nijkamp, P., Lehn, J.M., Rabbinge, R., Scheffer, M., Schuster, P., Serageldin, I., Stuip, J., de Vries, J., van Vierssen, W., & R. Willems. (2010). Transdisciplinary EU science institute needs funds urgently. *Nature,* 463(876).

Wigginton, N.S., Fahrenkamp-Upper, J., Wible, B., & D. Malakoff. (2016). Cities are the Future. *Science*, 352(6288), 904-905.

Woolf, S. (2008). The Meaning of Translational Research and Why It Matters. *Journal of the American Medical Association*, 299(2): 211-213.

World Bank. (2009a). *Intra-Urban Spatial Inequality: Cities as "Urban Regions."* Retrieved from https://openknowledge.worldbank.org/handle/10986/9144

World Bank. (2009b). Systems of Cities: *Harnessing urbanization for growth and poverty alleviation*. Retrieved from http://documents.worldbank.org/curated/en/877591468163481401/pdf/518600WP0Urban10Box342051B01PUBLIC1.pdf

World Bank (2010). *Cities and Climate Change: An Urgent Agenda.* Retrieved from http://siteresources.worldbank.org/INTUWM/Resources/340232-1205330656272/CitiesandClimateChange.pdf

World Bank. (2011). From Farm to Firm: *Rural-Urban Transitions in Developing Countries.* Retrieved from https://openknowledge.worldbank.org/bitstream/handle/10986/2307/622590PUB0farm0476B0extop0id0186230.pdf;sequence=1

World Bank. (2016). *Global Platform for Sustainable Cities*. Retrieved from http://pubdocs.worldbank.org/en/850961461622541329/GPSC-booklet.pdf

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