PERSPECTIVE OPEN



A convergence research perspective on graduate education for sustainable urban systems science

José Lobo no¹^{1∞}, Marina Alberti², Melissa Allen-Dumas no³, Luís M. A. Bettencourt no⁴, Anni Beukes no⁴, Luís A. Bojórquez Tapia⁵, Wei-Qiang Chen⁶, Anne Dodge⁴, Zachary Neal⁷, Anna Perreira⁶, Deirdre Pfeiffer⁶, Aromar Revi¹⁰, Debra Roberts no¹¹, Céline Rozenblat no¹², Shade Shutters no¹³, Michel E. Smith no¹⁴, Eleanor Stokes¹⁵, Deborah Strumsky¹⁶ and Jianguo Wu no¹²

Sustainable urban systems (SUS) science is a new science integrating work across established and emerging disciplines, using diverse methods, and addressing issues at local, regional, national, and global scales. Advancing SUS requires the next generation of scholars and practitioners to excel at synthesis across disciplines and possess the skills to innovate in the realms of research, policy, and stakeholder engagement. We outline key tenets of graduate education in SUS, informed by historical and global perspectives. The sketch is an invitation to discuss how graduates in SUS should be trained to engage with the challenges and opportunities presented by continuing urbanization.

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INTRODUCTION

Sustainability science as a distinct discipline is barely two decades old^{1,2}. A recent assessment of the field identified six capacities that sustainability research must display: measuring sustainable development, promoting equity, understanding adaptation, informing transformations, linking knowledge with action, and facilitating governance³. Although this framework offers a guide to the field's further development, we believe it insufficiently emphasizes that the challenge of sustainability is an urban challenge, and therefore that sustainability science has significant overlap with the emerging field of urban science⁴⁻⁶. Both the National Academies of Science and the National Science Foundation of the United States have called for the development of a new sustainable urban systems (SUS) science (also referred to as urban sustainability science). SUS reflects the need to understand the fundamental processes underpinning urbanization, so that urbanization can continue to be both a driver of socioeconomic progress and a catalyst for the global transition towards sustainable development and a contributor towards climate change resilience^{7,8}. The arrival of a new science requires new training to prepare the next generation of scholars and practitioners who will advance the construction and implementation of SUS science.

A recent report by the National Academies of Sciences, Engineering and Medicine of the United States finds that there is limited agreement among established sustainability science degree programs on essential competencies, capacities, and content areas⁹. The absence of a pedagogical consensus is even more pronounced in the newer fields of urban science and urban sustainability science. We propose that the continued

development of urban sustainability science will require the training of new generations of urban sustainability scientists, and that both the content and manner of training will be different from existing degree programs. Here, we offer a preliminary outline as an invitation to a vigorous discussion of the training of future academics, researchers, and practitioners of urban sustainability science.

SUSTAINABILITY SCIENCE AND URBAN SCIENCE

Urban areas agglomerate people and socioeconomic activities (already nearly 60% of the planet's inhabitants live in cities) and most of the human activities which affect the environment—like agriculture or resource extractions—are linked to cities, for example in terms of consumption, technology development, and control. As a result, many of the challenges and opportunities of sustainable development are inherently urban in nature. To be clear, this does not imply that challenges to sustainability only occur in cities; indeed, many challenges to sustainability will continue to occur in non-urbanized locations even as the world becomes a planet of cities. Instead, we argue that sustainability is inherently urban in nature because (1) challenges to sustainability will increasingly be the result of demands growing cities place on the environment, and (2) the people and institutions making those demands and with the agency to mitigate their environmental harms are based in cities. Confronting the increasingly urban locus of sustainability will require merging the goals and tools of sustainability science and urban science. It would go beyond the scope of this comment to fully articulate the theories and

¹School of Sustainability, College of Global Futures, Arizona State University, Tempe, AZ, USA. ²Urban Ecology Research Laboratory, Department of Urban Design and Planning, University of Washington, Seattle, WA, USA. ³Climate Change Science Institute and Urban Dynamics Institute, Oak Ridge National Laboratory, Oak Ridge, TN, USA. ⁴Mansueto Institute for Urban Innovation, University of Chicago, Chicago, IL, USA. ⁵Laboratorio Nacional de Ciencias de la Sostenibilidad, Instituto de Ecología, Universidad Nacional Autónoma de México, México, D.F, México. ⁶Institute of Urban Environment, Chinese Academy of Sciences, Xiamen, People's Republic of China. ⁷Psychology Department, Michigan State University, East Lansing, MI, USA. ⁸Department of Architecture, Faculty of Engineering & Technology, University of Guyana, Georgetown, Guyana. ⁹School of Geographical Science and Urban Planning, Arizona State University, Tempe, AZ, USA. ¹⁰Indian Institute for Human Settlements, Bangalore, India. ¹¹Sustainability and Resilient City Initiatives Unit, eThekwini Municipality, Durban; School of Life Sciences, University of KwaZulu-Natal, Durban, Republic of South Africa. ¹²Institute of Geography and Sustainability, Faculty of Geoscience and Environment, University of Lausanne, Lausanne, Switzerland. ¹³School of Complex Adaptive Systems, College of Global Futures, Arizona State University, Tempe, AZ, USA. ¹⁴School of Human Evolution and Social Change, Arizona State University, Tempe, AZ, USA. ¹⁵Universities Space Research Association, Columbia, MD, USA. ¹⁶Cutler Institute, Muskie School of Public Service, University of Southern Maine, Portland, ME, USA. ¹⁷School of Life Sciences and School of Sustainability, Arizona State University, Tempe, AZ, USA. ¹⁸Chool of Public Service, University of Southern Maine, Portland, ME, USA. ¹⁷School of Life Sciences and School of Sustainability, Arizona State University, Tempe, AZ, USA. ¹⁸Chool of Public Service, University of Southern Maine, Portland, ME, USA. ¹





methods of such a science, so here we briefly highlight how the intersection represents something new.

Urban areas concentrate the consumption of natural resources by humans. Several human-environmental or social-ecological systems analytical frameworks highlight the governance and use of natural resources to sustain social systems, and the social, economic, and political settings in which resource systems are embedded. The coupled human and natural systems perspective emphasizes the patterns and processes that link human and natural systems ¹⁰ while the social-ecological systems perspective emphasizes the social and ecological interactions and links in attempting to understand sustainability processes and outcomes¹¹. Sustainable urban systems science engages with the interaction between social and natural environments by studying how the social interactions embedded in the physical space of cities affects and is affected by natural environments 12,7 Although for many the essence of urban life is a separation between the social and the natural, in reality the functioning of cities makes such a boundary illusory 14-16.

The urban environments that humans have created and continue to create are multifaceted and involve ecological, social, economic, cultural, and physical processes through which energy, material goods and information are used and distributed 17. Urban science represents a convergence among diverse disciplines including urban economics, economic geography, regional science, urban sociology, urban planning, urban ecology, anthropology, archaeology, quantitative history, transportation engineering, network science, sustainability science-, and complexity science—seeking to integrate accumulated insights and generate new ones. The field cannot be represented by any single academic unit or professional school; it is, by construction, an interdisciplinary field, involving work across traditionally defined disciplines, using diverse methods, and addressing multiple scales from local issues to global challenges 18-25. At the same time, urban science offers a framework that is critical to accelerating understanding of cities to better meet challenges and respond to opportunities.

Urban sustainability science seeks to study urbanization and urban systems resulting from fundamental socioeconomic processes embedded in natural environments and built spaces. Like any scientific field, USS is delineated by the questions it asks. While not exhaustive, the following list illustrates the types of questions animating urban sustainability science and suggests elements necessary in the training of its future practitioners:

- How can we systematically better understand the functioning of urban areas as interacting social, natural, and built environments shaping multiple sustainability outcomes across temporal and spatial scales?
- How do changes in urban systems affect human well-being, equity and the distribution of benefits and costs across urban and non-urban communities, and planetary boundaries?
- How can the processes of innovation and growth unleashed by urban environments lead to more equitable and environmentally positive development?
- How does the interplay between technological change and fundamental social processes affect the sustainability of urban systems?
- How do we measure and compare the sustainability of urban and non-urban social systems?
- How can urbanization continue to be a principal driver of socioeconomic development without causing irreparable damage to human well-being and the natural environment?

To answer these types of questions and to foster the coproduction of knowledge among researchers and communities, the next generation of scholars and practitioners must be trained in a new way. Rather than debating what the best institutional and organizational settings for this training—whether it requires new graduate programs or can be accommodated within existing schools and departments—we address the content of a new educational pathway.

NEW TRAINING NEEDED FOR URBAN SUSTAINABILITY SCIENCE

In this section, we highlight some core features that a flexible graduate training template in urban sustainability science should include. The design draws from discussions held at an NSFsponsored conference held at Arizona State University (in September 2019) and subsequently enriched with comments from consultations with experts who did not attend the conference²⁶. The proposed educational pathway incorporates elements already implemented in some graduate training programs focused specifically on sustainability science (e.g., the School of Sustainability at Arizona State University, School for Environment and Sustainability at the University of Michigan), urban science (e.g., the Mansueto Institute for Urban Innovation at the University of Chicago, the Centre for Advanced Spatial Analysis (CASA) at University College London), urban informatics (New York University's Center for Urban Science and Progress (CUSP) and urban practice (the Indian Institute for Human Settlements). Training in urban sustainability science should allow students to choose among and utilize standard methods, analytical frameworks and data but also equip them to use and develop new models for studying the interactions between natural and social systems which occur in urban settings.

Graduate students in urban sustainability science ought to contribute, in a variety of ways, to an improved understanding of the interdependencies, trade-offs and consequences for human and environmental well-being of different urban development pathways. Those seeking to advance urban sustainability science—through research and practice—need to be able to cross organizational, institutional, and scientific boundaries.

CONVERGENCE RESEARCH

It is now widely accepted that a distinguishing characteristic of multidisciplinarity and transdisciplinarity is the production of knowledge by collaborations among scientists from different fields and between scientists and societal actors. We do not wish to participate in the definitional conflicts as to what is multidisciplinary or transdisciplinary research. Instead, we echo the notion of convergence research advanced by the National Science Foundation of the USA (www.nsf.gov/od/oia/convergence/index. jsp): "Convergence research is a means of solving vexing research problems, in particular, complex problems focusing on societal needs. It entails integrating knowledge, methods, and expertise from different disciplines and forming novel frameworks to catalyze scientific discovery and innovation. Convergence research is related to other forms of research that span disciplinestransdisciplinarity, interdisciplinarity, and multidisciplinarity." Convergence research is driven by problems and questions of which are scientifically interesting and societally pressing and it is characterized by deep integration across academic disciplines and scientific fields.

Research on urban sustainability focuses on answering questions which cut across disciplinary barriers, rather than applying a specific preset of tools. Graduate training must prepare students to become effective members of teams which intentionally intermingle insights, theories, methods, data, and research traditions. To be clear, urban sustainability science does not displace or render obsolete the many disciplines which study cities and urban phenomena. But it is premised on there being aspects of urban life and dynamics-, which necessitate the integration and interplay of analytical perspectives. This goes beyond assembling research teams which embody different disciplinary approaches and instead proposes thinking about

cities as multidimensional entities generated by several interacting processes. Facilitating this type of deep disciplinary integration might be achieved by housing a sustainable urban systems science program in an institutional unit that is not associated with a single discipline and relying on faculty who already view themselves as multidisciplinary to deliver instruction. Central pedagogical challenges include pluralistic inclusion of different theoretical traditions and translation across discipline-specific terminologies. However, such multidisciplinary faculty are well-positioned to overcome these types of challenges.

DEEPLY SOCIAL

Urban sustainability involves many dimensions, but the social, cultural, and political aspects of cities make them a unique manifestation of human sociality across scales. For example, economics has shown that the benefit and costs of concentrated populations are captured through agglomeration effects²⁷. Similarly, urban sociology has demonstrated that cities can be viewed as networked systems (human ecologies) with components connected at both local and global scales²⁸, while the distinct psychological impacts of urban life have been noted for well over 100 years^{29,30}. Academic training in urban sustainability must reflect the insight that cities are social and ecological systems, but the social aspects of cities are what connect urbanization across time and geographies. Yet the fundamental but complex social dimensions of urban sustainability are often ignored in both academia and in global forums, and so training should also focus on politics and underlying power structures. Academic training in urban sustainability must put people and the "social" at its center. Urban sustainability science builds upon the accumulated insights of so many disciplines that choices must be made regarding the aspects of cities and urbanization that are truly essential for urban sustainability. An urban sustainability scientist should therefore be conversant with the principal findings of, for example, urban economics, economic geography, and urban political economy.

WHAT IS URBAN?

The seemingly straightforward query of what constitutes a city turns out to be guite challenging to answer in practice. The field of Urban Studies has long grappled with the modifiable areal unit problem whereby results from investigating-specific spatial units (metropolitan areas, for example) can be artifacts of how spatial boundaries are delineated³¹. Operationalizing a view of cities as settings for social interactions, which is to say assembling a set of spatial units of analysis which capture the relevant social aspects of settlements, requires choices about the use of existing data, the assignation of data to locations and periods, and the delineation of the spatial boundaries of inhabited areas. What is considered urban in practice varies around the world also. In developed economies, cities evoke and entail publicly provided infrastructure, formal governance, well-defined property rights, clear separation between workplaces and places of residence, and regulated labor markets. In contrast, cities in the global South are often characterized by the lack of public infrastructure (running water, electricity, roads), and informality (of governance, housing, and employment) is the norm. This means that training in urban sustainability will need to equip students to recognize and cultivate sustainability in both formal and informal contexts and better appreciate these stark differences as parts of an integrated set of urban phenomena. The duality, or more accurately, the spectrum, of formal and informal represents an intellectual and humanitarian challenge for SUS, as UN Habitat indicates that 3 billion people could be living in informal settlements by 2050. To the extent that urban science highlights social interactions, and not specific types of built environment or urban forms, as definitional of urban agglomerations, training in urban sustainability science needs to span the diverse realities of the urban.

SYSTEMS AND COMPLEXITY

Individual cities are themselves systems of systems: individuals coordinated by social customs and practices, political institutions coordinated by influential leaders, private enterprises coordinated by market forces, and built and natural environments shaped by planners. Each of these systems interacts in complex ways with the others to generate urban life that unfolds simultaneously in physical places and social spaces. Individual cities also constitute networked regional, national, and international urban systems where the functioning of any one city depends on the flow of people, goods, and information among cities of that system. A recent report sponsored by the IPCC highlights the need to take a systems approach to devise effective strategies for mitigating and adapting to the effects of climate change on cities and urban systems³². The same report characterizes cities as "open, complex, self-organizing, adaptive and evolving formations that are embedded in broader social, ecological, economic, technical, institutional and governing structures." (p.4), a portrayal which we fully agree with. Given the inherent complexity of such networked systems, training in urban sustainability should encompass key insights from systems, complexity, ecology, and network science^{5,33–35}.

Understanding cities as instances of networked and complex adaptive systems will in turn give students a broad understanding of the nonlinearity between drivers and impacts, natural and social tipping points, feedback loops, and transitions more generally (cite IUS). Such understanding is crucial for designing, or at least influencing, interventions intended to effect shifts at a system level. A systems-level perspective can also help make bridges between disciplines and mitigate the siloing of much urban research.

HISTORICAL PERSPECTIVE

As sustainability science tends to be confined in its temporal scope, Clark and Harley¹ have recently called for the field to focus more on long-term and large-scale patterns. A general framework regarding the social processes behind urbanization needs to account for empirical regularities that are common to both contemporary cities and past settlements known through archaeology and history. Only by adopting an explicitly historical perspective can such enduring patterns be identified, and can significant deviations or exceptions be noted³⁵. By connecting ancient and recent history of human settlements during episodes of formation, persistence, and collapse with contemporary urbanization, students can learn how cities can adapt and change in response to the enduring challenges posed by sustaining urban development. As such, the focus must also expand beyond western urbanization, which is only one way in which recent urbanization has unfolded, to include other urbanization experiences that persisted longer and in different cultural milieus and natural environments.

GLOBAL IN SCOPE, ATTENTIVE TO LOCAL CONTEXT

In developed countries, urbanization is currently stable, with upwards of 85% of national populations residing in urban environments. Urban growth is proceeding almost entirely in societies in the Global South, and at unprecedented scales, scopes, and rates. An awareness of the commonalities across urbanization experiences and of the processes and interactions occurring at a global scale, which affect urban systems everywhere needs to be balanced by a respect for local context, availability of resources, ecological limits, conceptualizations of equity, and culturally



driven choices. Urbanization requires local, place-based solutions and actions that link-up global-scale insights on urbanization. Scholars, scientists, and practitioners must be trained in solutions and implementation-oriented thinking and in inclusive, participatory and co-production approaches involving citizens, communities, local governments, businesses, and knowledge institutions.

DATA LITERACY

Students should be prepared for situations where officially recorded data are sparse or messy and where longitudinal data sets do not (yet) exist. They must have the skills to use not only data from standard sources, such as national statistical bureaus, but also remote sensing data, satellite data, mapping tools, and data collected by urban residents and communities themselves (e.g., citizen science initiatives). Technologically and organizationally, urban communities are now able to collect copious and varied data about themselves which they can use to tell powerful stories about their needs and aspirations. These stories can in turn inform policy-making at local, city, national, and international levels. There are no more technological and organizational excuses for urban solutions not to be informed strongly by the actual needs of and insights from the communities they intend to serve^{36–38}. Thus, like nearly every other scientific discipline, urban sustainability science students will face demands to be trained in data science skills such as statistical software packages and mapping tools.

FUTURES THINKING

Rapid urbanization and environmental change require that students are trained in future thinking and methods of strategic foresight including theory, simulation modeling, and scenario planning³⁹. Achieving urban sustainability implies that urban scientists and planners collaborate in designing solutions that account for uncertainty, anticipating how robust are alternative strategies under plausible future conditions, and identifying early warning signals to detect critical trends. The next generation of urban scholars and practitioners should be able to see beyond the near future and expand to incorporate uncertainty in seeking scientific answers and in decision-making. Simulation modeling and scenario planning together offer a systematic and powerful approach to bring the future into present decisions by challenging assumptions and expanding old mindsets⁴⁰.

RESEARCH AND ACTION

It is anticipated that not everyone who receives advanced training in urban sustainability science will aspire to become an academic or researcher; some urban sustainability scientists will work in national laboratories, think-tanks, municipal governments, businesses, and policy-making organizations, or work with communities and civic organizations directly effecting change. There is a need to train the people who can span these two tracks—the bridge builders between the worlds of academia and practice. They are increasingly in demand and often occupy sustainability related positions in governmental, non-governmental and business organizations. To train these professionals, graduate training in sustainable urban systems must develop academic tracks for students who will become practitioners. For the practitioner track, the ability to engage with a variety of stakeholders (especially neighborhood communities and small-scale enterprises), to participate in community data collection efforts, bridge the natural and social sciences, and to formulate communityresponsive research questions will be essential skills. Training must also encompass comparative research, applied and practiceoriented, undertaken through transdisciplinary teams that combine academic and nonacademic stakeholder groups. Projectbased learning, experiential learning, and longer-term projects that immerse students in practitioner organizations will prepare students to address complex urban sustainability challenges. Curiosity, a willingness to learn and rectify, a disposition to listen attentively, good facilitation skills, the ability to synthesize information from very diverse fields, the ability to communicate complex information simply; flexibility, patience, intellectual humility—these are traits that will serve urban sustainability science practitioners well.

ANTICIPATED OBSTACLES AND RESPONSES

The training path outlined above represents an ambitious agenda. and a training program for future urban sustainability scientists may seem to imply that what is needed are academic superheroes rather than enthusiastic, curious, creative, and diligent students. In fact, we propose training that will create a cohort that shares a worldview along with a discrete set of skills, and then diversifies internally with individual specializations. We recognize the danger of broad but shallow training at the expense of adequate training in any of the various strands of SUS. To remedy this, the training will ask students to choose specific educational paths—building upon their academic backgrounds, career interests, life experiences, cognitive aptitudes, geographic locations, and social and political commitments—through which they will acquire a combination of the skills, training, and knowledge described above. This will create a cohort of researchers and practitioners among whom the new training will be distributed and who, together, will advance the development of urban sustainability science.

Student demand for scientific and civically oriented urban sustainability training is strong and growing; nevertheless, we acknowledge that the conferring of untested degrees creates risks for graduates, such as a lower ability to secure employment, uncertainty regarding potential wages, and an undefined career path. These risks should be weighed when designing new curricula and might be offset by required practical courses or marketable certifications/minors. Also, practitioner tracks within the training offer a substantive pathway to employment, particularly with the integration of professional internships and placements.

At the level of the individual universities, schools, departments, and programs engaged with urban studies and sustainability science will need to break down the proverbial academic silos that hinder the multidisciplinary dialogues everyone endorses but which nevertheless occur all too infrequently. However, a recent report by the National Academy of Sciences of the USA is a pertinent example of the type of discussion needed to strengthen sustainability science programs and curricula⁹. University-based undergraduate and graduate educational programs and their leaders will need to put aside competitive urges to proclaim themselves the first, the best, and the most unique to forge a truly global and collaborative training effort.

A CALL FOR INSTITUTIONAL COLLABORATION AND COOPERATION

No academic program or institution needs, or even should aspire, to provide training programs encompassing all the key competencies considered here. A division of labor will surely take place through which existing and new programs in sustainability science, urban science and urban sustainability science contribute to training the next generation of urban sustainability science researchers and practitioners. Active dialogues among the various educational, research and praxis organizations and institutions engaged in urban sustainability science, throughout the world, will be necessary to combine their strengths, foster collaborations, and work toward an integrated urban sustainability science training model.

Despite the inevitable obstacles of institutional and disciplinary inertia, we feel that the twin forces of urbanization and climate change call for a rapid institutional response, from within and across our own disciplines and areas of practice. Our proposed training-focused, collaborative effort will orient us and our students toward the future, creating a new training pathway that synthesizes knowledge across sectors and elevates community engagement to the level of science within the academy. We ask for the commitment of scholars, practitioners, and, crucially, the highest levels of leadership at educational and research institutions, to move forward with coordinated and cooperative efforts, informed by the recommendations presented here, for the training of urban sustainability science scholars and practitioners.

DATA AVAILABILITY

No data were used or generated in the preparation of this manuscript.

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AUTHOR CONTRIBUTION

J.L. coordinated the production of the manuscript. J.L., Z.N., and S.S. wrote the first version of the manuscript with contributions from all authors and produced the revised version. M.A., M.A.D., L.B., A.B., L.B.T., W.C., A.D., A.P., D.P., A.R., D.R., C.R., M.S., E.S., D.S., and J.W. reviewed, commented, and contributed to the writing of the manuscript.

COMPETING INTERESTS

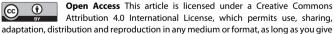
The authors declare no competing interests.

ADDITIONAL INFORMATION

Correspondence and requests for materials should be addressed to José. Lobo.

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