A Social-Ecological-Infrastructural Systems Framework for Interdisciplinary Study of Sustainable City Systems

An Integrative Curriculum Across Seven Major Disciplines

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Summary

Cities are embedded within larger-scale engineered infrastructures (e.g., electric power, water supply, and transportation networks) that convey natural resources over large distances for use by people in cities. The sustainability of city systems therefore depends upon complex, cross-scale interactions between the natural system, the transboundary engineered infrastructures, and the multiple social actors and institutions that govern these infrastructures. These elements, we argue, are best studied in an integrated manner using a novel social-ecological-infrastructural systems (SEIS) framework. In the biophysical subsystem, the SEIS framework integrates urban metabolism with life cycle assessment to articulate transboundary infrastructure supply chain water, energy, and greenhouse gas (GHG) emission footprints of cities. These infrastructure footprints make visible multiple resources (water, energy, materials) used directly or indirectly (embodied) to support human activities in cities. They inform cross-scale and cross-infrastructure sector strategies for mitigating environmental pollution, public health risks and supply chain risks posed to cities. In the social subsystem, multiple theories drawn from the social sciences explore interactions between three actor categories—individual resource users, infrastructure designers and operators, and policy actors—who interact with each other and with infrastructures to shape cities toward sustainability outcomes. Linking of the two subsystems occurs by integrating concepts, theories, laws, and models across environmental sciences/climatology, infrastructure engineering, industrial ecology, architecture, urban planning, behavioral sciences, public health, and public affairs. Such integration identifies high-impact leverage points in the urban SEIS. An interdisciplinary SEIS-based curriculum on sustainable cities is described and evaluated for its efficacy in promoting systems thinking and interdisciplinary vocabulary development, both of which are measures of effective frameworks.

Infrastructures and Sustainable Cities

A majority of the world's people now live in cities (UN 2008) that are interdependently embedded in larger-scale coupled social–biophysical systems. In the biophysical system, cities are embedded within large-scale transboundary electricity, water, and transportation infrastructures that draw vast quantities of natural resources (directly or indirectly) for use in

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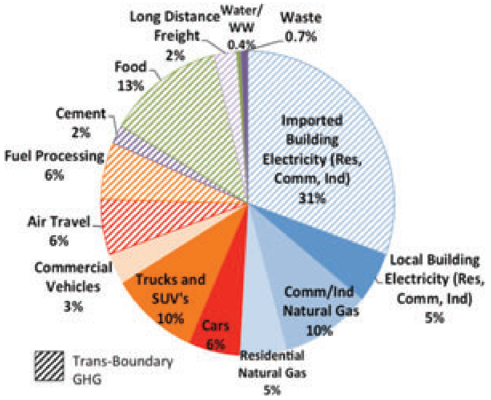


Figure 1 An infrastructure supply chain greenhouse gas (GHG) emissions footprint for Denver, Colorado, USA, includes direct GHG emissions within city boundaries (solid colors) as well as embodied GHG emissions (hatched) associated with transboundary buildings, energy, transportation, water, wastewater, and food infrastructures. The transboundary contributions far exceed in-boundary contributions. Denver's per capita total approaches the U.S. average of 25 tonnes of carbon dioxide equivalents per person (t CO_2-eq/capita). Adapted from Ramaswami and colleagues (2008).

cities, resulting in supply chain vulnerabilities (Sovacool and Sovacool 2009), local environmental pollution (Molina and Molina 2004), global greenhouse gas (GHG) emissions (Kennedy et al. 2009; Ramaswami et al. 2008), and associated public health impacts (Cambell-Lendrum and Corvalan 2007).

The importance of transboundary infrastructures can be seen in the fact that fewer than 7% and 4% of U.S. counties have power plants and oil refineries, respectively, within their jurisdictions (DOE 2010; EPA 2007), thus these transboundary infrastructures provide essential energy for the vast majority of cities and counties in the United States. Indeed, while the spatial scale of cities is on the order of tens of miles, electricity transmission distances exceed 200 miles[1] (Hirst 2000), freight travels 600 miles (BTS 2009), and food travels an average of 1,200 miles in the United States (Weber and Matthews 2008). Studies of international cities, including megacities such as Delhi, India, reveal a similar reliance on transboundary infrastructures for electricity, petroleum, water, food, and construction materials (Chavez et al. 2012).

The relatively small spatial scale of cities compared to the much larger engineered infrastructures in which they are embedded poses unique challenges in quantifying the environmental sustainability of cities. For example, energy used for electric power generation, oil refining, airline travel, and water supply typically occurs outside the jurisdictional boundary of the cities using these infrastructure services (thus the term transboundary; see figure 1, hatched areas) and can exceed direct fossil fuel combustion within city boundaries. Numerous recent studies have shown that measuring only direct energy use within city boundaries does not capture the global GHG impact of cities on the environment (Hillman and Ramaswami 2010; Kennedy et al. 2009; Ramaswami et al. 2008). Similar issues arise in measuring direct water use in cities versus water embodied in electricity, fuel, food, and other critical goods and services used by cities. Thus to address environmental sustainability both in terms of resource use and global pollution impacts, activities and infrastructures within city boundaries must be explicitly integrated with transboundary infrastructures that span hundreds of miles and draw in vast quantities of natural resources, directly or indirectly, to meet city demand, as illustrated in figure 2a (top).

The environmental and human health impacts of such infrastructures also span spatial scales from local to global. For example, fossil fuels combustion in urban energy supply and transportation infrastructures can result in indoor air pollution, urban heat island effects, regional air pollution, as well as global climate change, all of which can have profound effects on human health (WHO 2009). Climate constraints on regional water resources can in turn directly affect water supplies as well as indirectly impact the provision of electric power and food for urban residents (e.g., the recent power outage in India [Nessman 2012]); such supply chain risks can affect both economic activity and public health in cities (Hess et al. 2011). The multiple and multiscale risks posed to cities by infrastructure–environment interactions are illustrated in figure 2b.

The transboundary infrastructures serving cities are intricately tied to cross-scale actors, whose behaviors are shaped by institutions that refer to rules (e.g., city zoning codes, clean air standards), social norms, and shared strategies in communities (Ostrom 2005). Figure 2c presents examples of institutions and associated actors that span the spatial scale and influence energy use in cities in different ways. These actors include *home dwellers*, whose energy demand is shaped by community norms (i.e., institutions), and *infrastructure designers and operators* (i.e., architects, engineers, and power plant operators), who shape both energy demand and supply, guided by codes (e.g., neighborhood association rules, state utility guidelines, national clean air standards, and global protocols) that are developed by *policy actors* at local, state, national, and international scales. Thus social actors are the primary agents of change, and institutions are the instruments through which actors shape the current and future trajectory of urban infrastructures in terms of resource use, pollution, climate risks, and health impacts. Any study of resource-efficient, environmentally sustainable, and healthy cities must necessarily incorporate transboundary infrastructures serving cities, along with associated cross-scale social actors and institutions that govern these infrastructures. Correspondingly, pedagogical and research tools are needed to engage students, researchers, and practitioners in integrative work across multiple disciplines spanning the natural sciences (environmental sciences), infrastructure engineering, industrial ecology, architecture and urban planning, behavioral and economic sciences, public affairs, and public health.

However, available frameworks and models describing cities do not address all the above interacting components across the spatial scale, nor do they articulate theoretical and

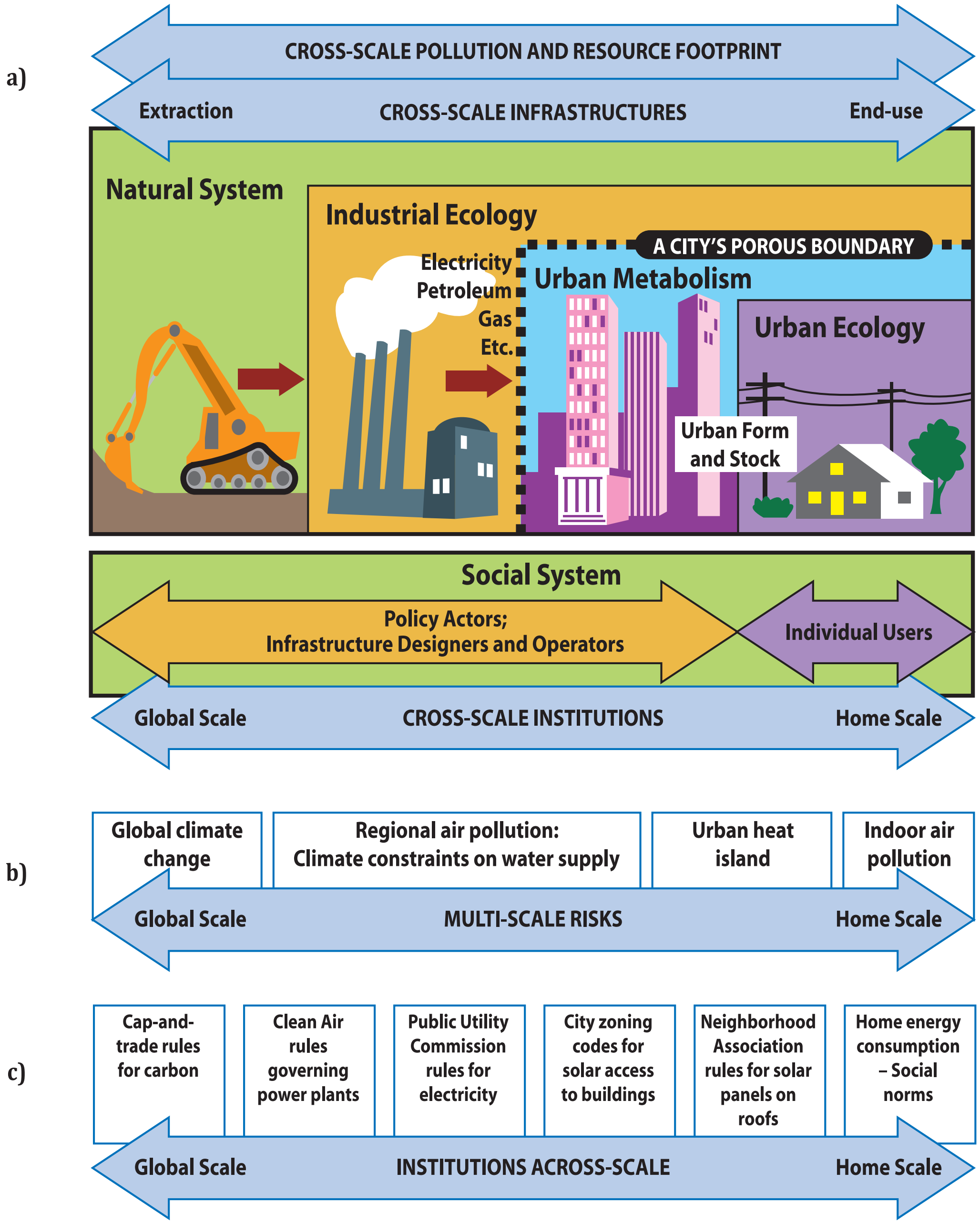


Figure 2 Pictorial illustration of the social-ecological-infrastructural systems (SEIS) framework depicting: (a) integration across the spatial scale of infrastructures, urban metabolism, industrial ecology, and urban resource/pollution footprints with social actors and institutions; (b) multiple and multiscale risks posed to cities by infrastructure–environment interactions across scales; (c) select examples of institutions that shape energy use and greenhouse gas (GHG) emissions across scales.

methodological tools to integrate them. The objective of this article is to present a social-ecological-infrastructural systems (SEIS) framework for interdisciplinary study of sustainable city systems that addresses transboundary and cross-scale linkages between the natural system, engineered infrastructures, actors, and institutions that shape a city's sustainability outcomes. We first identify novel aspects of the SEIS framework and describe how component theories and models integrate across various disciplines. We then illustrate the application of the SEIS framework in developing and implementing a broadly interdisciplinary curriculum, "Sustainable Infrastructure, Sustainable Cities," demonstrating key learning outcomes.

This article is relevant to the International Society of Industrial Ecology's newly formed Sustainable Urban Systems section, which has declared integration across disciplines to inform the development of sustainable urban systems its mission. The article also presents the SEIS framework as a first exploration of "how to make interdisciplinarity happen," in theory and in practice, to advance the science of sustainability.

What Makes a Framework? Contributions of the Social-Ecological-Infrastructural Systems Framework

Drawing upon a robust literature on frameworks from the social sciences (Laudan 1978; Ostrom 2005; Weible and Nohrstedt 2012), we note that frameworks are intended to "specify the scope of enquiry and establish general conceptual categories along with basic definitions and general relations." Effective frameworks also delineate component theories that "narrow the scope of enquiry, offer testable hypotheses and postulate causal relationships among concepts" (Weible and Nohrstedt 2012). Theories further yield models that develop explicit relationships between relevant variables. In applying the concept of frameworks from the social sciences to the coupled social–biophysical system shown in figure 2, it becomes important to also delineate physical laws that govern the natural and infrastructure subsystems (i.e., the laws of conservation of mass, thermodynamics, fluid flow, electricity flow, and others). Thus effective frameworks must delineate concepts, theories, laws, and models (see figure S1 in the supporting information available on the Journal's Web site).

Presently available frameworks of urban sustainability begin to but do not fully address the transboundary and cross-scale linkages between natural systems, engineered infrastructure, actors, and institutions that shape city sustainability outcomes, while also providing detail on underlying theories and linkages across diverse disciplines. We describe below some of the key features and limitations of some of the currently available approaches.

Urban Ecology

Urban ecology studies typically focus on human activities in cities and associated water, energy, and chemical fluxes *within* city boundaries (e.g., vertical carbon fluxes in urban forests) or *across* rural-to-urban gradients (see the review by Churkina [2008]). The design of large-scaled transboundary engineered infrastructures serving cities—such as the power grid, and freight and airline networks—are not explicitly a part of urban ecology studies. While urban ecology frameworks (Grimm et al. 2008; Pickett et al. 2001) allow for a diversity of social actors in power hierarchies (similar to organisms), the practical focus to date has largely been on household behaviors as drivers of consumption; theories describing the interdependent behaviors of multiple social actors have not been delineated.

Urban Metabolism

Urban metabolism studies focus on material and energy flow analysis (MEFA) *across* city boundaries, and more directly address the role of infrastructures in cities (Kennedy et al. 2007). Different types of urban metabolism studies focus on bulk material flow, energy, and substance flow analysis, as summarized in a recent review (Barles 2010). However, infrastructures outside city boundaries would not appear in urban metabolism accounts (e.g., an urban MEFA would not capture jet fuel use by a city if its regional airport is outside the city's boundary). Furthermore, upstream embodied energy associated with the material and energy flows are not consistently included in urban metabolism accounts (i.e., the embodied energy in producing jet fuel is not considered unless the refinery is within the city). Thus the impact of different production technologies that shape the global GHG emissions associated with urban activities is not captured. Urban metabolism studies provide important insights on the drivers of demand for end-use energy and materials within cities. Important issues outside the city boundary, such as the upstream energy and materials use outside the boundary, the vulnerability of the city's supply chain to various risk factors, or the mitigation of such risks by resilient design of the larger-scaled electric power grids and water supply systems in which a city is embedded, are not addressed by urban metabolism.

Urban Resource Use and Pollution Footprints

The impact of cities across their boundary and vice versa is better reflected in the emerging literature on urban environmental footprints (Hillman and Ramaswami 2010; Peters 2010; Ramaswami et al. 2011a; Wright et al. 2011). Transboundary resource use and pollution emission footprints of cities (illustrated in figure 2, top) combine urban material and energy flows across city boundaries (a key component of urban metabolism) with life cycle assessment (LCA) of the larger-scale production systems (a key component of analysis of industrial systems), thereby linking the use of materials and energy in cities with their supply chain from resource extraction to transformation. A recent review article represents urban footprinting as closely aligned with, yet separate from, urban metabolism studies (Barles 2010). Moreover, different types of urban footprints are being articulated (described next) that assign responsibility for environmental impacts to different activity sectors, explicitly addressing that cities include both producers and consumers (Ramaswami et al. 2011a).

Infrastructure-based footprints (e.g., figure 1) incorporate both direct and embodied energy in multiple and transboundary infrastructures serving cities (Hillman and Ramaswami 2010; Kennedy et al. 2009; Ramaswami et al. 2008). These footprints can serve two unique functions. First, they help quantify system-wide energy and GHG savings across spatial scales and across infrastructure sectors serving individual cities, stimulating innovative cross-scale and cross-infrastructure strategies for GHG mitigation (Ramaswami et al. 2011a). Second, spatially disaggregated infrastructure footprints inform the multiscale risks posed to cities by infrastructures and the environment (illustrated in figure 2a). These footprints are therefore ideally suited to address transboundary and cross-scale impacts of infrastructures on urban sustainability. Emerging research is establishing mathematical relationships between infrastructure supply chain footprints that serve the city as a whole (i.e., homes, businesses, and industries, including those that export goods or services) versus consumption-based footprints of cities that focus largely on resident household expenditures (Chavez and Ramaswami 2011).

Dynamic Urban Simulation and Visualization Models

To date, urban metabolism and urban footprint studies have mostly been conducted in a static manner (i.e., for a baseline year) from which scenario analyses are performed. Their continuous evolution over time can be described with various types of dynamic urbanization models. Top-down global models of urbanization project broad changes in population, urban migration, demographics, technology, and household income in various world regions (O'Neill et al. 2010). These variables are then translated to changes in energy use, water use, and GHG emissions. Bottom-up models simulate interactions between land use change, select actors (e.g., city residents and land developers), and their impact on infrastructure demand in cities (e.g., travel demand in UrbanSim; Waddell and Ulfarsson 2004). More recently, integrated urban energy models (Keirstead et al. 2010) integrate energy use with energy supply, examining spatial and temporal relationships. However, these simulation models typically consider key policy actors as exogenous to the system. They offer model results and visualization as decision support to policy makers (Waddell and Ulfarsson 2004), but do not capture the rich interactions of policy actors with other social actors and with the biophysical system that stimulate change in the policy system.

Decades of research in public affairs and political science has shown that policy actors are not merely receptors of technical information in simulation models, but are themselves embedded in complex relations shaped by political forces from other actors (Jenkins-Smith et al. 1991). However, to date, no framework representing urban sustainability explicitly represents policy actors and the politics of infrastructure changes in relation to sustainability in an integrated manner. Yet, policies and politics are important drivers of change.

Social-Ecological Systems Frameworks in Public Affairs

The interactions of social actors with the natural resource system and the governance system are represented in the social-ecological systems (SES) framework and its sister framework, the institutional analysis and development (IAD) framework (Ostrom 2005). The SES builds off the IAD framework and its theory of common-pool resource management, which has mostly been applied to the management of single resource streams (e.g., forests, fisheries) in relatively small and homogeneous communities (Ostrom et al. 1994, 2005), or situations where social actors are located in close proximity to the resources being managed. This literature has identified examples of communities that have sustainably managed resources at risk of overdepletion, including fisheries, groundwater basins, irrigation systems, and forests, by developing and implementing a flexible set of rules (institutions) with associated sanctions (Ostrom 1990).

A key question to ask is if and how social actors associated with urban infrastructures can govern cities and natural resource systems toward sustainability goals. City systems, unlike forests and farms, are much more challenging with resource users in cities often located many hundreds of miles away from the natural resource systems they are using, being connected to the resource system via large-scale transboundary engineered infrastructures. There is no SES framework to date that addresses multiple cross-scale engineered infrastructures and multiple resource streams (water, energy, materials) flowing into large, heterogeneous populations in cities. Thus we introduce an SEIS framework that combines key concepts from the urban footprinting literature with those from the SES and IAD frameworks, with suitable modifications to address actor heterogeneity. The name SEIS is derived because transboundary infrastructure supply chain embodied water, energy, and GHG emissions footprints of cities are now integrated with social actors and institutions across scales, after the SES framework. The cross-scale linkages between transboundary infrastructures, natural resource systems, actors, and institutions are illustrated in figure 2. Key advances offered by the SEIS framework include

- The concept of transboundary infrastructure footprints of cities that address multiple resources (water, energy) and diverse environmental impacts (e.g., GHG emissions, water resource depletion) arising simultaneously from multiple infrastructure sectors serving human activities in cities.
- By integrating multiple cross-scale infrastructures serving cities, the infrastructure footprints enable both cross-scale and cross-sector strategies for mitigating a city's environmental footprint to be assessed (e.g., substituting waste fly ash in "green" concrete, substituting telepresence for airline travel, saving water by saving electricity, etc.). Spatially delineated urban infrastructure footprints can describe economic supply chain risks as well as multiscale public health risks posed to cities by infrastructure interactions with the environment.
- A unique multiactor, multitheoretical approach describes the cross-scale interactions between policy actors, infrastructure designers and operators, and individual resource users with each other and with infrastructures across scale. Such a multiactor, multitheoretical approach in the social system has not been applied to urban systems to date; most studies focus on single theories or single actor categories.
- Social science theories describing actor behavior and outputs (such as actor participation rates in various sustainability interventions) are coupled with physical laws, spatial constraints, and infrastructure design principles to shape sustainability outcomes of cities, providing for a platform for deep integration across multiple disciplines, described in the next section.

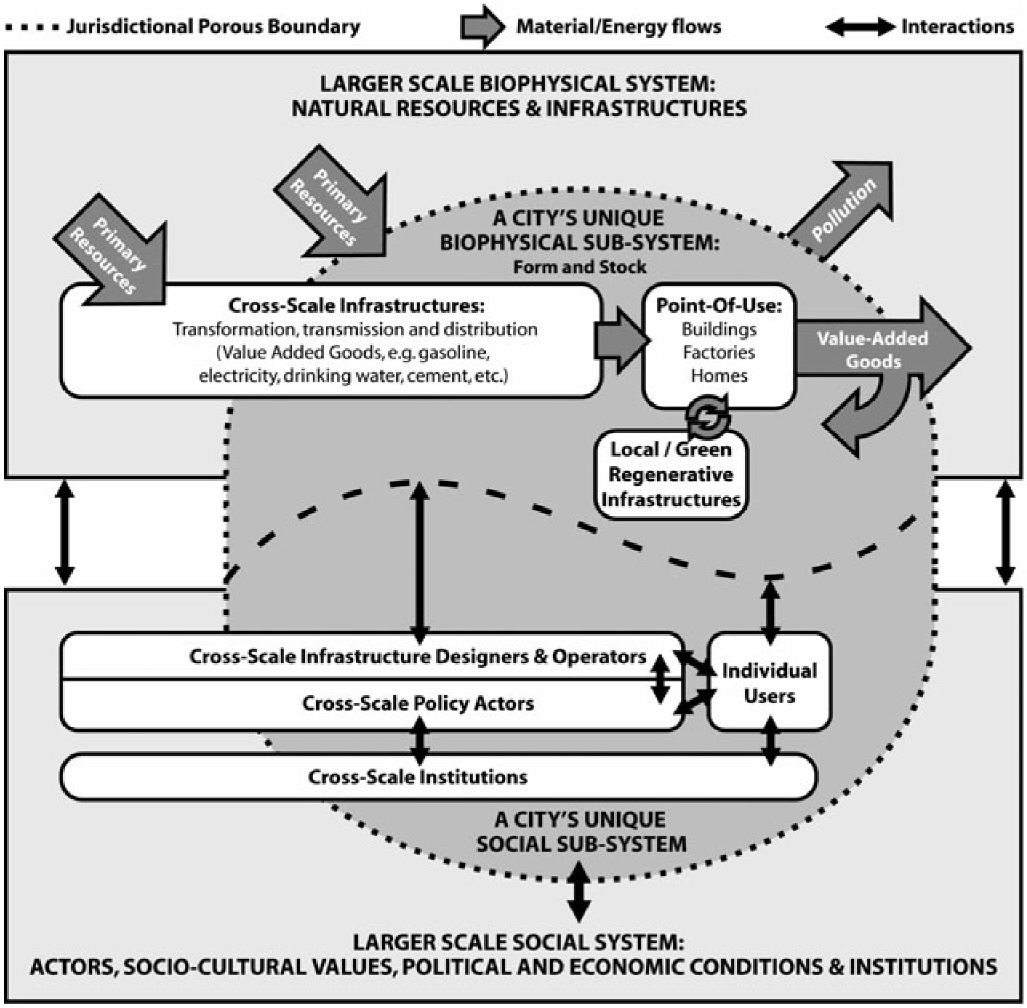


Figure 3 Schematic representation of the social-ecological-infrastructural systems (SEIS) framework for sustainable cities with material and energy flows (block arrows) represented in the biophysical infrastructure systems (top) and interactions (simple arrows) between and within the social system (bottom).

The Social-Ecological-Infrastructural Systems Framework and Integration Across Multiple Disciplines

Key concepts in the SEIS framework (sketched in figure 2) are detailed in figure 3.

First, a smaller-scale city with a porous boundary is shown embedded within a larger coupled social-biophysical system in figure 3. The city is characterized by its unique urban form and sociocultural features within its jurisdictional boundary.

In the biophysical subsystem, cross-scale infrastructures convey primary resources directly or in the form of transformed resources, such as electricity or gasoline, for point of use in cities. Block arrows represent large resource flows in infrastructures, with the diminishing size of the block arrows representing energy losses during resource transformation (e.g., energy conversion efficiency in thermoelectric power plants). A relatively small proportion of regenerative infrastructures are also depicted, representing waste to energy, solar roofs, urban agriculture, or other regenerative processes in cities. The infrastructures within cities are shown to be influenced by urban form.

The flow of primary energy and materials into the city yields value-added goods and generates pollution emission footprints all along the infrastructure supply chain from resource extraction to resource-use in cities. Such urban economic activity (value-added goods) is shaped by the education level and available labor force in the city, which in turn shapes household income (O'Neill et al. 2010). These interactions (among others) between the biophysical and social subsystems are represented by simple arrows between the two subsystems in figure 3.

Three main categories of social actors are identified in the social subsystem based on their specialized function described below:

- *Individual users* represent households and businesses within the city whose demand for water, energy, and resources results in the commissioning of infrastructures serving cities.

- *Infrastructure designers and operators* are responsible for the design, operation, maintenance, and dismantling of the infrastructures, and are shown to cross spatial scale.
- *Policy actors* include elected, appointed, and civil government officials, and many types of nongovernment actors (e.g., citizen groups, scientists, journalists, special interest groups, and coalitions), who attempt to shape the processes and outcomes of infrastructure governance, ranging from cooperative management to top-down regulation. Corresponding to the reach of infrastructures, the policy actors governing them are also shown to span spatial scale in figure 3. Note that policy actors encompass several actors in addition to policy makers.

The delineation into three broad actor categories presents a necessary simplification of the social system based on the functionality of the actors that supports further theoretical study, described next.

Multiple theories can be applied to describe the interdependent behaviors of the three actor categories, thus laying the foundation for a robust framework.

- *Individual users:* Large-scale dynamic trends in labor and household incomes in cities and their subsequent impact on consumption are described by global urbanization models (e.g., the population-environment-technology model; O'Neill et al. 2010). Against these trends, the proclivity of individual users in cities to adopt environmentally friendly conservation behaviors can be described by a few different theories. The value belief norms theory posits that a causal chain from altruistic values to beliefs about the benefits of environmentally friendly actions shapes norms (e.g., participation in recycling efforts) (Stern 2000). In contrast, the theory of social norms (Schultz et al. 2007) suggests that clear messaging around peer behavior can encourage other individuals to follow those same environmentally friendly behaviors (independent of their values and beliefs); the use of pledges and prompts reinforces these behaviors, guided by the theory of planned behavior. These insights have been effectively used to design successful energy conservation campaigns in homes (e.g., the company OPOWER, working with utilities, observed about 3% electricity savings utility-wide) (Alcott and Mullainathan 2010). Dietz and colleagues (2009) estimate voluntary changes in household behaviors have the potential to mitigate as much as 7.4% of GHG emissions in the United States, although facilitation by policy actors may be needed to realize this potential. Diffusion of innovation (Rogers 2003) facilitated by social networks is also being explored as a means to engage the general public in sustainability strategies.
- *Infrastructure designers and operators:* Little is known in the literature about this actor category, and why individual engineers and architects innovate in areas of green design and operations (Monroe 2003). However, the collective behavior of individuals in firms has been explored using the neoclassical theory of the firm, revealing barriers for businesses to invest voluntarily in energy efficiency upgrades (e.g., split incentives and organizational structures that inhibit agency; Howarth et al. 2000). The participation of firms in voluntary environmental programs can also be spurred by several factors, described by club theory (Potoski and Prakash 2009), including the threat of pending regulations (being developed by policy actors) and/or the benefits of public perceptions (i.e., the individual actor category). Thus interactions between actor categories are important drivers for change.
- *Policy actors:* At the municipal government level, theories such as the institutional collective action framework (Feiock 2007) might explain why policy actors create intergovernmental agreements for a range of services from treating water to garbage collection; these agreements shape the transboundary nature of infrastructures serving individual cities. At the national level, the multiple streams theory has been used to explain the adoption of cap-and-trade regulations in Germany (Brunner 2008); such policy changes can occur when public opinion, problem definition, and policy solutions championed by government bureaucrats are aligned, thus creating a "window of opportunity." A more nuanced view of the interactions between different types of policy actors (media, special interest groups, government bureaucrats, and elected officials) is offered by the advocacy coalition framework (Sabatier 1988), which has been used to describe how these actors engage in coalitions to influence policy outputs. The IAD framework (described previously; Ostrom 2005) addresses cross-scale interactions of actors with each other and with institutions, and with the natural resource system.

The above interactions between actors, between actors and institutions, and between the social and biophysical subsystems in the SEIS framework are shown via simple arrows in figure 3. Thus figure 3 presents a conceptual view of the framework.

Operationally, integration between the social and biophysical subsystems in the SEIS framework requires a broadly interdisciplinary effort illustrated in figure 4, which shows how laws, theories, and models from different disciplines are integrated in the SEIS. The left-hand side shows that theories from the social, behavioral, and policy sciences (many summarized above) help describe the behavior of the three categories of social actors: policy actors, firms and businesses, and individual users. The outputs from the social actor system include changes in behavior or changes in policy, the former influencing participation rates of households and firms in voluntary environmental programs, while the latter may yield new pollution emission standards or technology standards. These outputs from the social system shape the diffusion of sustainable infrastructure strategies in society.

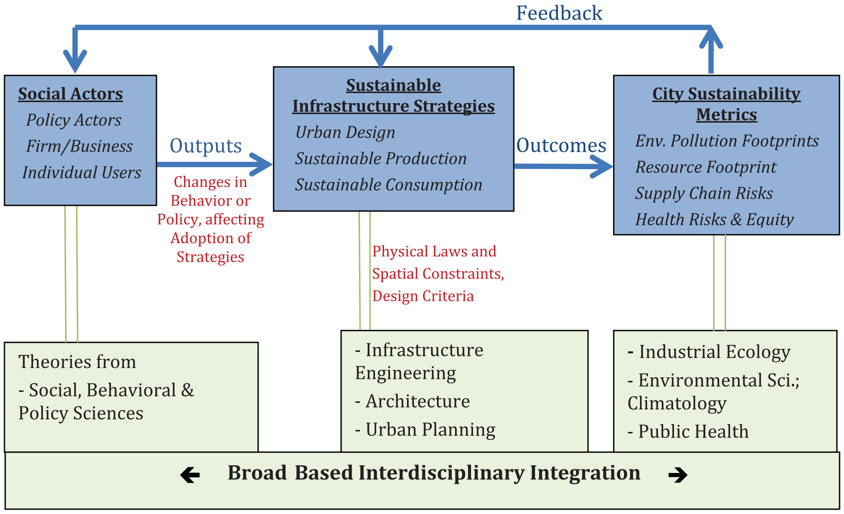


Figure 4 Schematic showing how outputs, outcomes, and feedback in the social-ecological-infrastructural systems (SEIS) framework (top) are informed by concepts, theories, and laws drawn from multiple disciplines (bottom).

Three broad categories of sustainable infrastructure strategies are shown in figure 4 (middle): (1) sustainable production (e.g., renewable energy, resource efficient, and nontoxic industrial production systems; Anastas and Zimmerman 2003); (2) urban design strategies such as green buildings, smart growth (Transportation Research Board 2009), and urban industrial symbiosis that can shape both production and consumption; and (3) sustainable consumption, achieved through various types of environmental and social marketing campaigns aimed at households and neighborhoods (McKenzie-Mohr and Smith 2010). Each of these sustainability strategies are physically constrained, spatially constrained, and are subject to the laws of physics. Infrastructure design specifications from the disciplines of engineering, architecture, and urban planning reflect these physical constraints.

Combining the impact of social actors who govern the adoption of sustainable infrastructure strategies with resource-efficient and low-pollution designs in the infrastructure system yields overall sustainability outcomes in cities, including economic development, resource efficiency, environmental pollution, public heath, and equity outcomes (right side of figure 4). As described previously, urban footprint tools enable assessment of several of these outcomes. Methods from industrial ecology, climate sciences, and public health must be integrated to assess these city sustainability outcomes, which in turn have a feedback effect on both the actors and the infrastructure system, as illustrated in figure 4, forming a fully integrated SEIS.

Figure 4 provides an operational "map" for integrating key concepts, theories, models, and laws across the seven major disciplines shown therein. The application of the SEIS framework to develop integrative interdisciplinary field research and pedagogy on sustainable city systems is described in the remainder of this article.

Interdisciplinary Curriculum Design Using the Social-Ecological-Infrastructural Systems Framework

The SEIS framework (figures 2–4) helped in the design of an interdisciplinary graduate certificate on Sustainable Infrastructures, Sustainable Cities, offered over the past 3 years to cohorts of students drawn from engineering, environmental sciences, architecture, planning, public affairs, and health and behavioral sciences at the University of Colorado Denver, Denver Colorado, USA. The program is delivered in a sequence of four courses:

1. *Introduction to Sustainable Urban Infrastructure* introduces the SEIS framework and provides an overview of key concepts, general relations, and example theories and models from different disciplines.
2. *Theories for Change Among Social Actors* provides a deeper understanding of the theories describing the three actor categories.
3. *Defining and Measuring Sustainability* provides an integrative active-learning fieldwork experience wherein teams of students work directly with Colorado communities to learn about their sustainability priorities, conduct a baseline assessment of energy and pollution footprints, and strategize action options among the three actor groups (Ramaswami et al. 2011b).
4. *Infrastructure and Public Health*, currently in evolution and offered as an elective, describes urban public health outcomes as a complex combination of infrastructural, environmental, cultural, and socioeconomic factors explored using both quantitative and qualitative research methods (Northridge et al. 2003).

Students take all four interdisciplinary courses and obtain a certificate in Sustainable Infrastructures, Sustainable Cities, while gaining a concentration in their home disciplines where they receive their graduate degrees (see figure S2 available in the supporting information on the Web). The combination of training within home disciplines, complemented with the interdisciplinary certificate, enables students to gain both the depth and breadth needed to embark on interdisciplinary research projects on infrastructures and social actors in sustainable city systems. (See figure S2 in the supporting information on the Web for a depiction of the relationship of four interdisciplinary courses to seven major disciplines.)

The introductory overarching course, Sustainable Urban Infrastructure, is described here. The course follows figure 4 from the right to the left, first discussing desired sustainability outcomes as a motivation for studying sustainable cities, and then discussing infrastructure strategies and social actor theories that together shape these outcomes. The course is offered in three modules.

Module 1: Why Study Sustainable Cities and Introduction to Urban Systems Concepts. Before discussing the sustainable development of cities, the course first explores desired *human development* outcomes using Amartya Sen's human capability approach (Fukuda-Parr 2003). The roles of natural resources and infrastructures in enhancing (or inhibiting) human development are discussed both for developing nations and affluent nations (Steinberger and Roberts 2010). Population growth, globalization, urbanization, and their impacts on scarce water, energy, and mineral resources are discussed (e.g., Bartlett 2010; Rijsberman 2006), against which backdrop the projected impact of climate change on cities (Cambell-Lendrum and Corvalan 2007) provides a compelling case to study sustainable urban infrastructure. Students are then introduced to systems concepts drawn from neoclassical economics, ecological economics, and industrial ecology (e.g., the tragedy of the commons, the IPAT (environmental impact, population, affluence, and technology) equation, environmental Kuznet's curves, concepts of 10xE and rebound; Chertow 2001; Daly 2005; Gottron 2001; Hackett 1998; Hardin 1968). A literature on hard path and soft path approaches toward sustainability (Gleick 2003) motivates the need for integrating the biophysical infrastructure system and the social system in cities, laying the groundwork for introducing the SEIS framework (this article).

Module 2: Exploring Sustainability Strategies and Measuring Their Effectiveness. The second module explores principles underlying sustainability strategies drawn from different disciplines, addressing production, consumption, and urban design (see figure 4). Tools (e.g., LCA, MEFA) for measuring the effectiveness of these strategies are introduced, using case study examples. This module covers principles of green engineering, industrial ecology, green buildings, smart growth, and community-based sustainability interventions. Case studies such as the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model's analysis of biofuels (ANL 2011), industrial symbiosis at Kalundborg, Denmark (Ehrenfeld and Gertler 1997), and recent metastudies of green buildings (Turner and Frankel 2008) and "smart growth" in U.S. cities (Transportation Research Board 2009) highlight the importance of measurement to verify that the principles indeed yield intended outcomes.

Module 3: Diffusion of Sustainability Strategies Among Social Actors. The last module briefly touches upon motivators and barriers that affect the adoption, implementation, and diffusion of the above sustainability strategies by social actors. Case studies (Brunner 2008; Goldstein et al. 2008; OPOWER 2011; Ramaswami et al. 2007; Stern 2000) introduce students to practical applications of some of the social actor theories described in the framework. These theories are examined in more detail in the second course, Theories of Change Among Social Actors. Because multiple actors and strategies are necessary to achieve even modest urban sustainability goals, effective practices are needed to engage diverse social actors in sustainable urban infrastructure management. Practices such as community-based participatory research (Israel et al. 1998) and frameworks such as IAD are discussed for this purpose, recognizing that neither has previously been applied to large-scale urban infrastructure systems but may be adapted to such purposes.

The concepts covered in the three different modules are summarized in table S-1 (available as supporting information on the Web), showing the flow of this 15-week course along with key readings and resources.

Integrative group projects and long-term field work utilize the concept of carbon stabilization wedges (Pacala and Socolow 2004) to illustrate how multiple social actors and multiple strategies from multiple disciplines are needed to make modest and measurable sustainability gains in an urban SEIS. For example, a critical review of GHG mitigation strategies identifies high-impact infrastructure changes as well as key social and policy changes that are needed to achieve even modest GHG mitigation in U.S. cities in the short term (Ramaswami et al. 2012).

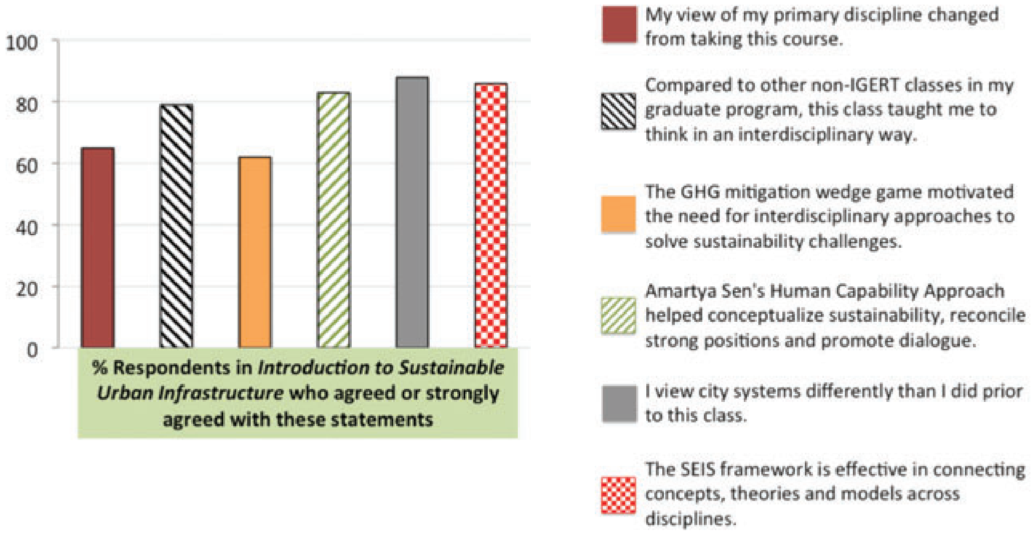
An introduction to the SEIS in the first course, followed by more detail on social actor theories in the second, leads to the third capstone course wherein groups of students conduct interdisciplinary integrative field projects with partner cities (Ramaswami et al. 2011b). The fieldwork entails computing the infrastructure supply chain GHG emission footprints of Colorado cities, evaluating cross-scale and cross-sector strategies for mitigating the GHG footprints, and conducting surveys and focus group sessions to uncover barriers to implementing these strategies among different actor categories, thereby identifying relevant theories for deeper analysis. Long-term research in the program is likewise organized around the themes in figure 4, relating the combined outputs from the social and engineering subsystems to measurements of sustainability outcomes in cities. Participatory research with many cities over the long term is needed to yield insights on the most relevant theories and key parameters that must be tracked in the coupled SEIS to identify "leverage points of greatest impact" in cities.

Learning Outcomes Assessment: The Utility of the SEIS Framework

Numerous definitions of interdisciplinary study have emerged in the literature, yet they all tend to focus on three common features (Klein and Newell 1997): a *complex problem* that cannot be tackled from single-discipline perspectives and that requires *integration across two or more disciplines* to create a *new understanding*. Frameworks such as the SEIS provide the structure to facilitate such integrative study and to generate new understanding, which is key to interdisciplinary learning.

A deep assessment of the role of the SEIS framework in stimulating interdisciplinary learning is difficult, given the short time frame of the certificate program described in this article. Furthermore, much of the literature on interdisciplinary learning articulates expected outcomes of such learning: increased ability for systems thinking (Richter and Paretti 2009), having the knowledge structure to promote higher-order and critical thinking (Boix Mansilla and Duraisingh 2007; Ivanitskaya et al. 2002), and being able to better apply these principles in the real world (Crisp and Muir 2012; Richter and Paretti 2009). However, there has been no real agreement on how to assess such learning (Boix Mansilla and Duraisingh 2007; Cooper et al. 2001; Ivanitskaya et al. 2002). A few instruments utilize lengthy student writings or interview data (Boix Mansilla and Duraisingh 2007; Crisp and Muir 2012), which do not translate readily across different curricula.

Consequently, learning assessments in the curriculum on sustainable cities used a graduated, sequential approach to evaluate the role of the SEIS framework in promoting interdisciplinary learning. We first evaluated student awareness of concepts drawn from other disciplines using self-reported survey data from the introductory course (see figure S4 in the supporting information on the Web). Student competence in applying these concepts is evaluated in course work, homework, and quizzes (not shown here). We also surveyed students on changes in their thinking, in particular their evolving view of their own disciplines, their concept of the city as a system, and their capacity to dialogue across disciplines as stimulated by the SEIS curriculum (figure 5).



Select Quotations Illustrating Self-Reflection Among Students

Improved Interdisciplinary Vocabulary: "I am better able to relate my work to concepts and processes used by other disciplines and to communicate with other specialists in working toward a goal."

Transformed Sustainability Thinking: "However I think about the subject, there is probably another way to think about it 180 degrees differently."

Improved Understanding of Primary Discipline: "I am more aware of the limitations and advantages of my primary discipline."

Acquired Interdisciplinary Skills: "Better understanding of which theories, models, and frameworks from my discipline are best applied to "real world" questions."

Figure 5 Outcomes assessment of systems learning after exposure to the social-ecological-infrastructural systems (SEIS) framework in the introductory course on sustainable urban infrastructure. TOP: Survey responses ($n = 26$). BOTTOM: Select quotations illustrating self-reflection among students.

The data in figure S4 (in the supporting information on the Web) shows that students learned of several key concepts pertaining to sustainable cities from the interdisciplinary SEIS curriculum versus their home discipline or exposure outside of academia. Some concepts, such as peak oil, tragedy of the commons, and Leadership in Energy and Environmental Design (LEED) buildings, were familiar to many, while a majority of the concepts in the SEIS were new to most students, enhancing their awareness of other disciplines. The students were drawn from engineering and environmental sciences, architecture and planning, and social sciences (see figure S3 in the supporting information on the Web). Figure 5a reveals that >85% of students found the SEIS framework effective in its stated objective of enhancing systems thinking and demonstrating relations between theories and concepts from diverse disciplines. Transformative learning experiences were reported by students, noted by their statements quoted in figure 5b. Further detail is provided in figure S4 in the supporting information on the Web.

Student survey responses revealed a few key challenges that had to be overcome in implementing the integrative SEIS curriculum, including preconceived bias about capabilities and core philosophies of different disciplines; vastly different definitions of theories, models, and frameworks in different disciplines; and unfamiliarity with the analytical methods of other disciplines. For example, social science students often questioned the need for quantitative LCA, material flow analysis (MFA), and wedge analysis in the introductory course, but recognized the value of such tools in the fieldwork capstone course. Likewise, engineering students were initially overwhelmed by the large number of social science theories introduced, but gained familiarity with social science methods through the second and third (fieldwork) course. The potential to have real-time impact on policies and actions in communities was cited as a powerful motivator to break down disciplinary barriers. Thus we have developed a long-term outreach model with more than 20 cities in Colorado wherein student–faculty teams conduct user-inspired research projects focused on various aspects of sustainable city development (Ramaswami et al. 2011b).

The SEIS framework and the associated graduate certificate described in this article are a result of faculty collaborations across diverse disciplines within one university (as reflected by the coauthors). Research across multiple universities is needed to understand the factors that sustain such. Early results in figure 5 illustrate the utility of the SEIS framework in vocabulary building across disciplines and in enhancing a systems view of cities, as reported by students.

Frameworks such as the SEIS provide a platform for integrative research and learning among diverse disciplines, essential for training the next generation of environmental scientists, engineers, architects, planners, policy makers, government officials, and public heath professionals to work together to solve the sustainability challenge.

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Note

1. One mile (mi) ≈ 1.61 kilometers (km, SI).

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Supporting Information

Additional supporting information may be found in the online version of this article.

Supporting Information S1: This supporting information consists of four figures and a table. The first figure depicts the key elements of effective frameworks. The remaining three figures provide information about the sustainable urban infrastructure program at the University of Colorado Denver (UCD): integration of interdisciplinary courses on sustainable urban infrastructure into graduate programs at UCD; student enrollment across multiple disciplines in the program; and student learning of various social-ecological infrastructural systems concepts. The table shows concepts covered in the introductory course on sustainable urban infrastructure, organized by module with supporting resources.