We present an international, interdisciplinary lecture-fieldwork course that trains students to address the challenges of developing environmentally sustainable and healthy cities.

International, Interdisciplinary Education on Sustainable Infrastructure and Sustainable Cities

Key Concepts and Skills

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This paper presents the development, delivery, and assessment of an interdisciplinary education program on Sustainable Infrastructure and Sustainable Cities offered to cohorts of graduate students from the United States, India, and China. Developed by an interdisciplinary team of university instructors from the three countries, the curriculum explores how the interaction of engineered infrastructures with social and natural systems shapes urban sustainability outcomes pertaining to resource management, environmental pollution, climate change, and public health. Five key concepts and skills form the foundation of the curriculum: (1) sustainable urban systems concepts; (2) interdisciplinary systems thinking and teamwork skills; (3) intercultural skills; (4) fieldwork, including community-based interactions; and (5) knowledge of ethics in interdisciplinary and intercultural settings

The curriculum is designed for students from six disciplines: engineering, industrial ecology, environmental sciences and climatology, urban planning, public health, and public affairs. An innovative, hybrid lecture-plus-fieldwork format is delivered in several cities in each country, exposing the students to multiple cultures and diverse learning experiences.

Most current infrastructure systems are unsustainable, together being responsible for 95% of US greenhouse gas emissions and more than 10 million premature deaths worldwide.

Background

Impacts of Rapid Urbanization

The year 2009 heralded a historic shift as, for the first time in human history, records showed that more than half of the world's people lived in urban instead of rural areas. And the urban share of the world's population is projected to increase to about 70 percent by 2050, with the urban population almost doubling from approximately 3.4 billion people in 2009 to more than 6.3 billion (UNEP 2009). Rapid urbanization is changing not only the landscape of individual cities but the Earth system itself—and the human experience.

Engineered infrastructures—defined broadly as the systems that supply water, energy, food, transportation, sanitation, buildings (shelter), and public spaces (such as parks, pavements, seawalls) (Chavez and Ramaswami 2013)—are critical to human well-being and economic development in cities. Unfortunately, most current infrastructure systems are unsustainable: they are responsible for more than 95 percent of US greenhouse gas (GHG) emissions and water withdrawals (EPA 2005; Kenny et al. 2009) as well as over 10 million premature deaths worldwide annually as estimated by the Global Burden of Disease (GBD) project[1] (Lim et al. 2012). GBD data show that indoor and ambient air pollution, primarily from energy and transportation, rival childhood underweight among the largest contributors to premature death (Lim et al. 2012).

Furthermore, health effects are exacerbated in cities, where people, resource demands, and pollutant emissions are concentrated spatially. And wide disparities in infrastructure, literacy, and socioeconomic status among different urban populations (e.g., migrant workers and slum dwellers) further contribute to negative health outcomes.

Effectively designing and managing infrastructure to accommodate the current and future needs of cities (e.g., by addressing aging infrastructure in developed cities and rapid demand in newly developing cities) is a critical challenge that will shape global and regional environmental sustainability as well as public health in cities worldwide.

The Need for International and Interdisciplinary Education

An integrated systems approach toward urban planning, infrastructure design, environmental assessments, public health, and public policy has the potential to address the current and emerging challenges of urban infrastructure. A recent review of experiments in infrastructure design and policy in 100 cities around the world illustrates the potential of such efforts (Broto

[1] This activity of the World Health Organization has provided comprehensive estimates of the health effects of diseases since 1990. Information is available at www.who.int/healthinfo/global_burden_disease/.

and Bulkeley 2013), highlighting the need to educate and train professionals from diverse disciplines to address the challenges (Frumkin et al. 2004).

We have developed an international and interdisciplinary curriculum on sustainable infrastructure and sustainable cities for students from China, India, and the United States with backgrounds in engineering, industrial ecology, environmental sciences and climatology, urban planning, public health, and public affairs. The curriculum is built on an interdisciplinary social, ecological, and infrastructural systems (SEIS) framework for developing environmentally sustainable and healthy cities (Ramaswami et al. 2012, 2014). The framework has a strong engineering foundation, focusing on the role of infrastructure and how it interacts with social and natural components.

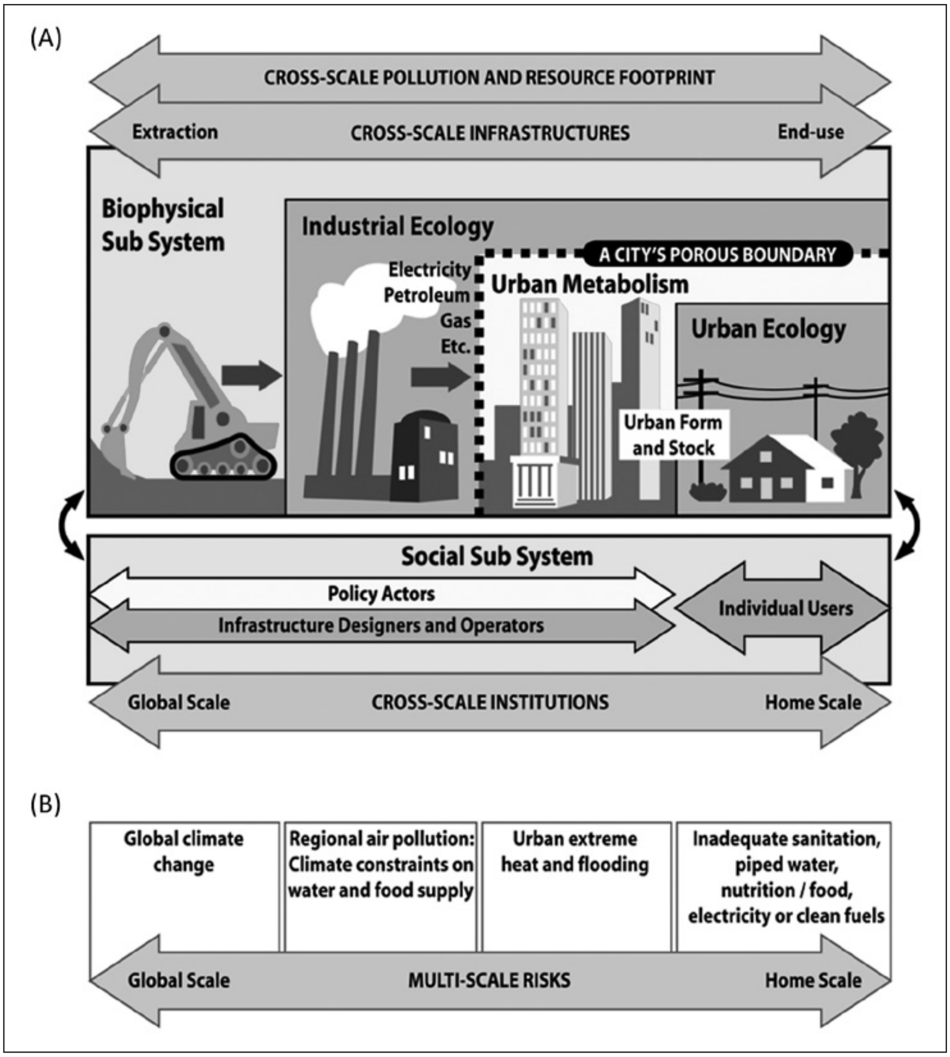

FIGURE 1 Schematic of the social-ecological-infrastructural systems (SEIS) framework, illustrating (A) environmental sustainability of cities: Cross-scale impact of infrastructures on the environment (biophysical subsystem) shaped by people (actors) and institutions interacting across spatial scale in the social subsystem; and (B) multiscale health risks to people in cities from infrastructure-environment interactions across scale. Source: Ramaswami et al. (2014).

A Systems Approach to Designing and Managing Urban Infrastructures

The SEIS framework shown in Figure 1 illustrates a number of 21st century challenges in designing and managing urban infrastructures for sustainability outcomes.

First, although resources were plentiful in the 19th and 20th centuries, local, regional, and global resource constraints loom large in the 21st century, affecting the provision of food, water, electricity, and land for cities (e.g., Bai et al. 2014). Second, the nexus of water, energy, and food is critical—water is necessary for energy and food/agriculture, and energy is needed to supply water and fertilizer for food—and amplifies dependencies and scarcities in the three sectors (Bazilian et al. 2011). Third, in a highly globalized world, trade both among cities and between cities and the hinterland is so intertwined that much of what a city requires in terms of its basic needs for water, energy, and other goods depends on complex transboundary supply chains; for example, food, freight (e.g., goods movement), and electricity travel more than 1,400, 600, and 150 miles, respectively, in the United States (Ramaswami et al. 2012).

Understanding Cities in Context

To address the environmental sustainability of cities, it is imperative to understand the physical environs of a city as embedded in both the greater biophysical system (e.g., large-scale engineered infrastructures such as electric grids, water supply and transportation networks) and the surrounding natural systems (e.g., watersheds, airsheds, and the global atmosphere; Figure 1A).

Infrastructure-environment interactions generate multiple risks at different scales—local, regional, and global—that affect the health of people in cities (Figure 1B). Human health risks are associated with inadequate infrastructure in homes (e.g., lack of water and sanitation in large urban slums in Asian and African cities); extreme heat and flooding at the city-scale exacerbated by poor design of community-scale infrastructure (e.g., concrete pavements, lack of trees and open spaces); pollution of local and regional air, water, and soil from energy, water, and sanitation sectors; and global climate change impacts that can threaten regional food and water supplies. Further, pollutants at one scale can exacerbate pollution at the other scales.

This embeddedness and interaction of risk factors must be taken into account in efforts to address public health in cities.

Interdisciplinary and collaborative approaches are needed to address the challenge of developing sustainable infrastructure for sustainable cities.

Role of Governments, Actors, and Policy Instruments

Because of the embeddedness of cities, local governments alone are unable to manage either the range of relevant infrastructures or their impacts across scale. Nor is it effective to address each sector independently in individual departmental silos, since water, energy, air, transportation, public spaces, urban buildings, and sanitation are all inherently and intricately interrelated, from their common intersection points in cities to their linkages along the supply chains that serve the cities. Integrated urban spatial planning and environmental policies are needed to coordinate across the home, neighborhood, city, regional, and global scales, as illustrated in the social subsystem shown in the bottom part of Figure 1A.

To that end, governments at all levels are increasingly leading multisector collaborations that engage a number of actors—businesses, nongovernmental organizations, and communities—to achieve environmental sustainability and public health goals. In terms of policy design, demand-side management is now becoming as important as supply-side management and cleaner production. As a result, policy instruments to manage infrastructures are evolving beyond "command and control" pollution regulations and infrastructure construction codes to include innovative voluntary programs that engage households, businesses, and infrastructure designer-operators in resource efficiency, conservation practices, and innovative enterprises such as bike and car sharing programs, urban farms, and local food markets.

Curriculum, Learning Objectives, and Methods

The complexity of the challenges described above requires highly interdisciplinary and collaborative approaches to support the development of sustainable infrastructure for sustainable cities. Use of the SEIS framework can enhance understanding of the linkages among engineered infrastructures, environmental sustainability, public health, and the people who use, design, manage, and regulate the infrastructures toward various goals. This understanding can in turn advance learning about how different geographies, infrastructure conditions, regional resource constraints, sociocultural norms, and administrative and political systems shape the design and management of infrastructures for sustainability and health.

What can and should be covered in an international and interdisciplinary curriculum that seeks to educate students about the challenges of developing environmentally sustainable and healthy cities? Our team, including the authors and additional collaborators from the University of Colorado Denver and the National Center for Atmospheric Research, has developed and pilot-tested a six-week summer school on Sustainable Infrastructure and Sustainable Cities. Held in India (2013) and China (2014), with a US session planned in 2015, the program brings together Indian, Chinese, and US students to engage in education and field research in multiple cities in these three countries.

Based on the SEIS framework and on pedagogy drawn from diverse sources and synthesized in an April 2013 workshop,[2] the authors identified five learning objectives for program students:

- Knowledge and understanding of sustainable urban systems concepts;
- Interdisciplinary systems thinking and teamwork skills;
- Intercultural skills;
- Field research, including community-based work; and
- Knowledge of ethics in interdisciplinary and intercultural settings.

We briefly describe each objective, review the resources used to promote learning, and then present early results from qualitative and quantitative evaluations that illustrate the impact of the program on students.

Sustainable Urban Systems Concepts

Sustainable urban systems concepts[3] are drawn directly from the SEIS framework shown in Figure 1 and cover the following topics:

- General concepts such as rapid urbanization, human capabilities, and health and well-being and their association with infrastructures and scarce resources.
- Methods and models to quantify the in-boundary and transboundary environmental impacts of infrastructures. Students learn the use of material-energy stocks and flow analysis, supply chain tracking, and lifecycle assessment to characterize the coupled water, energy, pollution, and GHG emission footprints of urban infrastructure (Figure 1A), thereby providing a baseline measure of a city's environmental sustainability.
- Methods and models to represent multiple risks posed to cities by infrastructure-environment interactions, characterizing mortality and morbidity from inadequate infrastructures (e.g., lack of water, sanitation), hazardous or polluting infrastructures (e.g., accidents and pollution associated with energy production, transportation, and industry), and climate extremes such as heat and flooding (Figure 1B).
- High-impact infrastructure design strategies that promote sustainable consumption and sustainable and cleaner production (e.g., of water and energy); integrated urban spatial planning that enables linkages and synergies across infrastructure sectors (e.g., industrial "symbiosis" for the beneficial exchange of resources among collocated industries and municipal utilities; Figure 2); medium-density mixed-use neighborhood design with efficient transportation systems; and integrated water infrastructure connected with "urban farms" and green spaces. Many of these interventions enhance both environmental sustainability and human health, an intersection that can be captured in the SEIS approach.
- Social and institutional factors that promote or inhibit the adoption of sustainability strategies, such as values, beliefs, and social networks that stimulate individual and corporate behaviors supportive of the environment and health; institutional arrangements such as the formation of regional transportation districts that enable cross-scale management of infrastructures and their impacts; and considerations of power and politics that shape the behavior of policy actors in implementing such changes.

Integrated field experiences are a powerful way to link across disciplines and promote intercultural and interdisciplinary competence as well as ethical awareness.

Students' proficiency in using these concepts is tracked before and after the summer school to assess their skill levels along Bloom's taxonomy continuum, ranging from knowing to understanding to application/synthesis and analytic capacity related to each concept. For example, assessments reported in Ramaswami et al. (2012) show that among a cohort of 26 students drawn

[2] "Sustainable Cities and Interdisciplinary International Education: A Workshop on Core Knowledge and Skills" was hosted by the National Academy of Engineering in Washington on April 24–26, 2013. The workshop objectives, agenda, and speaker presentations are available at www.nae.edu/Projects/CEES/57196/70831/PIREworkshop.aspx.

[3] We have identified more than 40 urban systems concepts that constitute a basic vocabulary across disciplines that address the major topics presented here. Details are provided in Ramaswami et al. (2012).

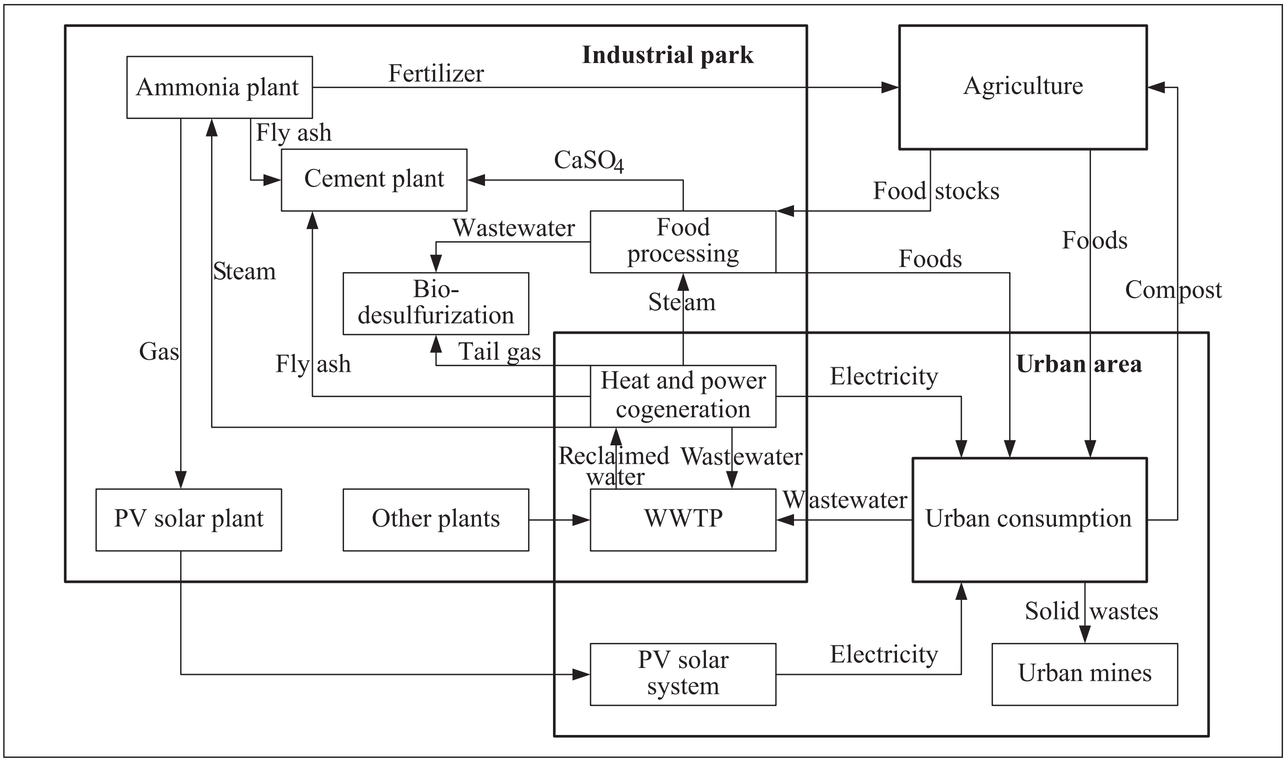

FIGURE 2 Interactions among industries and multiple urban-area infrastructure sectors—such as electricity, energy (steam), water supply, wastewater treatment plants (WWTP), and food systems—in the city of Yixing, China, show the potential for industrial symbiosis that can increase local resource availability. $CaSO_4$ = calcium sulfate; PV = photovoltaic. Source: Professor Shi Lei, Tsinghua University, China.

from engineering, urban planning, and public affairs, general concepts such as human capabilities, measures of water scarcity, and the linkage between infrastructures and human capability were not known to more than 80 percent of the students before the course. Afterward, they indicated that these concepts, in particular as put forth by Amartya Sen (2005), provided them with a broad view of sustainability and helped reconcile strong differences in ideology among participants. Likewise, specific principles and methods pertaining to development of environmental footprints or understanding of institutions were not initially known to more than 80 percent of the participants, but were reported among the skills and applications learned during the program (Ramaswami et al. 2012).

Interdisciplinary Systems Thinking and Teamwork Skills Linked with Fieldwork

Not all students are expected to achieve the highest skill levels in using all 40 concepts. We consider it more important for them to learn to work in teams by interpreting and transferring results across disciplines to address larger systems questions. Thus an urban planner need not be fully skilled in implementing air quality models, but should have the skill to understand the significance of model results. Such team-based interdisciplinary learning is promoted by using the schematic shown in Figure 3, which shows how learning about both social and infrastructure systems shapes sustainability outcomes.

Complementing the mapping of concepts in Figure 3 is the exposure of students to real-world field experiences in international cities. Such fieldwork involves tracking material-energy stocks, flows, and footprints of urban infrastructure, linking them with air quality and climate models, computing health effects based on populations exposed to diverse risks, and conducting surveys and interviews to assess how individuals, communities, firms, and policy actors respond to the various environmental and health outcomes. Figure 4 illustrates such integrated fieldwork in the context of understanding the burning and management of waste in Indian cities from a combined social, infrastructural, and environmental perspective.

Integrated field experiences are a powerful way to link disciplines and promote intercultural and inter-

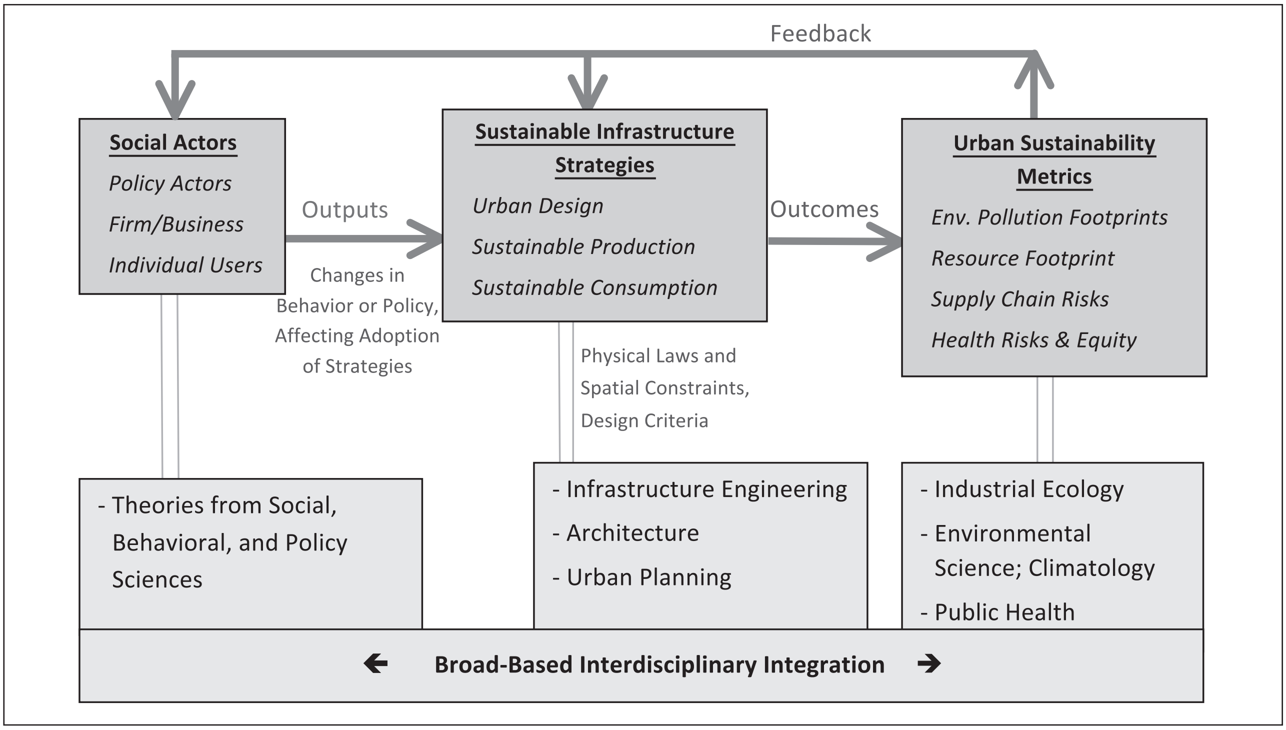

FIGURE 3 Schematic illustrating how integration across disciplines (bottom row of boxes) supports implementation of the social-ecological-infrastructural systems (SEIS) framework (top row of boxes). Adapted from Ramaswami et al. (2012).

disciplinary competence as well as awareness of ethical frameworks and responsibilities, as explained below.

Intercultural Skills

Intercultural learning requires an increased awareness of self and the ability to navigate differences with "the other" (the differences may be in gender, culture, profession—and, in this course, discipline).

Using Bennett's continuum for intercultural awareness (Figure 5; Bennett 2004, pp. 62–77) it is possible to assess various stages of development, from denial of other cultures (or disciplines) to polarization (assumption of the superiority of one culture or discipline over another) to minimization of differences (i.e., "we are all basically the same") to acceptance of differences and, at the highest level, the ability to negotiate and adapt to such differences.

For the 2013 summer school course in India, students' intercultural competence was assessed before and after, using the Intercultural Development Inventory (IDI; Hammer and Bennett 2009) to gauge their awareness of personal beliefs, understanding of the dynamics of interpersonal interactions across cultures, and development of their ability to reflect on and change their behaviors in real-world situations. Cultural and disciplinary differences and challenges were made explicit and discussed openly as part of the training program.

Wide variation was seen in cultural competence among individuals, reflecting the challenge as well as the reality of working across cultures and disciplines. To promote intercultural learning we used online resources collated by various universities,[4] books and videos presenting the history of India and China,[5] selected TED talks,[6] and, most importantly, opportunities for unstructured conversation and for "learning by doing" as students of different backgrounds worked together.

[4] For example, the On-Line Cultural Training Resource for Study Abroad, a resource established by the University of the Pacific School of International Studies and Tulane University's Payson Center for International Development and Technology Transfer with support from the Department of Education and the University of Southern California. Available at www2.pacific.edu/sis/culture/.

[5] For example, a BBC TV documentary series, "The Story of India," written and presented by historian Michael Wood, about the 10,000-year history of the Indian subcontinent in six episodes. Available at https://www.youtube.com/watch?v=cip4VmtCBWA.

[6] For example, a 2009 TED talk by Devdutt Pattanaik, "East vs. West: The myths that mystify," on myths of India and of the West. Available at www.ted.com/talks/devdutt_pattanaik.

IDI assessment results showed that most of the students transitioned from polarization toward minimization, the cusp between a monocultural and an intercultural mindset (Figure 5). Most students agreed afterward that “Learning how different disciplines and people from different backgrounds interact, both on a personal and professional level, was a good experience.” One participant noted, “I learned so much from my peers. It was interesting to see the cultural differences seep into all conversations and discussions. I loved coming back and experiencing everything from a different perspective.”

Knowledge of Ethics

Given large disparities in socioeconomic factors and infrastructure from one city to the next and from one country to the next, ethical questions are central to discussions of the development of sustainable infrastructure for sustainable cities. Discussions of ethics help bridge disciplines, professions, and cultures. Our curriculum incorporates ethics in five primary ways:

- *Distributional ethics* considers differences in benefits and burdens for different groups of people. What are the ethical frames for addressing social and environmental justice concerns associated with externalities

FIGURE 4 Integrated Fieldwork on Social, Infrastructural, and Environmental Factors in Cities. Some of the best opportunities for fieldwork arise spontaneously. Such was the case during the first summer school in India, when students spotted (and smelled) the burning of waste on streets. This practice affects air quality and respiratory health in many cities in India. Field work is exploring current and potential future waste infrastructure options, environmental/health impacts, and social actors, as illustrated in these photos. (A) Although banned in some cities, trash burning is widespread, serving not only to dispose of trash but also to provide heat in winter. Fieldwork is measuring the amount, composition, and frequency of waste-burns. (B) Air pollution monitors placed in the city assess the contribution of waste-burning to air pollution, and models estimate the health risks. (C-D) Interviews with social actors—households (left) and waste collectors (right)—assess their perceptions of health risks from waste-burning and views of alternative waste management strategies. (E) Studying areas with effective trash collection reveals what is working well both in the design of infrastructure and in social/behavioral practices.

of development, such as the higher risks that pollution and climate change may pose to children, the elderly, the poor, those living in particular locations, or even those in the future? Such frames include "polluter pays," Kantian duty ethics, and Rawlsian principles of protecting the weakest in society (Grubb 1998).

- In the context of *procedural ethics*, questions addressed include: Who has or should have standing to participate in discussions and decision making about issues that affect urban residents and workers? What are or should be the social processes? Do they ensure that all have a claim to justice? Scientific expertise is routinely part of societal decision making; how is it recognized and engaged in the process? Do procedures used in policy analysis, cost-benefit analysis, stakeholder engagement, or community-based research involve those most affected by an action? What does fairness require and what are the distributive consequences of one procedure rather than another? Questions of process and distribution also involve professional and research ethics.

- *Professional ethics* concerns the various disciplines and professions represented in Figure 3. Do they address questions of distribution or process? Intersections in statements of ethics among practitioners of engineering, urban planning, public affairs, social science and anthropology, and public health help students understand how each profession views its ethical responsibilities—and how an interdisciplinary team may define a new ethic to address the challenges of sustainable urban development (CSEP 2014).

- *Research ethics* is relevant to standards for researchers. Interdisciplinary work involves reconciling different professional codes and informal norms concerning matters such as publication credit, mentoring responsibilities, treatment of human and animal subjects, and data management. More recently, community-based participatory research has raised questions about research process, distribution of benefits, and community engagement in research design.[7]

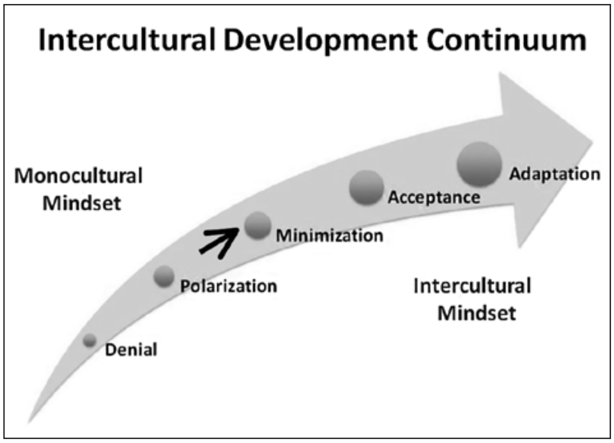

FIGURE 5 Intercultural Development Continuum (large arrow). The small black arrow shows the intercultural development of the 2013 cohort before and after the 6-week India summer program, measured using the Intercultural Development Inventory (IDI; Hammer 2014). The cohort transitioned from polarization to the cusp of minimization.

- *Cross-cultural ethics* applies to researchers from the same discipline who may have trained in different countries/locales with differing research codes and norms. Team members' views about what behaviors are acceptable in the field may be influenced by different cultural norms; attentiveness to these norms may be important to demonstrate respect for the host community, to complete the research successfully, and to develop long-term relationships based on mutual trust and respect. For example, it was helpful that US students grasped the need for cultural sensitivity in discussing the resource constraints of newly developing cities, given the large per capita allocation in developed economies.

Overall Evaluation of Various Learning Objectives

Individual learning objectives were assessed as shown for example, in Figure 5, for intercultural competence and, as reported in Ramaswami et al. (2012), for knowledge gained on sustainability concepts. In addition, students were queried about the effectiveness of the course in their own learning:

- 80 percent reported that the course was effective in promoting interdisciplinary systems integration and increasing their awareness of ethical dilemmas and responsibilities,

- 67 percent reported that the course promoted learning teamwork across disciplines, and

[7] See, for example, the Northeast Ethics Education Partnership (NEEP), a joint project of Brown University and the State University of New York College of Environmental Science and Forestry (SUNY-ESF). Information available at www.brown.edu/research/research-ethics/neep.

- 60 percent indicated the course was effective in promoting teamwork skills across cultures.

In their qualitative comments, the students described specific strengths and challenges associated with the course. Among the strengths, they reported that "we talked about culture & ethics as well as the subject matter relating to sustainable infrastructure, sustainable cities"; "The instructor spent time and effort on intercultural learning and interdisciplinary work. It was…a recurring theme in a very good way"; "International students, friendships, group work and small projects were the things that worked best"; "Meeting international faculty, specialists in their respective fields", "intercultural knowledge sharing" and the "SEIS framework—interdisciplinary and sustainability research that tied together"; "The opportunity to see parts of India and development challenges."

The challenges students experienced in India included "Lack of reliable communication with home"; "logistics around booking transport and accommodations"; "Too long and intensive"; "syllabus of 1 semester we had to finish in 1 month"; "difficult to reach every student."

The Way Forward

The summer school program on Sustainable Infrastructure and Sustainable Cities was implemented in India in 2013 and in China in 2014. Lessons learned from the first year informed the second year, including the addition of a preprogram in-person orientation and training for the participating students, improvements in travel logistics and planning, and reduction in the length of time spent abroad from about 7 weeks in India to 5 weeks in China.

The curriculum is intensive and requires much planning and about a 6-week commitment from students, but student feedback suggests that once logistical and time challenges are overcome, the impact can be high, increasing capacity for research and workforce development relevant for building sustainable cities in different countries. Students reported rich interdisciplinary, intercultural, field-based learning experiences about developing sustainable and healthy cities in an ethical manner.

Our experience demonstrates that focusing on the learning objectives described above in an international, interdisciplinary, blended lecture-fieldwork course can be an effective way to prepare leaders skilled at working in teams across disciplines and national borders to develop environmentally sustainable and healthy cities.

Acknowledgments

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