Transitioning Toward Sustainability: Advancing the Scientific Foundation: Proceedings of a Workshop

DETAILS

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Transitioning Toward Sustainability

ADVANCING THE SCIENTIFIC FOUNDATION

Proceedings of a Workshop

Dominic Brose, Yasmin Romitti, Ryan Anderson, and Alison Macalady, *Rapporteurs*

Committee on Transition Toward Sustainability after 15 Years:
Where Do We Stand in Advancing the Scientific Foundation

Science and Technology for Sustainability Program

Policy and Global Affairs

Board on Atmospheric Sciences and Climate

Division on Earth and Life Studies

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COMMITTEE ON THE TRANSITION TOWARD SUSTAINABILITY AFTER 15 YEARS: WHERE DO WE STAND IN ADVANCING THE SCIENTIFIC FOUNDATION

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Preface and Acknowledgments

In 1999 the National Academies of Sciences, Engineering, and Medicine released a landmark report, *Our Common Journey: A Transition Toward Sustainability*, which attempted to "reinvigorate the essential strategic connections between scientific research, technological development, and societies' efforts to achieve environmentally sustainable improvements in human well-being." The report emphasized the need for systems approaches to sustainability, proposed a research strategy for using scientific and technical knowledge to better inform the field, and highlighted a number of priorities for actions that could contribute to a sustainable future. More than 15 years later, the scholarship and practice of sustainability has matured, making it timely to reflect on how the recommendations of *Our Common Journey* have been implemented. To facilitate this reflection with leading scientists in the field of sustainability science, the National Academies of Sciences, Engineering, and Medicine convened a workshop on January 14–15, 2016. The workshop was a collaboration between the Science and Technology for Sustainability Program and the Board on Atmospheric Sciences and Climate.

This Proceedings of a Workshop was prepared by the workshop rapporteurs as a factual proceedings of what was presented and discussed at the workshop. The planning committee's role was limited to planning and convening the workshop. The statements made are those of the rapporteurs and do not necessarily represent positions of the workshop participants as a whole, the planning committee, or the National Academies of Sciences, Engineering, and Medicine. We wish to extend a sincere thanks to all the members of the planning committee for their contributions in scoping, developing, and carrying out this project.

This report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Academies of Sciences, Engineering, and Medicine's Report Review Committee. The purpose of this independent review is to provide candid and critical comments to assist the institution in making its published report as sound as possible and ensure the report meets institutional standards for quality and objectivity. The review comments and draft manuscript remain confidential to protect the integrity of the process. We wish to thank the following individuals for their review of this report: Andrew Hoffman, University of Michigan; Anthony Janetos, Boston University; Roberta Marinelli, University of Southern California; Stephen Polasky, University of Minnesota; and Billie Turner, Arizona State University. Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the content of this report, nor did they see the final draft before its release. The review of this report was overseen by Lynn Scarlett, Nature Conservatory. Appointed by the Academies, she was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the rapporteurs and the institution.

Jerry Miller, *Director*, Science and Technology for Sustainability Program
Amanda Staudt, *Director*, Board on Atmospheric Sciences and Climate

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Introduction

In 1999 the National Academies of Sciences, Engineering, and Medicine released a landmark report, *Our Common Journey: A Transition Toward Sustainability*, which attempted to "reinvigorate the essential strategic connections between scientific research, technological development, and societies' efforts to achieve environmentally sustainable improvements in human well-being."[1] The report emphasized the need for place-based and systems approaches to sustainability, proposed a research strategy for using scientific and technical knowledge to better inform the field, and highlighted a number of priorities for actions that could contribute to a sustainable future.

Now, more than 15 years later, the scholarship and practice of sustainability has matured, making it timely to reflect on how the recommendations of *Our Common Journey* have been implemented, what have been the most significant hurdles to date, what new challenges will need to be faced in the transition to sustainability, and what possible course corrections will need to be taken. *Our Common Journey* outlined three priority tasks for advancing sustainability science:

- "Develop a research framework that integrates global and local perspectives to shape a 'place-based' understanding of the interactions between environment and society;
- Initiate focused research programs on a small set of understudied questions that are central to a deeper understanding of interactions between society and the environment; and
- Promote better utilization of existing tools and processes for linking knowledge to action in pursuit of a transition to sustainability."

The past 15 years brought significant advances in observational and predictive capabilities for a range of natural and social systems, as well as the development of other tools and approaches useful for sustainability planning. In addition, other frameworks for environmental decision making, such as those that focus on climate adaptation or resilience, have become increasingly prominent. A careful consideration of how these other approaches intersect with sustainability is warranted, particularly in that they may affect similar resources or rely on similar underlying scientific data and models.

[1] National Research Council (NRC). 1999. *Our Common Journey: A Transition Toward Sustainability*. Washington, DC: The National Academies Press.

Our Common Journey made a strong call for indicators as an essential way to track progress toward attaining sustainability. At the time, the report committee found there was "no consensus on the appropriateness of the current sets of indicators or the scientific basis for choosing among them." Some progress has been made since. For example, federal agencies developed such measures to support their sustainability research. The U.S. Environmental Protection Agency (EPA), for instance, developed a framework in response to the recommendation in the 2011 National Research Council report *Sustainability and the U.S. EPA* that the agency "develop a set of indicators and associated metrics (associated with goals and objectives) and indicators associated with international reporting protocols" to assess progress toward national objectives and goals.[2] Other agencies undertook similar initiatives. On a global scale, Rockstrom et al. (2009) proposed defining "planetary boundaries within which we expect that humanity can operate safely."[3] However, despite these efforts, no set of indicators has been widely adopted, questions remain about whether our current observing systems are sufficient to track changes in sustainability, and federal agencies continue to struggle with how to monitor and measure the effectiveness of their sustainability initiatives and progress toward achieving sustainability.

To further the discussion on these outstanding issues, the National Academies of Sciences, Engineering, and Medicine convened a workshop on January 14–15, 2016, for leading scientists in the field of sustainability science. Participants discussed progress in sustainability science during the last 15 years, potential opportunities for advancing the research and use of scientific knowledge to support a transition toward sustainability, and challenges specifically related to establishing indicators and observations to support sustainability research and practice. A focus on indicators and observing capabilities at the workshop tied into several other ongoing dialogues at the national level. The Office of Science and Technology Policy recently unveiled a new climate data initiative intended to accelerate the nation's ability to make use of environmental observations to improve climate resilience,[4] the U.S. Global Change Research Program developed a pilot system of indicators,[5] and lastly, the Board on Atmospheric Sciences and Climate (BASC) released a report on abrupt impacts of climate change that recommended the development of an early warning system for identifying emerging climate threats.[6]

This workshop was a collaboration between the Science and Technology for Sustainability Program and BASC, and was organized around several key questions:

- What are the major advances in sustainability science since *Our Common Journey* was released in 1999, what are the remaining gaps, and what have been critical barriers to progress?
- What progress has been made in establishing sustainability indicators, what are the remaining gaps, and what have been critical barriers to progress?
- What progress has been made in developing models that are appropriate for supporting decisions related to sustainability, what are the remaining gaps, and what have been critical barriers to progress?
- What advances in other areas of science (e.g., observing capabilities, models, technology development, indicator development, social sciences) might be usefully applied to advancing sustainability science?
- How can advances in other frameworks for environmental decision making (e.g., climate adaptation, resilience, early warning systems) inform advances in and be integrated with sustainability science?
- What new efforts might be needed to address the range of needs and opportunities related to sustainability?

The workshop was divided into several panels that addressed specific activities, and included the following:

I. Sustainability and Economic and Population Growth
II. Urban Systems and Resource Sustainability

[2] National Research Council (NRC). 2011. *Sustainability and the U.S. EPA*. Washington, DC: The National Academies Press.
[3] Rockstrom, J., et al. 2009. Planetary boundaries: Exploring the safe operating space for humanity. *Ecology and Society* 14(2):32.
[4] Data.gov. Online. Available at http://climate.data.gov.
[5] U.S. Global Change Research Program. 2014. *Indicators of Climate Change*. Online. Available at http://www.globalchange.gov/what-we-do/assessment/indicators-system.html.
[6] National Research Council (NRC). 2013. *Abrupt Impacts of Climate Change: Anticipating Surprises*. Washington, DC: The National Academies Press.

III. Sustainable Manufacturing
IV. Sustainable Food Systems and Diet
V. Ocean Sustainability
VI. Integrated Analysis
VII. Paths Forward

The following workshop summary captures the presentations and discussion from each of these panels. Each panel was tasked with focusing on advances in three areas: sustainability indicators and metrics, models for supporting decision making, and opportunities to inform decision making.

Ralph Cicerone, President of the National Academy of Sciences, in his opening remarks on the state of sustainability science and role of the Academies since the publication of *Our Common Journey*, indicated that there has been substantial progress in sustainability science. In particular, there have been significant advances in metrics and indicators due, in part, to the number of satellite instruments and observatories in place, as well as statistical measurements, such as in the areas of demography and public health. It is important, he said, to note which measurements are necessary to make the adjustments needed to navigate a transition and hopeful trajectory toward sustainability. Dr. Cicerone concluded by providing a brief overview of the goals for the workshop, which included determining progress in the science of sustainability and providing clarity on which goals are central to sustainability. He challenged the participants to engage during the workshop to better define the goals of sustainability, identify the remaining large questions that are pertinent to those goals, examine how those goals have been approached, and finally, to deliberate on the prospects for future progress.

Pamela Matson, Chester Naramore Dean of the School of Earth, Energy and Environmental Sciences, Richard and Rhoda Goldman Professor in Environmental Studies, and senior fellow at the Woods Institute for the Environment at Stanford University, provided an overview of the state of sustainability science in her keynote remarks at the onset of the workshop. The report committee for *Our Common Journey* stated that there were many goals that needed to be met to sustain planetary life support systems (e.g., oceans, climate, water). The report also stated that although there had been great improvements in many metrics within these life support systems, there remained major outstanding needs. Society's efforts to meet the needs of people resulted in major unintentional negative consequences, such as airshed-wide smog, climate change, loss of biodiversity and ecosystem services, and major changes in global biogeochemical cycles.

The report committee for *Our Common Journey*, Dr. Matson said, identified key priority areas: create and use a framework for integrative understanding of and problem solving in social environmental systems, create focused research programs on under-studied issues, and promote the use of knowledge and tools for linking knowledge and action. The report committee also identified priority areas for action, which included human population, agriculture, living resources, energy, industry, and cities. The report committee discussed many other issues, but addressing the nexus between resource domains was key to the discussion. These domains do not exist in isolation, but instead interact and affect each other. For example, in order to address food security, other issues must also be addressed, such as ecosystems, water security, and climate change (Figure 1-1).

Dr. Matson said that launching the sustainability science section of the *Proceedings of the National Academy of Sciences* was an important step that allowed the scientific community to ask big questions about the characteristics of sustainability science. Her list of characteristics of sustainability science included the following:

- Involves use-inspired fundamental research
- Is interdisciplinary
- Focuses on coupled social-environmental systems
- Recognizes complexity of interactions, feedbacks, thresholds, and potential for unintended consequences
- Links knowledge to action

Researchers engaged in sustainability science come from many different disciplines and use different methods and frameworks. Thus, to better link and integrate work across different fields requires a "bridge" for framing research questions, such as specific "use" questions. Interdisciplinary scientists are an imperative. A diversity of

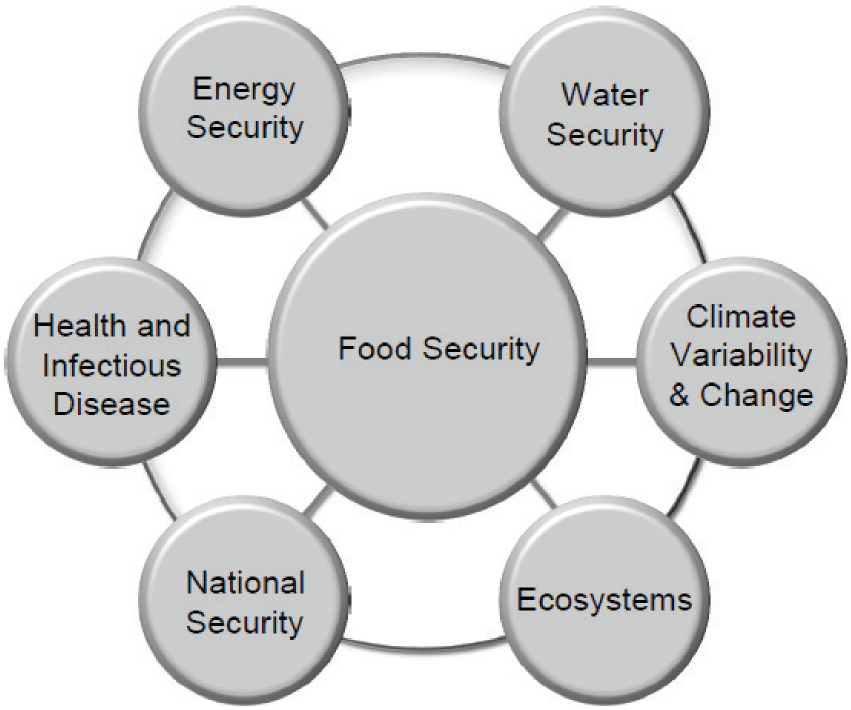

FIGURE 1-1 The nexus of food security and factors that affect it, as an example of interactions among resource domains.
SOURCE: Pamela Matson, Presentation, National Academies of Sciences, Engineering, and Medicine, January 14, 2016, Newport Beach, California.

knowledge and perspectives is needed from many different disciplines, cultures, and perspectives. Coupling social research to environmental systems is a fundamental component to place-based analysis, which was discussed extensively in *Our Common Journey*. The complexity of interactions, feedbacks, and unintended consequences can be illustrated well with biofuels. Corn ethanol production has multiple interactions and trade-offs among resources, including competition for agricultural lands designated for food crops and large ranges of water withdrawals that vary regionally depending on irrigation needs. The final characteristic Dr. Matson presented was linking knowledge to action. Sustainability scientists intend that the knowledge developed through research be usable. *Our Common Journey* recommended that the design of research programs and systems promote collaborative production of trusted knowledge, engage stakeholders in its creation, and create science and technology systems from the funding needed to accomplish these initiatives and develop more usable knowledge.

Dr. Matson presented five observations on progress. Firstly, there has been tremendous progress in the reorientation of research so that science can better address the needs of decision makers. Researchers are building on basic and applied sciences to create new approaches, tools, and methods for understanding social-environmental systems. Areas of use and solutions-oriented fundamental research for sustainability goals include hazards and resilience, food security, climate change, natural capital and ecosystem services, and global health. Secondly, there has been progress in the focusing and framing of the study and pursuit of sustainability. Researchers are moving away from environmental-, economic-, or socially-focused efforts, and instead are integrating all three into sustainability-focused efforts. Reaching intergenerational well-being results in long-term sustainability, but there are many factors involved, such as goods and services and consumption processes (Figure 1-2).

This conceptual framework reminds us that no one scientist will provide knowledge of all determinants of well-being; and that this knowledge comes from many fields. Some scientists may focus on natural capital, but

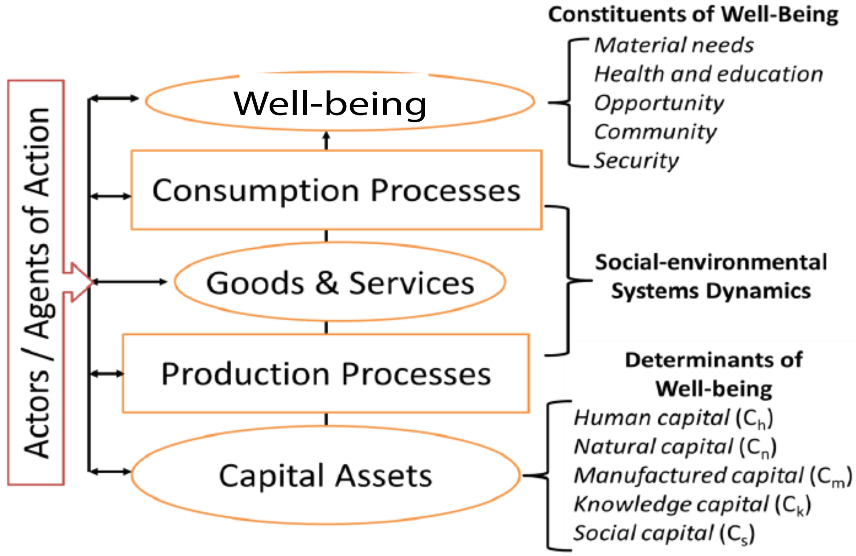

FIGURE 1-2 Processes and factors contributing to meeting well-being and long-term sustainability.
SOURCE: Pamela Matson, William C. Clark, and Krister Andersson, 2016. Pursuing Sustainability: A Guide to the Science and Practice. New Jersey: Princeton University Press. Adapted by Pamela Matson, for presentation, National Academies of Sciences, Engineering, and Medicine, January 14, 2016. Newport Beach, California.

others may focus on social capital, governance, financial situations, or other factors that determine how the relationship between manufactured capital and natural capital is managed.

Thirdly, there has been much progress in developing metrics and indicators. For example, indicators are increasingly integrative. Indicator systems help decision makers understand trade-offs and gain a fuller understanding of coupled social-environmental systems. There are also novel uses of information technology for collecting and sharing indicators and metrics. Researchers made advances toward an inclusive set of indicators related to capital assets, such as with the inclusive wealth index, which aims to provide countries with a realistic understanding of their wealth and prospects for long-term sustainability.[7] In some research areas, however, there is a drive to create new indicators while not giving enough attention to how indicators relate to other indicators. Instead of collecting data on new indicators, it would be more useful to map existing indicators against ongoing efforts.

Fourthly, the number of data-rich empirical models that support decision making increased significantly and are increasingly more precise and rigorous. Ecosystem services models, for example, are used more in strategic planning. Dr. Matson said there is an interesting debate on integration assessment models in that they may be grossly underestimating the risks of climate change. Assumptions built into economic models imply that impacts and costs of climate change will be modest. These economic models are then incorporated into the overall integrated model which leads to underestimates of the impact of climate change. There is a call for a new generation of climate models focused on livelihoods that also include human migration and conflict.

Lastly, Dr. Matson said, there has been much progress in efforts and opportunities to link knowledge to action with advances in efforts to engage stakeholders, run deliberative knowledge-action processes, and improve such processes. One example is boundary organizations, which play a functional role at the science-policy interface; however, there is little research documenting where knowledge was used in decision making and the extent of success it had.[8] Researchers have generally not developed the type of knowledge decision makers need. It takes

[7] See inclusivewealthindex.org.

[8] See the special feature Sustainability Governance and Transformation 2016: Informational Governance and Environmental Sustainability in Current Opinions in Environmental Sustainability: www.sciencedirect.com/science/journal/18773435/18.

important skills to link, interact, and be part of the boundary function between science and decision making. As a result, a lot of expertise is ignored. Linking knowledge to action needs to be collaborative and adaptive; thus, fragmentation remains a major challenge. A researcher may work on their part of a problem, but no one may be working on the next piece. Ecosystem services models and insufficient data for ecosystem services models is one example of this fragmentation. There needs to be a way to incentivize the development of knowledge for decision makers.

Dr. Matson concluded that there have been important strides in the scientific foundations for sustainability and a lot of useful knowledge created, but more can be done. Opportunities and organizations need to be created to help achieve more. Actors engaged in the supply chain of knowledge to action at universities needs to be incentivized around particular problems and engaged with nongovernmental organizations, corporations, municipalities, and federal agencies. A professional organization that draws the discussion together around sustainability science would also help advance efforts and build capacity. The field of sustainability science is in a transition, but researchers need to keep designing research efforts that focus on the supply chain of knowledge needed to push the field forward.

2

Decision Sciences, Demography, and Integrated Assessment Modeling

John Weyant, professor of management science and engineering at Stanford University, discussed the progression of integrated assessment modeling (IAM) since 2000 and future research needs in the field. Dr. Weyant defined an integrated assessment as an analysis of two or more major earth system components and at least one natural and one human component. These assessments are not always models but often cover as much of a global earth system as possible. Integrative assessments can capture uncertainties and emergent behavior of systems that would otherwise "fall through the cracks" in interdisciplinary research performed in silos or subcomponents. During Dr. Weyant's role in the 2000 Intergovernmental Panel on Climate Change (IPCC) climate assessment, a number of gaps were identified that related to understanding the linkages and feedbacks in the global climate system.[1] Dr. Weyant noted that without a fuller systemic understanding of linkages and related data, many of the integrated assessments in the early 2000s, specifically simplistic cost-benefit models, were only practical at local levels and lost their relevance at the global scale.

Recently, modelers and analysts improved the relevance of integrated assessments by incorporating more governance, land, water, and food capabilities; developing shared social-economic pathway scenarios to system modeling; and gathering diverse actors to advance regional integrated assessment initiatives. Examples include the MIT Global Integrated Systems Model (IGSM); and the Potsdam Institute for Climate Impact Research's (PIK's) Integrated Assessment Modelling framework (PIAM); both of which are described further on. Dr. Weyant indicated, however, there is a need to continue addressing gaps in understanding various systemic linkages, feedbacks, and uncertainties.

He suggested that further analysis is needed of subsystems that exist and operate within larger systems to adequately understand higher-level interactions and feedbacks. Such a method was applied to the IPCC's *Third Assessment Report* on sustainable development and international equity in 2001, which tried to model decisions made in climate policy.[2] A birds-eye view of how climate policy fits within larger frames of sustainable development and international equity was applied instead of a dissected analysis of individual decisions and actors (Figure 2-1). The climate-policy system may not have direct control of movement and activity in other systems such as "Environmental and Socio-economic Impacts" and "Equity and Sustainable Development Policy," but what

[1] Intergovernmental Panel on Climate Change (IPCC). 1995. Chapter 10: Integrated assessment of climate change: An overview and comparison of approaches and results. In *IPCC Second Assessment. Synthesis Report*. Geneva, Switzerland: WMO 1.

[2] Metz, Bert. 2001. Chapter 1 in *Climate Change 2001: Mitigation: Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press, 3.

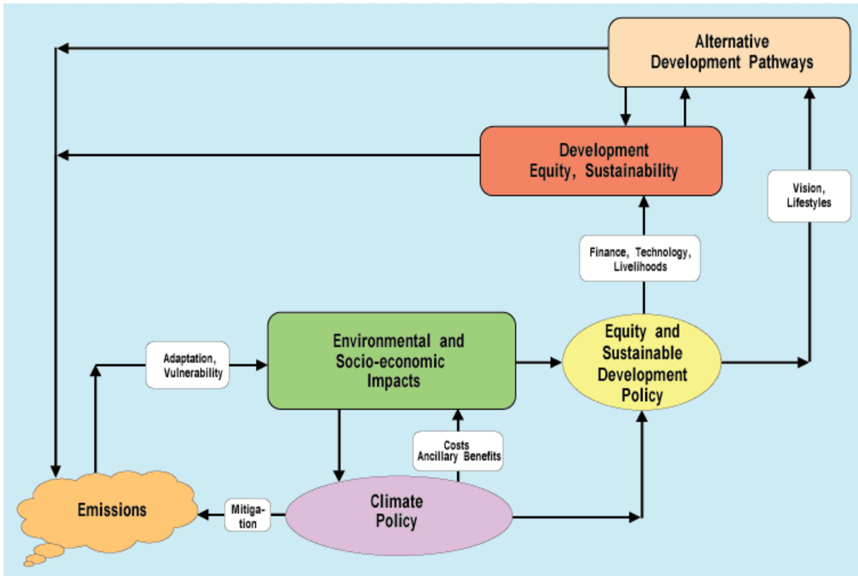

FIGURE 2-1 The interaction of the climate policy system within the larger context of larger systems such as sustainable development and international equity.
SOURCE: John Weyant, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 14, 2016, Newport Beach, California.

occurs in these other systems may constrain and influence the decisions made in climate policy and, ultimately, the amount of emissions released.

The efforts of integrative assessment models to identify higher-level connections and feedbacks, however, have been met with criticism regarding mistaken attribution or oversimplification. Dr. Weyant addressed these critiques by referencing the models Dynamic Integrated Climate-Economy (DICE), Policy Analysis of the Greenhouse Effect (PAGE), and Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) that quantify the social cost of carbon.[3] These models, while integrating across human and physical earth systems, only use a few factors—economy and population for human systems and carbon cycle for physical earth systems—to identify a correlation between global mean temperature with global damages. These models also establish a single fixed social price on carbon, even though additional factors may influence the relationship (Figure 2-2). Dr. Weyant emphasized that such a simplistic approach to integrated assessment is not embodied in all IAMs, particularly for the task of quantifying the cost of carbon that can range from as little as $37 per ton of CO_2 to as large as $1,000, depending on the factors assessed (Figure 2-2). Europe, for example, developed more complex IAMs for the cost of carbon by attempting to add input assumptions representative of different components of the earth system to capture more detailed costs and benefits, such as aggregate gross domestic product (GDP), GDP per capita, and gross climate outcomes.

The added complexities to these IAMs enable them to assess systems more holistically and to develop sustainability indicators that cover a diverse ground of human capital, economic, and environmental impacts and drivers, including land use, ecosystems, net primary productivity, water and heat stress, electric generation and capacity, and cost effectiveness. PBL's[4] Integrated Model to Assess the Global Environment (IMAGE) exemplifies diverse

[3] Statistical models used by the EPA to estimate the social cost of carbon—DICE (Dynamic Integrated Climate-Economy), PAGE (Policy Analysis of the Greenhouse Effect), and FUND (Climate Framework for Uncertainty, Negotiation, and Distribution).

[4] PBL Netherlands Environment Assessment Agency is the national institute for strategic policy analysis in the fields of the environment, nature and spatial planning of the Dutch government; PBL. 2016. http://www.pbl.nl/en/aboutpbl. Online. Available at: http://www.pbl.nl/en/aboutpbl. Accessed May 13, 2016.

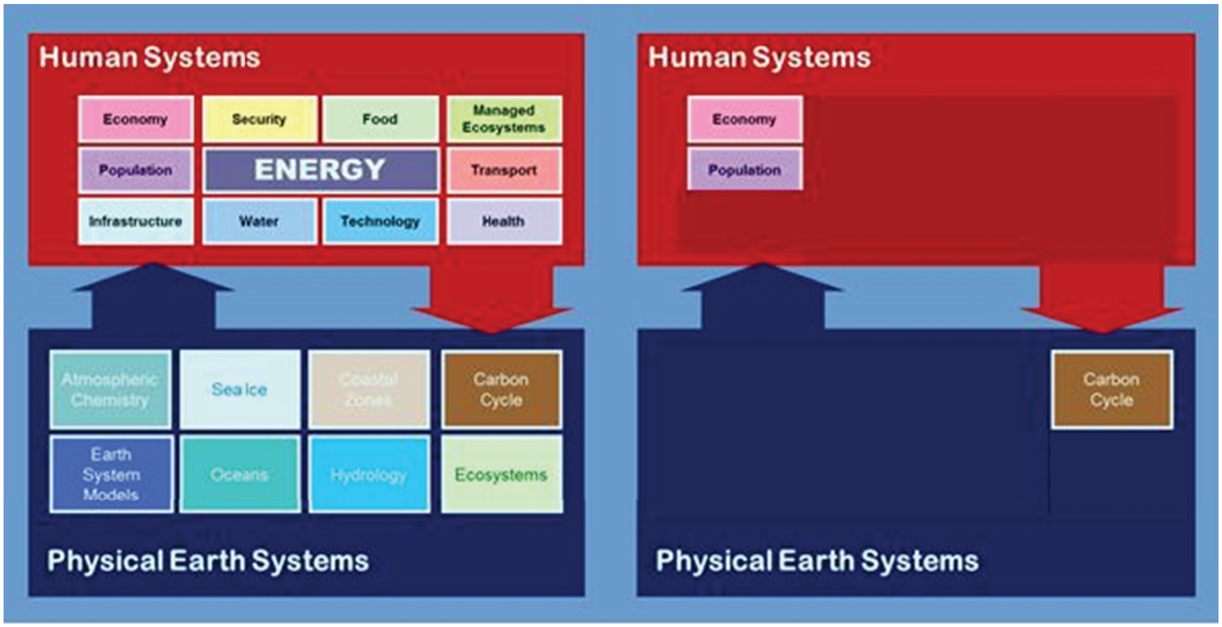

FIGURE 2-2 The left side of the diagram displays the many factors that contribute to integrated assessment models. The right side of the diagram covers the factors used in popular integrated assessments for the social cost of carbon.
SOURCE: John Weyant, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 14, 2016, Newport Beach, California.

capabilities of many of these models after including additional human system sectors such as agriculture, energy, and governance from an ecosystem model template created by past land-use accounting (Figure 2-3).[5] The wide range of sectors and systems represented in this model allow for tracing pathways for actions, decisions, and activities across food, water, land, technology, and population sectors.

Despite progress made in integrating human and physical earth systems in assessments, Dr. Weyant noted a lack of social indicators for things such as equity, connectedness, culture, and health in the six "complex" IAMs presented—IGSM, GCAM, PIK, MESSAGE, PBL IMAGE, and MERGE.[6,7,8,9,10,11] Integration could allow these assessments to factor in social indicators and costs, but only if the scientific community increases its flexibility and willingness to gather such information, as some important drivers for these models are inputs, not outputs. Other areas of need for IAMs include research on ocean acidification, irrigation potentials and aquifer net positions, black carbon, and subsurface carbon sinks.

During the brief question-and-answer session, Dr. Weyant was asked to describe if and how IAMs contribute to the policy landscape and practical work. He said many models could support decision making if downscaled to a regional context where policymakers act. These downscaled models, however, may leave out interactions and

[5] Stehfest, E., et al. 2014. *Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications*. The Hague, Netherlands: PBL Netherlands Environmental Assessment Agency.

[6] MIT Global Integrated Systems Model (IGSM).

[7] Joint Institute for Global Change Global Change Assessment Model (GCAM).

[8] Potsdam Institute for Climate Impact Research (PIK), referring specifically to the Potsdam Integrated Assessment Modelling (PIAM) framework.

[9] International Institute for Applied Systems Analysis (IIASA) Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE).

[10] PBL Netherlands Environmental Assessment Agency Integrated Model to Assess the Global Environment (IMAGE).

[11] Stanford University Model for Evaluating the Regional and Global Effects of GHG Reduction Policies (MERGE).

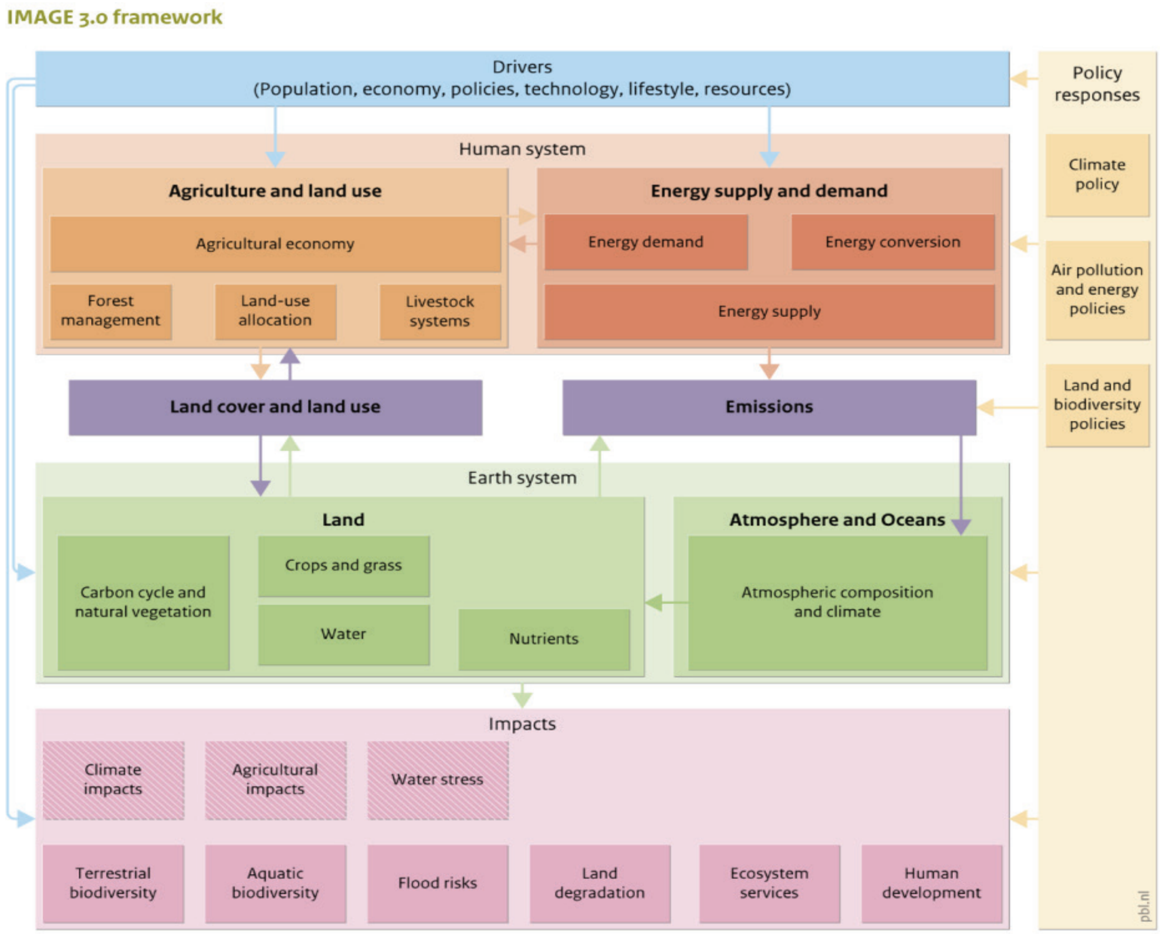

FIGURE 2-3 PBL Image Model including various human system sector components.
SOURCE: John Weyant, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 14, 2016, Newport Beach, California. PBL, 2014.

feedbacks occurring outside of the region that could heavily influence the region's decision making. For example, regional models may not adequately predict global water and crop shortage trends that constrain or enable trade and agriculture in a specified region. Due to limitations of regional models, he noted that decision makers could use their results as a baseline of potential outcomes.

Joseph Arvai, Max McGraw Professor of Sustainable Enterprise and director of the Erb Institute for Global Sustainable Enterprise at the University of Michigan, discussed the progress made in developing models to support decision making for sustainability and additional efforts still needed to address remaining challenges. He opened his discussion by pointing to the increasing prevalence of research in decision sciences and the emergence of studies that provide relevant context to sustainability. One study by Baba Shiv et al. (1999) on emotion versus cognition argued that if processing resources become limited and individuals feel cognitively taxed by the decision, then individuals often instinctively choose options that appeal to them on an emotional level.[12] This has direct application to individuals facing large sustainability decisions.

[12] Shiv, B., and A. Fedorikhin. 1999. Heart and mind in conflict: The interplay of affect and cognition in consumer decision making. *Journal of Consumer Research* 26:278–292.

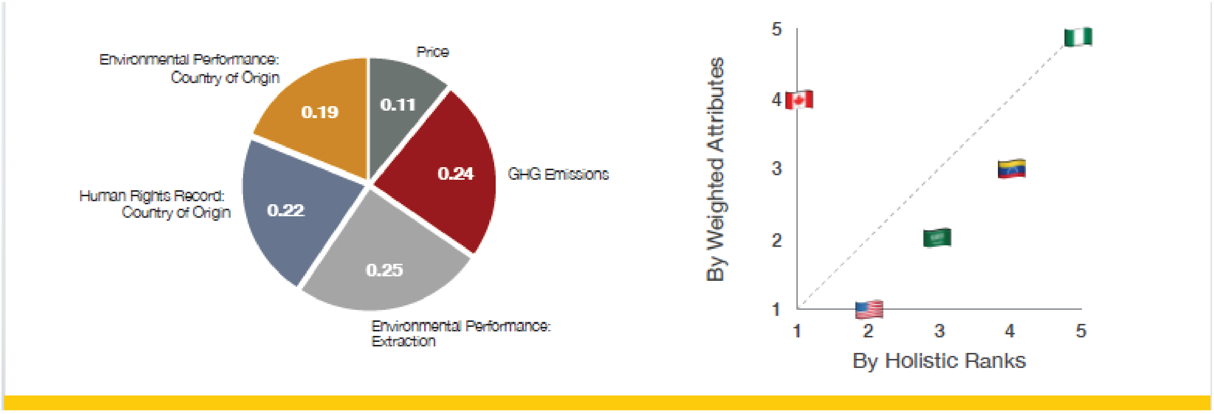

FIGURE 2-4 Trade-offs and preferences of Canadian consumers at the oil pump by weighted attributes.
SOURCE: Joseph Arvai, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 14, 2016, Newport Beach, California.

A study devised by Dr. Arvai and others on trade-offs compared consumer preferences at gas stations when prompted with information about a singular attribute of the gasoline versus information on multiple attributes.[13] When provided with only information on the location of oil extraction, the majority of Canadian participants chose gasoline from the oil sands of Canada first, followed by American oil second, Saudi Arabian third, Venezuelan fourth, and Nigerian fifth. Using the decision science technique of swing weighting, however, Dr. Arvai and his team found that Canadian preferences changed when provided with additional attributes such as origin, cost per liter, greenhouse gas emissions, overall environmental impact, and human rights score of the country of origin (Figure 2-4). On average, Canadians preference for Canadian tar sand oil dropped from first to fourth, U.S. oil from second to first, Saudi Arabian oil from third to second, Venezuelan oil from fourth to third, and Nigerian oil stayed at fifth. A complete lack of calibration between values important to individuals and the decisions they made persisted in different variations of the study with the rate never eclipsing 50 percent. Dr. Arvai called for framing these questions of preference in a manner that does not incite individuals to make decisions based on an emotional appeal, but instead in the larger context of intergenerational well-being.

Another example of prevalent research in decision sciences with relevant context to sustainability is the increasingly popular decision science concept of “nudging,” which provides an option to encourage individuals to make rational decisions based on their values as opposed to emotional decisions. Proponents of nudging suggest that if one can identify the instinctive patterns of biased preferences, then one can reconfigure the world to help individuals make choices internally consistent with their values.[14] Though such nudge studies have been highly successful, they suggest that individuals realize their internally consistent preferences in decision making without much effort, which does not completely align with the complexities associated with sustainability decision making. Using the concept of nudging to guide society in the right direction in making sustainability decisions may not make significant progress on some of the largest sustainability challenges.

Daniel Kahneman’s book *Thinking Fast and Slow* recognizes the need for more active cognition by advising individuals to slow down in high-stake decisions.[15] Dr. Arvai counter argues Kahneman’s speed argument for high-quality decision making by noting that individuals will simply make bad decisions more slowly due to the difficulty of weighing preferences and trade-offs. Increasing consultation, improving accessibility to high-quality

[13] Bessette, D., and J. Arvai. 2014. A lack of internal consistency plagues consumer and policy preferences. In prep.
[14] Thaler, R. H., and C. R. Sunstein. 2008. *Nudge: Improving Decisions about Health, Wealth, and Happiness*. New Haven, CT: Yale University Press.
[15] Kahneman, D. 2011. *Thinking, Fast and Slow*. New York: Farrar, Straus and Giroux.

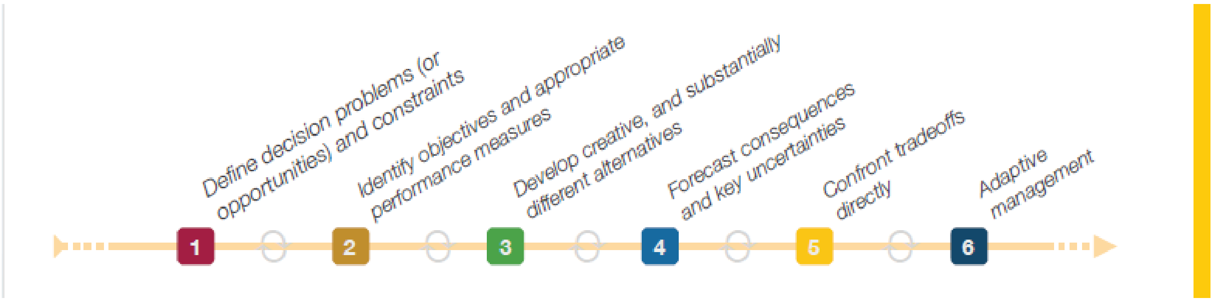

FIGURE 2-5 A decision support tool for sustainability decision making emphasizing internally consistent values and sustainability goals.
SOURCE: Joseph Arvai, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 14, 2016, Newport Beach, California.

information under science-based decision making, and creating platforms or environments that facilitate negotiation all constitute possible paths forward for decision support. Additionally, he said a missing essential element is imposing a structure that can decompose complex decision problems into cognitively manageable parts to help move society toward internally consistent choices that would lead to intergenerational well-being.

Dr. Arvai also discussed new efforts to address needs and opportunities related to sustainability and reiterated the importance of structure (Figure 2-5). Firstly, collaboration with communities and individuals may improve understanding, identification, and characterization of the decision problems and opportunities they face. In addition, identification of appropriate objectives and performance measures may be essential to decision making. In the sustainability context, dialogue often focuses on making more sustainable decisions without defining what "more sustainable" means. Regarding indicators, from a decision-making standpoint, some measurement challenges remain—a multitude of metrics for sustainability can be devised, yet an individual decision maker may only handle about five to seven at any one time. Thus, paring down the indicators most useful for decision making and developing a list of creative and substantially different alternatives may facilitate decision making. Confronting trade-offs directly is also a needed element in addressing sustainability decision making and finding pathways for individuals, whether sustainability decision makers or stakeholders, to make tough trade-off decisions. Further, an adaptive management and iterative decision-making process where individuals make decisions and then implement, evaluate, learn from, and remake those decisions can highly benefit sustainability decision making. As an example, he pointed to a research project with Michigan State University focused on decision making for an energy transition in the context of sustainability that developed a number of decision support tools to move individuals toward preferences more internally consistent with their values and sustainability goals.[16]

Dr. Arvai concluded his discussion by pointing to the need for further work in behavioral science dealing specifically with sustainability. There is also a need to scale up from purely behavior studies to prescriptive studies on how to move individuals to make decisions internally consistent with their values and objectives.

Wolfgang Lutz, founding director of the Wittgenstein Centre for Demography and Global Human Capital (a new collaboration between the International Institute for Applied Systems Analysis (IIASA), the Austrian Academy of Sciences and the WU-Vienna University of Economics and Business), examined global population trends in the context of sustainability. He discussed how human numbers and demographic differential vulnerability relate to sustainability challenges, as well as what well-being indicators and demography metrics offer for sustainability science. He began with a brief analysis of world population outlooks commenting that population metrics had varying degrees of uncertainty largely due to rapid fertility rate declines in Africa (Figure 2-6). He also presented

[16] Bessette, D., J. Arvai, and V. Campbell-Arvai. 2014. Decision support framework for developing regional energy strategies. *Environmental Science & Technology* 48:1401–1408.

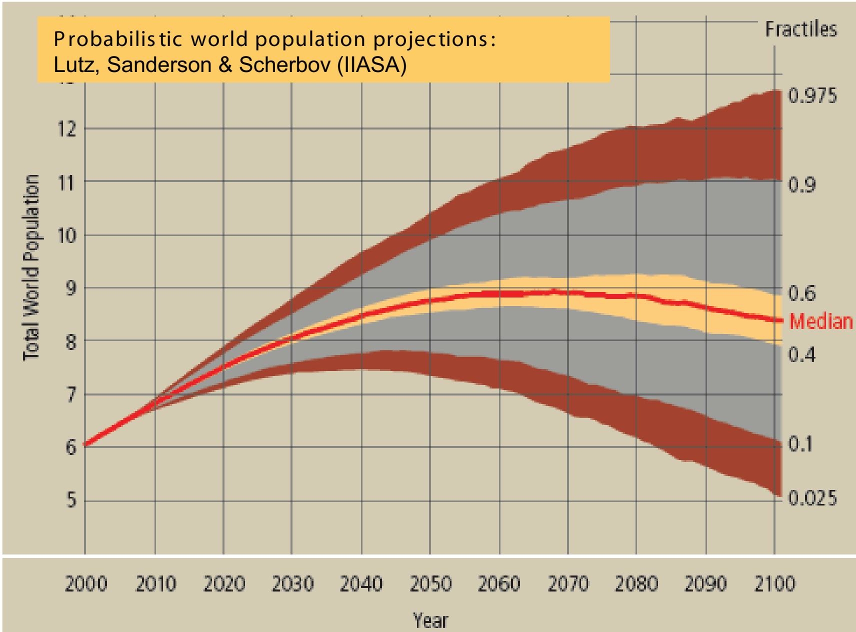

FIGURE 2-6 International Institute for Applied Systems Analysis (IIASA) probabilistic world population projections. The red segment represents a 95 percent uncertainty range for world population projections, the grey segment represents a 80 percent uncertainty range, and the yellow segment represents a 20 percent uncertainty range.
SOURCE: Wolfgang Lutz, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 14, 2016, Newport Beach, California.

population outlooks based on level of education (Figure 2-7). Recent research at the IIASA predominantly focused on producing what Dr. Lutz termed "the human core of the shared socioeconomic pathways," which includes population numbers, age structures, gender distributions, and educational attainment levels.

Regarding heterogeneity of the human population, education may be considered the single most important source of observable population heterogeneity after age and sex. In the context of population dynamics, the changing educational composition of the population directly influences changes in population growth and age distribution. Additionally, education is largely considered a crucial determinant of individual empowerment and human capital—driving socioeconomic development in public health, economic growth, quality of institutions, and democracy. As such, this type of analysis may provide important insights as related to sustainability.

Dr. Lutz elaborated on education as a demographic dimension by describing the education-cognition effect, where such variables as health, fertility, and other forms of behavior have an established functional causality to cognition and education. At the individual level, education increases cognitive skills, which may lead to less risky behavior by extending the planning horizon to enable a person to better plan ahead and learn from past damage at the individual and social level. Education can also positively affect health and physical well-being by acting as a growth enhancement. Better-educated societies typically tend to have a higher GDP, which may also decrease vulnerability. In one series of studies, IIASA asked the question, "What is more important for infant mortality, the mother's income or education?" The mother's education consistently proved the most important factor at the individual, household, and national levels.[17]

[17] Pamuk, E. R., R. Fuchs, and W. Lutz. 2011. Comparing relative effects of education and economic resources on infant mortality in developing countries. *Population and Development Review* 37(4):637-664.

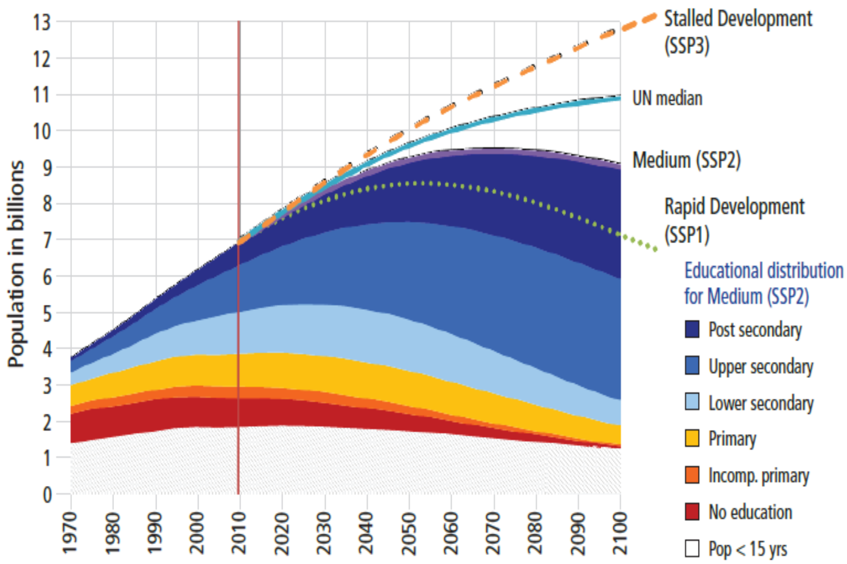

FIGURE 2-7 United Nations probabilistic world population projections.
NOTE: Chart 1 Historical trend and projections according to the medium scenario (SSP2) for the world population by six levels of educational attainment (see color coding). The additional lines are superimposed.
SOURCE: Wolfgang Lutz, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 14, 2016, Newport Beach, California.

In the context of human capital, demographers focus on the quantity of formal education for data measurement. They also consider informal education, though it is more difficult to measure. "Education stocks" typically measured in mean years of school or full distribution of highest educational attainment largely determines human capital. A population pyramid study for Singapore in the 1970s, 1980s, and 1990s observed a process of demographic metabolism and intergenerational change where the educated population increased as the country transformed from developing to developed. Another study conducted by Dr. Lutz and others at IIASA calculated projections of population growth based on education's relationship to fertility (Figure 2-8). In Kenya, highly educated populations had an average of two children compared with more than six children in uneducated populations.[18, 19]

Dr. Lutz addressed the issue of the human population's adaptive capacity to climate change. A recently completed 5-year project that forecasted society's adaptive capacity to climate change illustrates that society's capacity to innovate and develop green technologies and mitigation strategies is a function of education in society. Dr. Lutz and others pointed to a clear differential vulnerability in adaptive capacity to climate change where climate change does not affect the entire population, but rather affects livelihoods, health, and migration possibilities and depends on the individual's empowerment.[20] Similar results were summarized for vulnerability to natural disasters, where research established education as a key determinant.[21] Thus, generally empowering the population to adequately respond to climate change challenges may be more effective than only developing concrete climate change infrastructure. Such data may also indicate that, in addition to universal primary education, near universal secondary education may also improve sustainable development.

[18] Lutz, W., and S. KC. 2011. Global human capital: Integrating education and population. *Science* 333(6042):587-592.
[19] Lutz, W., W. P. Butz, and S. KC, eds. 2014. *World Population and Human Capital in the Twenty-first Century*. Oxford: Oxford University Press.
[20] Lutz, W., R. Muttarak, and E. Striessnig. 2014. Universal education is key to enhanced climate adaptation. *Science* 346(6213):1061-–1062.
[21] Muttarak, R., and W. Lutz. 2014. Is education a key to reducing vulnerability to natural disasters and hence unavoidable climate change? *Ecology and Society* 19(1):42.

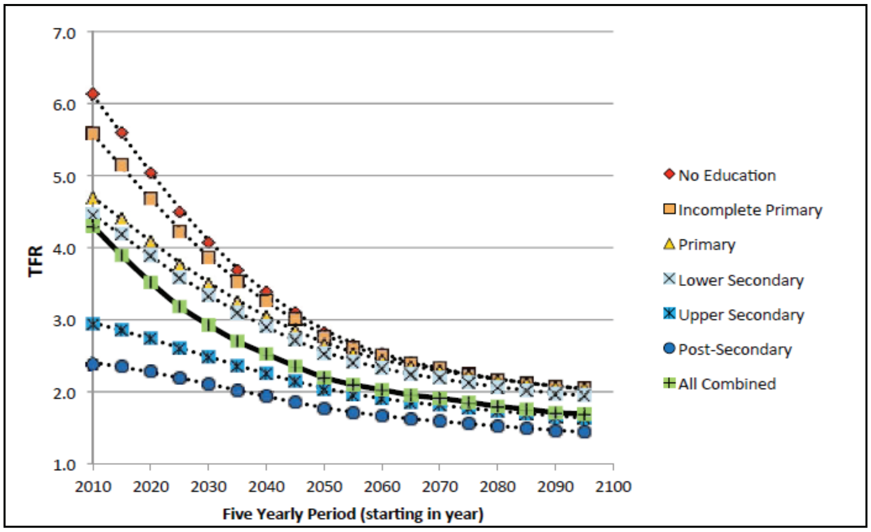

FIGURE 2-8 IIASA calculated population growth projection of Kenya based on the relationship between education and fertility (TFR=total fertility rate).
SOURCE: Wolfgang Lutz, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 14, 2016, Newport Beach, California.

In identifying other indicators relating to human well-being, he said that being alive is a basic prerequisite often missed by sustainability indicators and metrics. However, Dr. Lutz argued that mere survival may not sufficiently achieve sustainability and pointed to empowered life years as a possible alternative measure. Empowered life years could encompass healthy life expectancy (how many years an individual can expect to be alive and in good health), or literate life expectancy, poverty life expectancy, happy life expectancy, or any combination of these factors. A possible sustainability metric based on demographic indicators would measure empowered life expectancy and account for whether it declined over time in any subpopulation or not.

The question-and-answer session raised the issue of conflict and sustainability and if any studies examined the relationship between levels of education and conflict within the boundaries of a country. Dr. Lutz referenced a body of research that related empowerment and the education of a population to political outcomes and processes—indicating there is a relationship between demography and democracy. He also mentioned global migration and how the choice to migrate may be essential in terms of sustainability and that migration should be incorporated into integrative modeling. It was noted that as an extremely complex and multifaceted issue, migration may not have a single solution, particularly with respect to global environmental change.

INTEGRATED ANALYSIS

Kristie Ebi, professor, Department of Global Health and Department of Environmental and Occupational Health Sciences at the University of Washington, discussed drivers of indicators and metrics as they relate to frameworks for evaluating health systems and climate change. Many health indicators focus on children and often integrate many health issues, such as nutrition, vaccination of children, and childhood mortality. In 2015 the World Health Organization (WHO) released an operational framework composed of ten components related to building climate-resilient health systems (Figure 2-9).[22]

[22] World Health Organization (WHO). 2015. *Operational Framework for Building Climate Resilient Health Systems*. Available at http://apps.who.int/iris/bitstream/10665/189951/1/9789241565073_eng.pdf.

FIGURE 2-9 Ten components composing WHO's operational framework for building climate-resilient health systems.
SOURCE: Kristie Ebi, Presentation, National Academies of Sciences, Engineering, and Medicine, January 15, 2016, Newport Beach, California.

One challenge Dr. Ebi noted for developing metrics around climate-informed health programs is the need to better account for information provided by models of climate systems. For example, the public health sector creates metrics around heat-related mortality, but those metrics do not take into account short-term forecasts about climate change. This would help public health officials to better set up early warning systems and make action plans for periods of decades or longer. Indicators and metrics are needed to better understand what has been learned about climate programs and assess other ways to learn those lessons.

Related to this learning process is the incorporation of theory of change, which is "a comprehensive description and illustration of how and why a desired change is expected to happen in a particular context. It is focused on mapping out or 'filling in' what has been described as the 'missing middle' between what a program or change initiative does (its activities or interventions) and how these lead to desired goals being achieved."[23] Dr. Ebi noted that many organizations have adopted this approach for development projects and that there will be upcoming opportunities to review their work to assess successes and failures. In conclusion, Dr. Ebi said that there are many potential indicators related to sustainability in the literature and being used in practice, but that there needs to

[23] See www.theoryofchange.org.

be a systematic way of integrating them all. There is also the need for an institutional and political climate that encourages the development of indicators that aim to be broader than single issue-based foundations.

Elena Bennett, associate professor at McGill University, discussed models that support decisions related to sustainability, gaps and critical barriers to models, and new efforts needed to address opportunities related to sustainability. Dr. Bennett framed the discussion around sustainability development goals, and identified successes in an integrated assessment model as moving the needle closer to achieving those goals (Figure 2-10). One of the first applications of integrated assessment models was to understand environmental and economic impacts of acid rain on biological systems. From there, they were further developed for the International Panel on Climate Change (IPCC) to integrate climate and economics into an understanding of global systems. They were also developed for the Millennium Ecosystem Assessment, which integrated ecological feedback into biogeophysical models. This integration was accomplished with output from biogeophysical models used by the IPCC as input into models with ecological feedback incorporated, such as InVEST or other ecosystem service models.[24] Ongoing work with these models focuses on incorporating the needs and consideration of stakeholders and decision makers. The Madingley Model from Microsoft Research's Computational Science Laboratory in Cambridge is the first General Ecosystem Model, which attempts to simulate all life on Earth. The model couples key biological processes underpinning life cycles and behaviors of all of the planet's organisms.[25]

Dr. Bennett said integrated assessment models have become increasingly more robust and rigorous; however, successful models may result from increasing parameterization until desired outputs are achieved. The millennium assessment models were different, i.e., more robust, because they were more integrated and contained more feedbacks (e.g., climate, economics, ecology).

Remaining gaps include large scale models with limited focus that are not useful for decision making. For example, there is generally a single focus on the effect of a single intervention, such as food security with limited integration of energy systems. Ecology is often missing from models, and social systems are entirely nonevident except for economics. Feedbacks are rare and are limited in action within models, especially ecological feedbacks. There is limited model validation, so accuracy is unknown. Dr. Bennett said her research group ran InVEST on data for more than 190 counties with 12 different ecosystem services; however, there were only three services they could model using InVEST. There was also no correlation between the InVEST model output and actual data. This lack of correlation could be from inaccurate on-the-ground measurements or errors within the model. No amount of reparametrizing could correlate the model with data from the field. This raises questions about whether these models should be used for decision making when there is so much uncertainty and no means yet of addressing that uncertainty or risk.

Dr. Bennett discussed new efforts needed to further move toward well-being. Codesign and coproduction are key areas for development, which engages users not only at the end of the process but also as contributors to the development of scenarios and models. Dr. Bennett shared an example of a project that engaged shareholders in developing scenarios. The project focused on communities in a mostly agricultural region southeast of Montreal, Canada interested in land-use planning and designing better networks among forest patches to improve ecosystem services. Dr. Bennett's group engaged mayors and land-use planners to develop a scientifically and theoretically interesting project around ecosystems services that provided land-use planners with useable information.

The project further focused on land use and cover, which are parameters planners can manipulate to increase biodiversity. These parameters were tied to a set of 12 ecosystem services in the region. The relationships among land use, ecosystem services, and biodiversity were evaluated for the past, from the year1900 on, for the present, and into the future. Stakeholders were engaged to develop future land-use scenarios, and models were built around those scenarios. Different ecosystem services would be expected from different landscapes determined by land-use decisions (Figure 2-11). Land-use planners wanted to optimize ecosystem services, represented by different petals on a diagram, by adjusting where forest patches were located on the landscape.

Another key area for future efforts is in better thinking about futures, as in scenarios for modeling future outcomes. Dr. Bennett discussed Seeds of a Good Anthropocene, which is a project focusing on finding pockets

[24] See www.naturalcapitalproject.org/invest.
[25] See www.madingleymodel.org.

FIGURE 2-10 United Nations 17 Sustainable Development Goals.
NOTE: See https://sustainabledevelopment.un.org/sdgs.
SOURCE: Elena Bennett, Presentation, National Academies of Sciences, Engineering, and Medicine, January 15, 2016, Newport Beach, California.

of a better future that already exist today and using them to understand how, where, and why transitions occur. There are many utopian visions in classic literature and in modeled scenarios in scientific literature, but there is never an explanation of the transition needed to arrive at the scenario. Other key topics that are part of utopian narratives that need to be incorporated into integrative assessment models include cultural diversity, resilience, political economy, and urban centers. They collected 350 "seeds" from all around the world, which she described as not just good-news stories but examples that can lead to real transitions to sustainability and be used to rethink the future in entirely new ways.

Thomas Dietz, professor of sociology and environmental science and policy and assistant vice president for environmental research at Michigan State University, presented on informing sustainability science through advances in environmental decision making. The National Research Council (NRC) report *Our Common Journey* and the United Nations Millennium Ecosystem Assessment led to a body of scholarship on the relationships between human well-being and the environment. The focus on inclusive human well-being and the environment

FIGURE 2-11 Land-use planners were able to change petal diagrams representing ecosystem services from a given landscape by adjusting where forest patches were located on the landscape.
SOURCE: Elena Bennett, Presentation, National Academies of Sciences, Engineering, and Medicine, January 15, 2016, Newport Beach, California.

allows researchers and policy makers to focus on a select number of indicators that are broad, have normative consensus, and for which relatively good data exist. A more select list of indicators helps to avoid a cacophony of hundreds of indicators and can supplement standard economic measures, such as gross domestic product per capita.

There is an increasing amount of empirical research on the factors that influence well-being. Measures of resources, for example, are used as inputs along with contextual information to determine the factors that shape resource use. Another example is the relationships among carbon dioxide emissions, measures of stress on the environment, and measures of well-being. These relationships can be used to identify countries that seem to be doing very well in terms of well-being and examine the factors that led to success in those countries. For example, one factor is governmental institutions, which could develop strategies that would help move other countries toward better human well-being while maintaining minimal impacts.

Dr. Dietz said that further work is need in several areas, including on whether the environment and other species are the only means to human well-being, what other ethical theories or values justify endpoints, how varying ethical theories are reconciled, and what other theories can shape research on how resources, institutions, and people influence endpoints. The identification of measurement properties about endpoints is also needed, as well as an examination into how variables (indicators) that society conjectures drive endpoints. Lastly, the issue of discounting or substitutability of resources remains an outstanding challenge to address. Dr. Dietz said that ethical theories are a key area of investigation and that it has been empirically shown that peoples' values and concern with the biosphere (including other species) is correlated with, but also distinct from, altruism directed toward other people. An examination of whether major changes in the biosphere, such as Glacier National Park without glaciers or Joshua Tree National Park without trees, matter intrinsically to society is an example of how new ethical theories need to be brought into natural resource decision making.

Key lessons have been learned in this research area. There is widespread acknowledgment that there is global environmental change of coupled human ecology and natural systems and not just climate change. Such systems are complex and evolving, and researchers have to be cautious about how subsystems are isolated for studying or modeling. Interdisciplinary work is essential, and social networks are fundamental to learning about and responding to change. Sustainability is about linking the conservation community with the development community, but in considering development and well-being, it is also important to consider what other 21st century issues may affect human well-being and the environment, such as globalization, the Internet of Things, robotics, artificial intelligence, and bio- and nanotechnology; however, 19th and 20th century challenges also still exist—poverty, violence, and discrimination.

These issues need to be integrated to determine how they affect each other in addition to well-being. For example, what response would be needed if developments in robotics and artificial intelligence over the next 50 years substantially reduced the demand for labor? What effect would that scenario have on poverty and human well-being, and how would that fit into the current thinking about sustainability? This leads to another key lesson learned, Dr. Dietz said, which is that uncertainty pervades. At best, uncertainty can be characterized as quantifiable risks, but typically it is characterized as meta-uncertainty. Meta-uncertainty is uncertainty about how to characterize a system, including how other subsystems influence the overall system. Methods are being developed and approaches framed to understand and deal with this uncertainty, which is a form of adaptive risk management. Institutions and networks that learn in the face of such uncertainty are needed to further develop this idea of adaptive risk management.

Dr. Dietz said that there has been a lot learned about values and their influence on decision making. Researchers are beginning to learn how to link scientific analysis to public deliberation about values. Acknowledging values and learning how to incorporate values into research are important. There is an iterative communication process between the public and those conducting scientific analysis, which links public deliberation with the analysis. A 2008 NRC report on public participation concluded that "when done well, public participation improves the quality and legitimacy of decisions and builds the capacity of all involved to engage in the policy process."[26] Improvement in this context means that the quality of decisions or assessments is better.

There is a challenge, Dr. Dietz said, when conducting an analysis in figuring out how to engage multiple standpoints, acknowledge different types of expertise, and take advantage of social learning on networks. Individuals who engage in an analysis may have several different types of expertise. Scientific expertise is at the center of this, but there are multiple types of scientific expertise:[27]

- Scientific expertise about substance: expert knowledge about the systems and processes that will be affected by decisions.
- Scientific expertise about process and decision making: expert knowledge about individual and collective decision making, including valuation.
- Community expertise: knowledge based on life experience and living in systems that will be affected—"traditional ecological knowledge."
- Political expertise: knowledge about conflicts, assumptions, trust, and informal institutional arrangements based on engagement in policy systems.

[26] National Research Council (NRC). 2008. *Public Participation in Environmental Assessment and Decision Making*. Washington, DC: The National Academies Press.

[27] Dietz, T. 2013. Bringing values and deliberation to science communication. *Proc. Natl. Acad. Sci.* 110:14081–14087.

- Value expertise: everyone has legitimacy regarding values, but good processes and research may help articulate values and reduce value conflict.

Sustainability is about decisions and making trade-offs under uncertainty. There are many different theories on how to conduct trade-offs and address uncertainty, but there needs to be more work on learning how to integrate theories and determine which ones function best in which context. In general, more work is needed in being more attentive to context—context matters. There needs to be more consideration of individuals as being embedded in communities, which are embedded in nations. There is a tradition of place-based studies, but there is also a need to incorporate the individual and a need for the individual to be integrated into large macrocomparative (across nations, time, and/or institutions) analyses. Datasets are needed that provide comparable data on representative samples of individuals across large numbers of context and different nations. Such data would help to understand contextual- and individual-level effects. An example of how this can be accomplished is with the World Fertility Survey, where comparable surveys were conducted in a large number of countries.[28] These surveys examined how women's education affected fertility, as well as how the national context affected women's education on fertility. More data are needed, though, as is the need to build more of a community of new scholars and practitioners.

[28] See http://ghdx.healthdata.org/series/world-fertility-survey-wfs.

3

Urban Systems

Stephen Polasky, Fesler-Lampert Professor of Ecological/Environmental Economics at University of Minnesota, opened the panel by reiterating that world is becoming increasingly urbanized, and that it is important to assess how exactly this movement toward urbanization affects resource sustainability. He highlighted the importance of research on urban systems as new and innovative ideas, technologies, and policies, are increasingly being driven and produced by cities.

John Crittenden, director of the Brook Byers Institute for Sustainable Systems at the Georgia Institute of Technology, provided an overview of commonly used and emerging urban sustainability indicators. From a global perspective, Dr. Crittenden said that human society has many challenges in its path forward in reaching sustainability. He provided an example to illustrate what he termed society's global report card in regards to interfering with natural cycles. The expanding world economy and increasing population creates more waste than nitrogen, phosphorous, water, and carbon cycles can handle, and society may not use or recycle enough renewable resources and material to offset consequent damages. To date, renewable energy sources contribute 18 percent of global energy production, yet 28 percent of material use. Meanwhile, 8.6 gigatons of carbon is being released into the atmosphere and 4,000 billion cubic meters of freshwater is being utilized, which is about 43 percent of available freshwater globally.

Dr. Crittenden grouped sustainability indicators and metrics into three broad categories defined as ecological sustainability indicators, social sustainability indicators, and the environmental sustainability index. Ecological sustainability indicators such as ecological, carbon, and water footprint assessments evaluate the impacts on a certain natural system and/or cycle. Social sustainability indicators measure impacts across the social and economic spectrum. Examples include the genuine progress indicator that attempts to monetize all economic, social, and environmental factors; the happy planet index that measures the degree to which long and happy lives are achieved; and the human development index that combines life expectancy, educational development, and income. The environmental sustainability index uses indicators that measure two main components of environmental health and ecosystem vitality (Figure 3-1). Though many of these indicators may add value to sustainability decision making in urban areas, he noted that further development of these indicators was needed and thus developed a toolbox to help address gaps in knowledge (Figure 3-2). The toolbox's improvement strategies are grouped into three layers: data and design, modeling, and decision support.

Within the data and design layer, Dr. Crittenden indicated that modelers, scientists, and analysts could benefit from monitoring systems from within the larger infrastructure in which they exist. The cyber-physical infrastructure

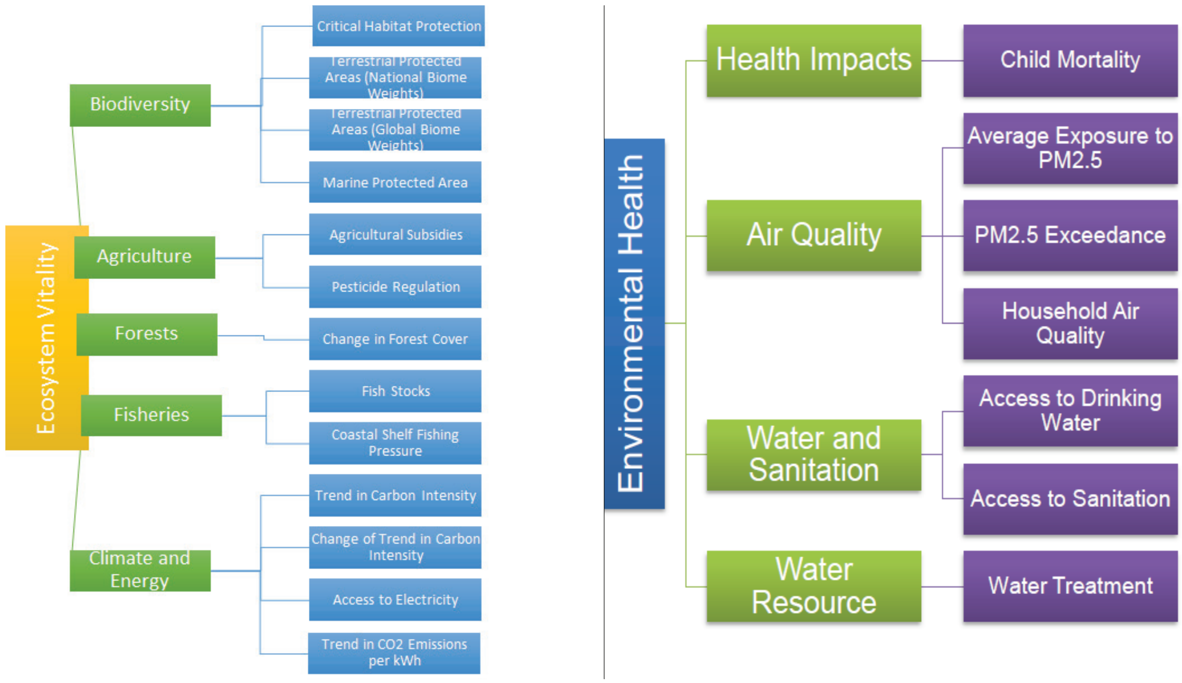

FIGURE 3-1 Indicators used for ecosystem vitality and environmental health, which are major components of the environmental sustainability index.
SOURCE: John Crittenden, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 14, 2016, Newport Beach, California.

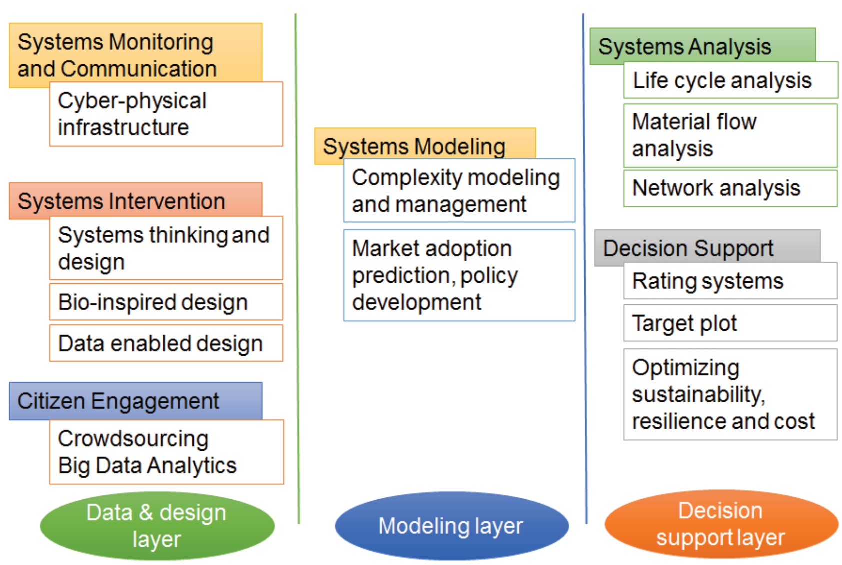

FIGURE 3-2 Framework for the toolbox to improve urban sustainability indicators and metrics.
SOURCE: John Crittenden, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 14, 2016, Newport Beach, California.

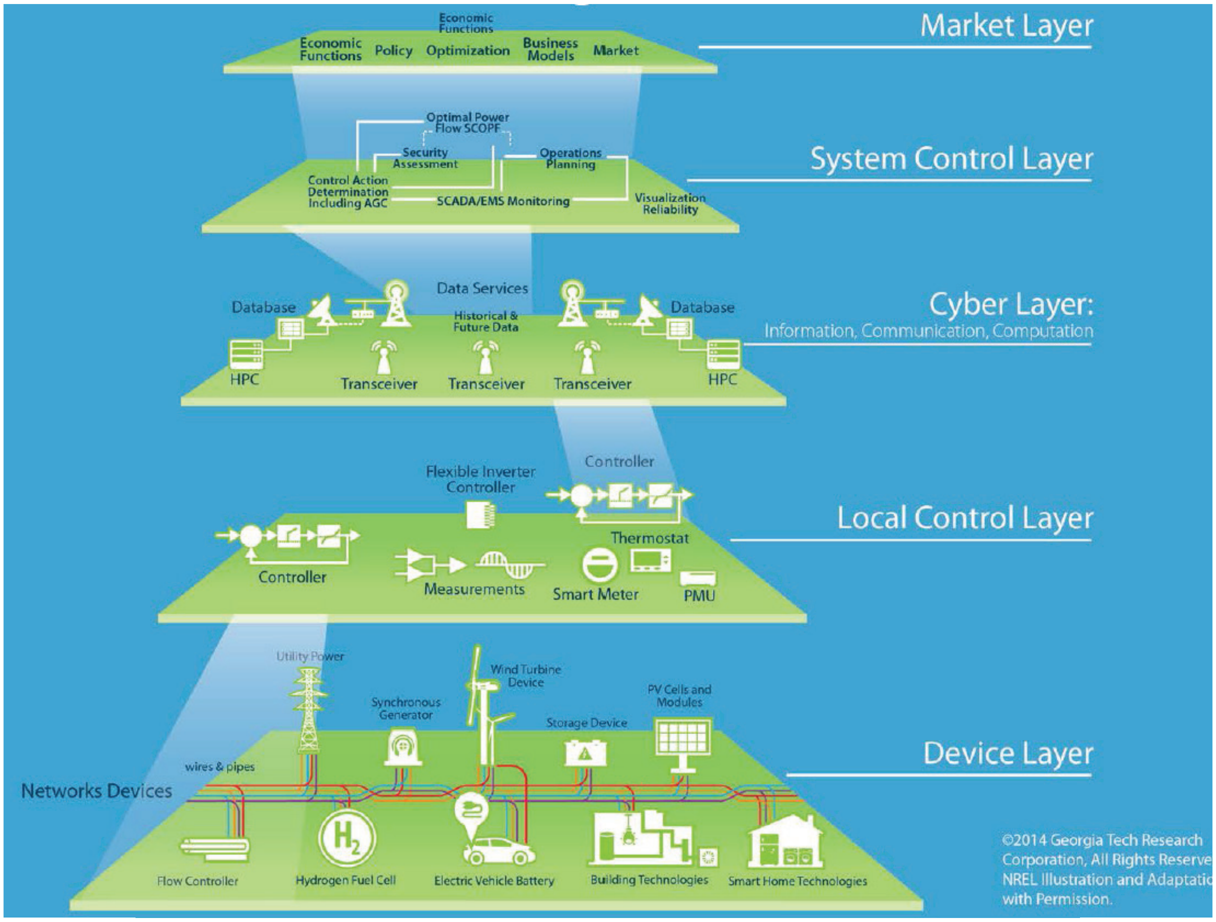

FIGURE 3-3 Cyber-physical infrastructure of the smart grid.
SOURCE: John Crittenden, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 14, 2016, Newport Beach, California.

of the smart grid illustrates one example where the devices involved in the grid, such as electric vehicles, wind turbines, and battery storage, rely on the flows and stocks that occur between the controllers, smart meters, thermostats, and measurements of the larger local control layer—the dependence of these activities continues to scale up until one assesses the interactions between policies, business models, and economic functions of the market layer (Figure 3-3).

Bio-inspired design, or biomimicry, adapts systems by applying ideas or structures from the natural world, such as designing a building to mimic the passive heat and cooling system of a termite mound. Dr. Crittenden provided examples from systems-thinking design, bio-inspired design, and data-enabled design to intervene in these systems and achieve positive outcomes within larger infrastructure. Systems-thinking design may stray from the traditional approach of building urban infrastructure by considering the interdependencies and interactions between socioeconomic and physical factors. The increase in low-impact development represents such new systems-thinking design of urban areas which, for example, incorporate ecology into grey infrastructure and reconfigures a city to handle water as a sponge instead of a transmitter of water to large pipes, storm-water collection, or other large water reservoirs. This added green infrastructure may create new recreational and public spaces that can improve social well-being, physical health, and property values.

Finally, the progression in data analytics improved the ability of urban sustainability decision makers to design around thousands of data points and individual preferences. In one study conducted by the Atlanta Regional Commission, a framework for autonomous vehicles was designed based on comments from more than 1,500 individuals, which identified future challenges such as protecting autonomous vehicles from cybersecurity threats, understanding how these vehicles will influence traffic congestion, and the policy incentives the city will need to establish the vehicles.[1]

Nevertheless, the data and design layer of urban sustainability modeling may need further development, and Dr. Crittenden stressed that science would benefit from analysis of the root of urban systems and structures—the citizens—and identify society's preferences and values in order to create agent-based models that reflect how society's decisions affect movement and interactions in the larger urban system. Cities and researchers frequently apply crowdsourcing to determine what citizens value and evaluate if the services that are provided fulfill these wants. In one study that Dr. Crittenden termed a *Mechanical Turk* study, the decisions made by a cohort of Atlanta citizens were analyzed at the microlevel of where these individuals lived, consumed, and worked. The study found that the city's development strategies of designing new buildings and highways did not align with the citizens' desires for an improved overall quality of life. In response, an agent-based model was developed that considered optimal land-use plans for Atlanta that provided amenities favorable to the adoption of a more sustainable infrastructure and improved quality of life.[2]

Dr. Crittenden acknowledged that agent-based modeling could improve its ability to capture complex and emergent properties of urban systems. As an example of progression in agent-based modeling, he presented the SMARTRAQ project (Strategies for Metropolitan Atlanta's Regional Transportation and Air Quality), an urban planning model of development pattern scenarios in Atlanta. Researchers are now able to assess information on more than 1.3 million parcels and project the city's growth patterns and potential to adopt compact growth practices based on an average of 35 attributes for each parcel, such as road type or owner-occupied tax value. Dr. Crittenden projected that growth will continue to sprawl and favor low to medium residential development in a business-as-usual scenario. More compact development action and policy, however, can reduce urban sprawl, increase land devoted to forests and greenways, and further commercial and residential growth.

He additionally discussed how enhancement of sustainability indicators and metrics can provide valuable decision support in urban areas, particularly advancements in network analysis. He concluded his remarks by highlighting the issue of urban sprawl, and presented a comparative fractal dimension study of the Washington, D.C., road network versus the Atlanta road network. In the study, a high fractal dimension number indicated more connections to roads, easing single passenger transit and urban sprawl, which, in turn, results in a higher carbon footprint. He reinforced this assumption by finding a higher fractal dimension figure and a higher carbon footprint for Atlanta of 3.36 and 1.52 metric tons of carbon per capita per year, respectively. The fractal dimension figure and carbon footprint for Washington, D.C., was 2.80 and 1.07 metric tons of carbon per capita per year.

William Solecki, professor in the Department of Geography at Hunter College–City University of New York, discussed the connections between science and public policy in the context of cities. In terms of trends, most population growth over the next several decades will occur in urban areas, specifically in low-income countries and small- to medium-sized cities. In addition, recent international agreements, protocols, and understandings have seen an emergence of urban issues on the international policy agenda. For example, urban areas featured prominently during the 2015 United Nations World Conference on Disaster Risk Reduction,[3] in Sustainable Development Goal 11, and in the upcoming Habitat III summit.[4]

[1] Atlanta Regional Commission. 2015. *The Region's Plan: Phase II Survey Report*. Online. Available at http://documents.atlantaregional.com/The-Atlanta-Region-s-Plan/ARC-Phase-2-Survey-Report-Final.pdf. Accessed March 24, 2016.

[2] Atlanta Regional Commission. 2014. *ARC's Regional Plan Online – Phase 1: Data Analysis and Summary Report*. Prepared by AECOM. Online. Available at http://documents.atlantaregional.com/The-Atlanta-Region-s-Plan/Regional-Plan-Public-Survey-Phase-I-data-analysis-report.pdf. Accessed March 24, 2016.

[3] United Nations Office for Disaster Risk Reduction (UNISDR) Third UN World Conference On Disaster Risk Reduction, March 14–18, 2015, Sendai, Japan.

[4] United Nations Conference on Housing and Sustainable Urban Development (Habitat III), "The New Urban Agenda," October 17–20, 2016, Quito, Ecuador.

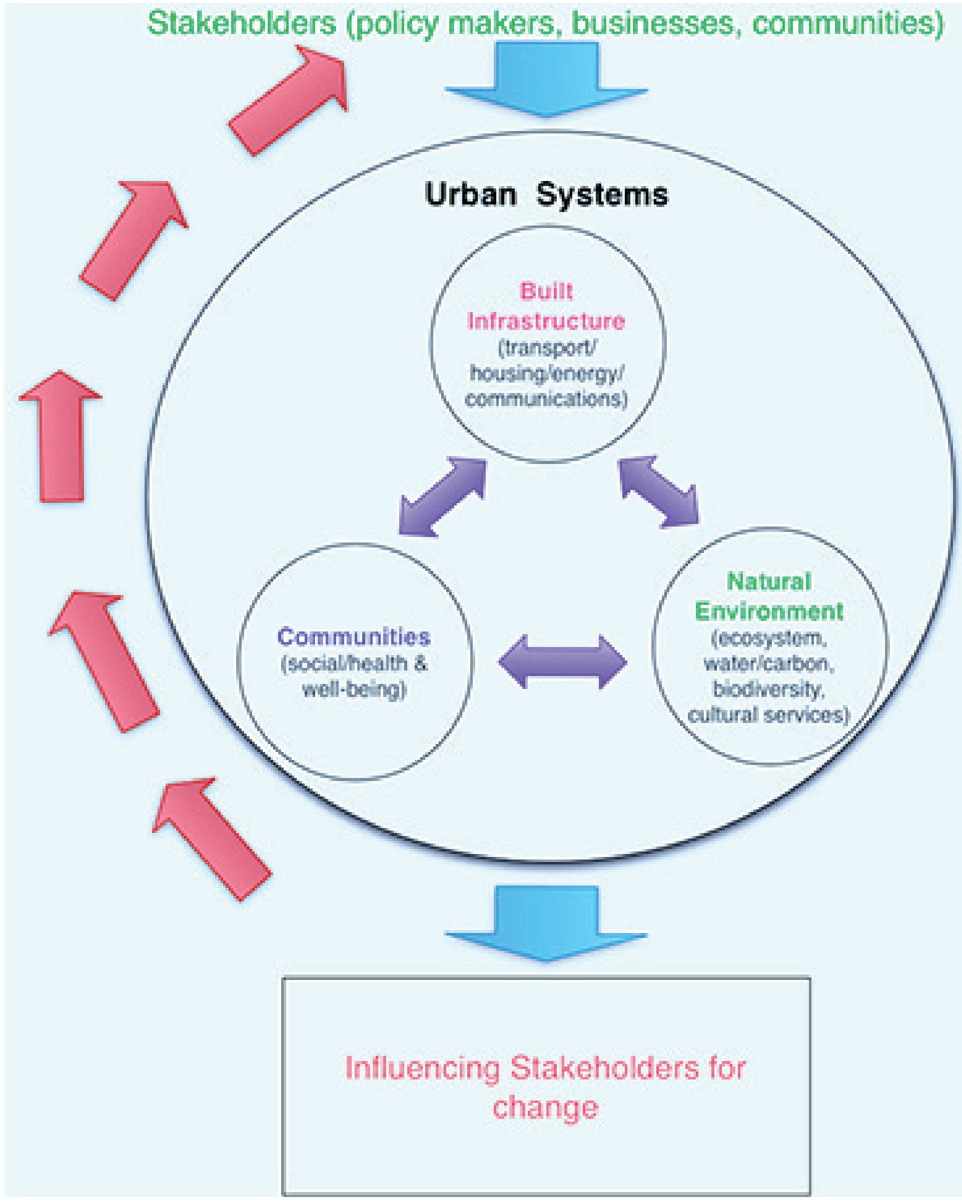

FIGURE 3-4 Conceptualization of urban science as a set of intersecting systems.
SOURCE: William Solecki, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 14, 2016, Newport Beach, California.

Dr. Solecki discussed the emergence of urbanization science and its conceptualization of urban areas, urban issues, and urbanization as a set of intersecting systems (Figure 3-4). Urbanization science research investigates interactions within this conceptualization and attempts to translate these data into information useful for policy and decision makers. Recent developments in translating urbanization science to policy include the robustness of data information about urban processes, uncertainty measures, likelihood measures, and climate work, which have highlighted the increased need for nuanced scientific information for decision making. Questions of current indicators and monitoring have also emerged, such as what indicators are still considered appropriate for cities or how can existing monitoring systems be integrated and directed toward new policy agendas of sustainability, resilience, or climate change adaptation? The urban domain has witnessed a tremendous amount of growth in community organization, bottom-up approaches, boundary organizations, and demands for open and transparent processes in decision making, and coproduction of knowledge.

Dr. Solecki further addressed traditional computational modeling, the role it plays in urban decision-making processes, and advancement in physical engineering (e.g., the built environment) and ecological system modeling (e.g., how urban ecosystems respond to stresses, evolve, and adapt to change) over the last 15 years. Computational models, however, may still require improvement to support decision making for the social side of urban issues. Other challenges may include a lack of appropriate data, capacity to operationalize urban systems analysis, basic science and expertise to address questions of sustainability, financial resources, and trust in products. One of the most flood-prone cities in the world—Calcutta, India—faces a data availability challenge because of a lack of access to a fully developed flood extent map for city officials to use in flood management.

For the most part, urban practitioners and researchers have done little work in creating an integrated modeling approach for urban spatial planning, with the exception of some European Union countries and China. Dr. Solecki indicated that city leaders work at the right level of governance to spearhead sustainability action due to their local understanding of their community's unique systems, risks, exposures, and vulnerabilities. In addition, these leaders retain links with local academic and research communities, direct contact with constituents, day-to-day management, and engagement with regional coordination efforts. Nevertheless, a number of challenges may remain for urban leaders, such as managing at a metropolitan scale, financing mitigation and adaptation measures, bridging differences between high- and lower-income cities, and maintaining momentum across municipal administrations and election cycles.

He also reiterated various types of science-policy linkages in an urban setting, such as the emergent concept of coproduction of knowledge where different groups come together in a collaborative process to define issues, solve problems, and produce and disseminate knowledge. One example of this concept of coproduction of knowledge is Future Earth, an international research platform bringing together scientists of all disciplines, society, and users of science to coordinate new and interdisciplinary approaches for global environmental change and sustainability. Another example includes the National Oceanic and Atmospheric Administration's (NOAA) Regional Integrated Sciences and Assessments (RISA) Program (see Figure 3-5), which promotes collaboration in the scientific community and information development directly with stakeholders to understand weather and climate risk issues, manage knowledge networks, and advance science policies (Figure 3-5). Dr. Solecki concluded by emphasizing the significant development of policy-relevant research on urban systems. Cogeneration of knowledge is an innovative frontier; however, a number of limitations remain, including the predominance of power relations, legal constraints, time intensiveness, stakeholder fatigue, and the possibility of the scientific community losing its "outside-the-box, cutting edge" thinking.

Karen Seto, professor of geography and urbanization and associate dean of research at the Yale School of Forestry and Environmental Studies, addressed various advances in urban systems that could inform sustainability science. Dr. Seto said that for urban systems, it is projected that cities will build more buildings and roads between now and 2050 than currently exist around the world. Further, if the built environment in the developing world reaches similar levels to developed countries, global carbon dioxide emissions will not meet the 2015 international agreement from Paris of holding the increase in global average temperatures to below 2 degrees Celsius above preindustrial levels. The dominant conceptualization of cities considers urban environments within spatial boundaries of a city with a minimal focus on what happens outside a city. She indicated that bringing cities and the process of urbanization into the sustainability dialogue would benefit this urban conceptualization, provide new frameworks that look beyond urban impacts on resources or the environment, and incorporate the interactions between people and the environment that extend beyond the spatial boundaries of a city.

As an example of progress in urban domains that could further inform sustainability science, Dr. Seto pointed to the creation of new institutions and programs on urban science. The Centre for Advanced Spatial Analysis at the University College London is an example of an institution looking at spatial patterns and fractal analysis, while the Senseable City Lab at the Massachusetts Institute of Technology provides another example of an institution focusing on "sensing" cities in real time. Dr. Seto notes, however, that these institutions and programs have not produced many new insights that challenge current understanding of urban systems.

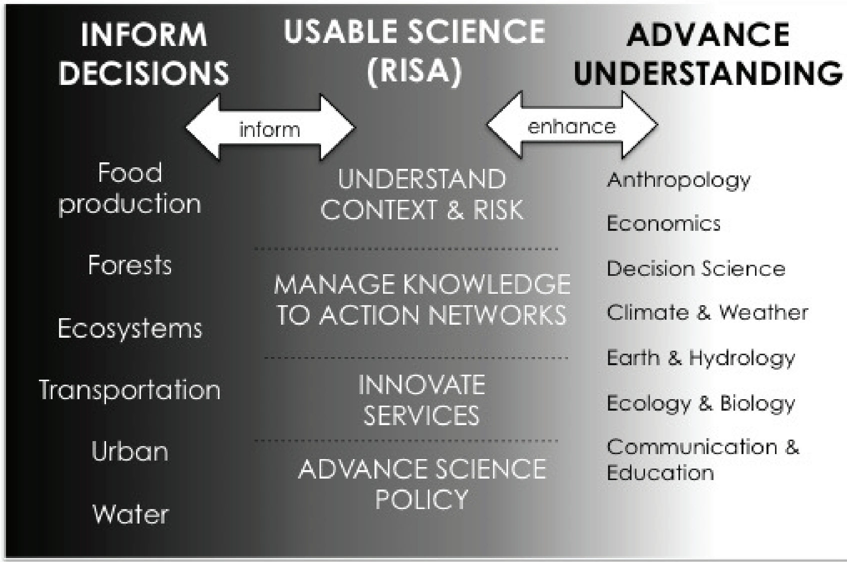

FIGURE 3-5 Structure of the NOAA RISA Program's coproductive knowledge process.
SOURCE: William Solecki, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 14, 2016, Newport Beach, California.

In light of the recent adoption of the Sustainable Development Goals, and Goal 11 on sustainable cities and communities, progress has been made in developing metrics and indicators for urban systems. The scientific community, however, has experienced a large degree of pushback in developing indicators and targets due to difficulty in data consistency and availability across countries. Other recent developments in urban science include a new interest by international organizations, development agencies, and foundations in developing new understandings and conceptualizations of cities.

Dr. Seto acknowledged that despite advancements in urban sustainability metrics and indicators, a large disconnect exists between the information produced by urban science and the information usable in management at the local scale. This disconnect is a challenge for efforts to fight climate change. There are also challenges to urban sustainability from resource demands and poverty, and the options to address these problems at the local level may be constrained by regional or national contexts.

Dr. Seto highlighted results from the International Panel on Climate Change (IPCC) that reflect on a need for new efforts and developments in science to better inform sustainability science in cities.[5] If the top 50 carbon-emitting cities were aggregated into one country, that country would still be the third largest emitter behind China and the United States. Large variations within or between developed and developing country cities' average per capita energy use suggest that developed country cities operate more efficiently than developing country cities (Figure 3-6). Scientist with different background would likely interpret these data differently. For example, a political scientist would interpret these graphs as illustrative of the varying institutions and governance across cities, an economist would point to the difference in economic structures, and urban planners would consider variations in transportation modes. Categorizing cities as either developed (Annex I) or developing (Annex II) does not provide the depth of needed information.

[5] Seto K.C., et al. 2014. Human settlements, infrastructure, and spatial planning. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. O. Edenhofer et al. Cambridge, UK, and New York, NY, USA: Cambridge University Press.

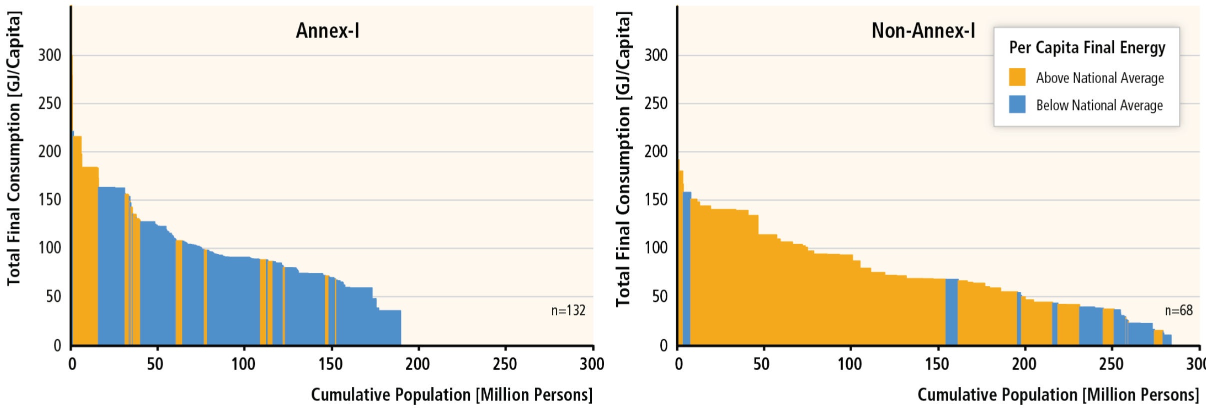

FIGURE 3-6 Variations in average per capita energy consumption between IPCC Annex-I (developed) and Annex-II (developing) country cities.
SOURCE: Karen Seto, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 14, 2016, Newport Beach, California.

Dr. Seto indicated that a large share of current research focuses on smart cities and sensing cities; however, further research should focus on different metrics and indicators of well-being rather than on ones targeting efficiency. In data gathering and analysis, the scientific community should look beyond measuring city growth. Observations and models of urban systems still lack sophistication compared with parallel observations and models of climate systems that have progressed not only spatially but also in complexity. An example of improving models of urban systems comes from researchers at the University of New Hampshire who utilized different types of satellite data to analyze the three-dimensional structure of cities.[6] Additional research, she said, is needed to understand the interplay between the social and environmental dimensions of urbanization. Dr. Seto stressed the importance of progressing from models that only analyze interactions within a city to a global model that incorporates global hinterlands and feedbacks across multiple levels (see Figure 3-7). Dr. Seto concluded her remarks by identifying two important research needs urban science can contribute to sustainability science—updating frameworks and theoretical development and improving data and metrics that analyze linkages and flows over space and time. She also added that since a sustainable city has yet to be defined, progress toward sustainability in the urban domain will remain a challenge.

In the question-and-answer session, the panelists discussed shared socioeconomic pathways (SSPs)[7] as a framework for considering development and progress toward sustainability. Dr. Solecki noted that the urban community is beginning to utilize such thought processes, but that the notion of the trajectory of cities remains crucial, and in many cases these trajectories are not necessarily within the realm of SSPs. Dr. Seto added that the urban community would benefit from alternative thinking about science for urbanization given the pace and magnitude of its development, noting that the urban community currently thinks in terms of optimization and best scenarios. The scientific community has yet to define the optimal solution for urban sustainability or what a sustainable city would look like.

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[6] Frolking, S., et al. 2013. A global fingerprint of macro-scale changes in urban structure from 1999 to 2009. *Environmental Research Letters* 8(2):024004.

[7] The SSPs are part of a new framework that the climate change research community has adopted to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation. The framework is built around a matrix that combines climate forcing on one axis (as represented by the Representative Forcing Pathways) and socio-economic conditions on the other. Together, these two axes describe situations in which mitigation, adaptation, and residual climate damage can be evaluated. Van Vuuren et al. 2012. A Proposal for a New Scenario Framework to Support Research and Assessment in Different Climate Research Communities. Global Environmental Change 222(1): 21-35.

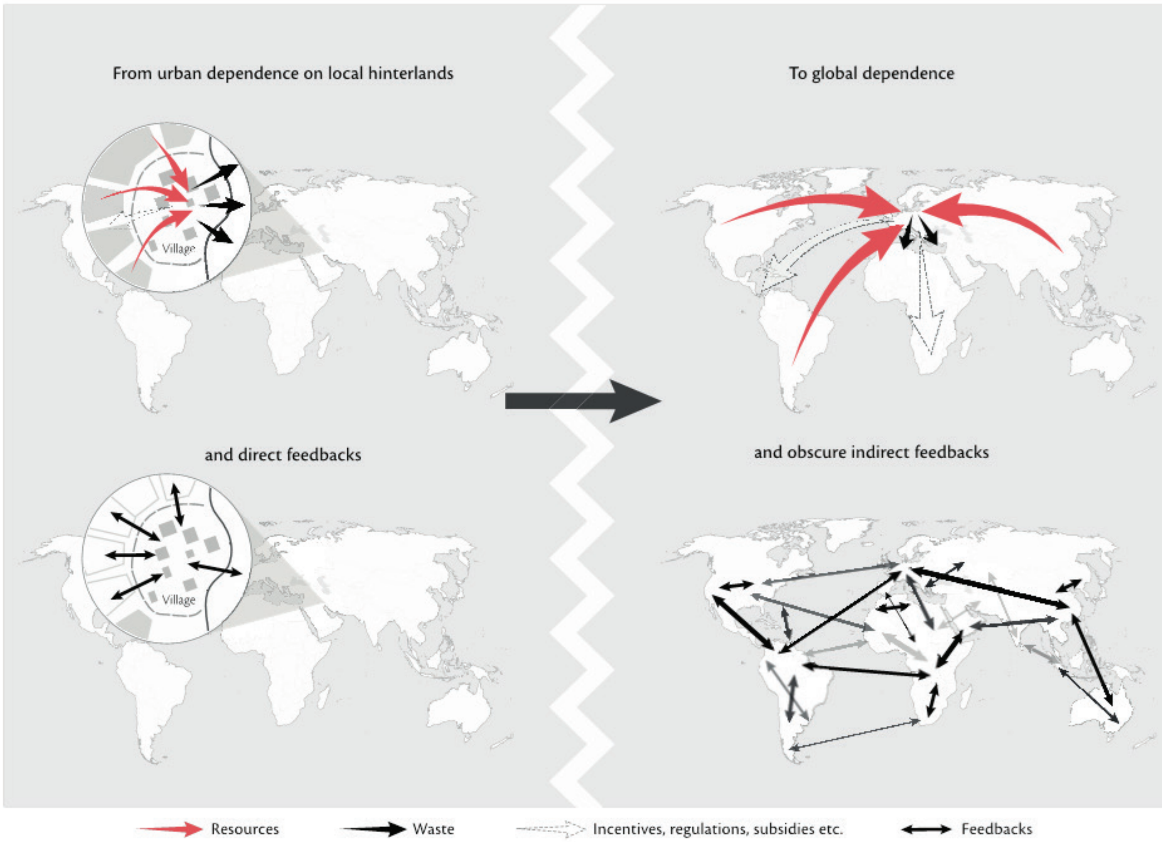

FIGURE 3-7 A possible global model incorporating global hinterlands and feedbacks across multiple levels for urban sustainability.
SOURCE: Karen Seto, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 14, 2016, Newport Beach, California.

The panelists also discussed efficiency indicators related to urban sustainability. Dr. Solecki said that for city managers, an efficiency indicator's ability to compare options using dollars allows for an easy measurement, but such an indicator does not account for all inputs, such as wellness and happiness, that are needed to achieve a sustainable city. Dr. Crittenden argued that the management of complex and diverse entities within a city is a more important role than ensuring urban efficiency by adopting a more sustainable infrastructure. Dr. Seto agreed, questioning whether efficiency measures really give the urban community any indication of well-being.

A final question posed to the panelists concerned the justification of thinking about urban systems as closed systems rather than coupled-urban systems, given that rural-urban migration affects both urban communities and rural communities. Dr. Seto said that such a framing reflects issues of data limitations, and in part the current methods of data analysis, wherein she reiterated the importance of advancements in theoretical frameworks for urban systems. Dr. Crittenden offered an alternative response, stressing that at this stage, the focus on interactions within cities—the city as an ecosystem—is still important for sustainability given the objectives of optimizing resource use and efficiency.

4

Sustainable Manufacturing

Anthony Ku, chemical engineer at General Electric (GE) Global Research, discussed possible approaches to closing gaps between knowledge and action in sustainable manufacturing. From Dr. Ku's perspective, while sustainability metrics and indicators used by companies have advanced, data would best stimulate action if the dots were connected between strategic activity taking place at the higher levels of enterprise (e.g., global and corporate administration) and the operational activities and decisions occurring at lower levels (e.g., individual products, processes, and manufacturing plants).

Dr. Ku discussed the importance of improving data quality in terms of accuracy, precision, frequency, and accessibility. In his research, Dr. Ku investigated the impacts of helium shortages on company activities, production, and profits. While the data was expected to suggest that helium shortages would negatively affect GE's health care business, the data instead discovered that many other GE products depended on helium to pass market quality standards, such as X-ray tubes, airplane engines, and nuclear fuel rods, which surprised decision makers and raised awareness of larger financial impacts that could result from helium shortages. Dr. Ku, however, stressed that the ability to overcome company firewalls and safeguards enabled access to information at the right level of granularity for actionable results, but this free flow of information does not occur everywhere in manufacturing, which may require creativity to navigate data constraints and achieve sustainable outcomes.

Dr. Ku also presented the economic case for sustainable manufacturing to businesses. McKinsey and Company leads many conversations about the business case for sustainability by using greenhouse gas cost curves (Figure 4-1). These cost curves display two opportunities in engaging private decision makers to consider more sustainable action by showing, firstly, that about a third of the curve's carbon-cutting activities is economical and profitable for businesses to implement, shown in Figure 4-1 as recycling and energy efficiency plotted against cost per ton of CO_2e; and secondly, that the immediate profit and benefit shown in this curve resonate with business decision makers, shown in Figure 4-1 by the low cost per ton of CO_2e of the capital intensity of carbon cutting activities, i.e., recycling and energy efficiency, and encourage consideration of further sustainable actions.

The second graph in Figure 4-1 further frames the issue of costs within the concerns of private decision makers by measuring capital intensity. In this context, the development of a set of scientific indicators and data points that link economic and financial values frequently occurring in business decision making may be beneficial.

Dr. Ku touched on the dynamics gap in sustainable manufacturing and business discussions and the importance of bringing experts from different disciplines to the table to explain unexpected and emergent phenomena. In an analysis performed on the relationship between rare earth consumption and light-emitting diode (LED) production,

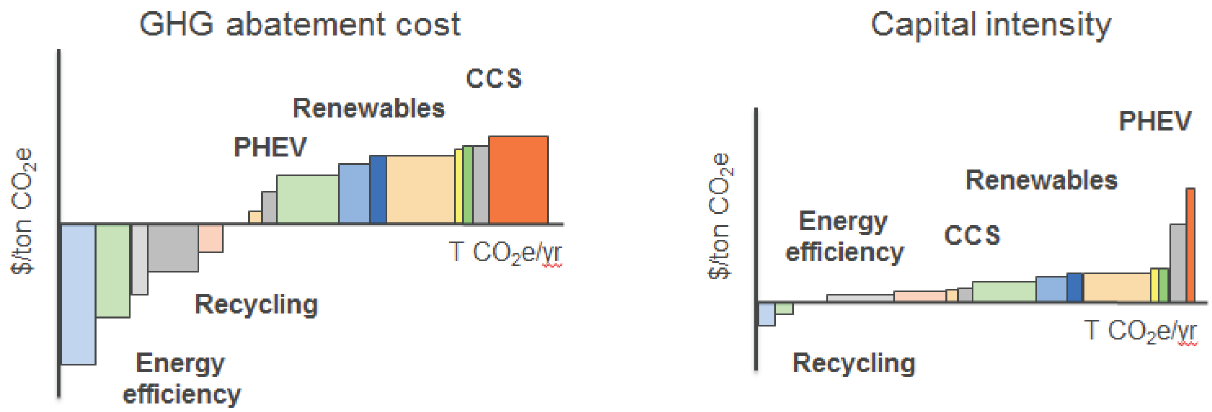

FIGURE 4-1 Marginal cost curves for CO_2 abatement.
SOURCE: Anthony Ku, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 14, 2016, Newport Beach, California. Adapted from McKinsey and Company 2009. Pathways to a Low-Carbon Economy Version 2 of Global Greenhouse Abatement Cost Curve.

most publicly available projections for rare earth consumption show linear increases as LED production increases; however, a reexamination of these projections through consultation with a colleague with domain expertise in phosphors provided information and insights that contributed to making smarter assumptions in analysis inputs, adding to the model's ability to simulate and determine the system's root causes, actors, and significant material flows.

Dr. Ku explained that seeking different input and perspectives from across the supply chain—e.g., legal department; environmental, health, and safety—has augmented his engineering and technology work. Cross-functional engagement may motivate decision makers to act on the collective knowledge generated. Future project designs and implementation could greatly benefit from collaborations between experts from different domains.

Julie Zimmerman, associate professor of environmental engineering jointly appointed at the Yale School of Engineering and Applied Sciences and the Yale School of Forestry and Environmental Studies, provided an overview of what the business status quo reveals about achieving success in the marketplace and how the sustainable manufacturing field has diverted or will divert from the status quo to improve product and process function, performance, and service. Popular status quo metrics, as well as assessments of cost-benefit analysis and risk assessment may take a limited approach to evaluating outcomes. In addition, such metrics and assessments may not accurately measure the systemic nature of the market. According to Dr. Zimmerman, the fragmented approach of these assessment tools has pervaded business policy, investment, supply chain, and design decisions. There is room for creative and innovative thinking to build future economies and businesses that benefit human well-being.

Dr. Zimmerman cited a number of examples where market trends and manufacturing outcomes deviated from the anticipated results of the status quo. Examples included the rise in demand for costlier green and healthy products, and billions of dollars spent in health care to treat disease and health problems associated with chemical exposure. These examples are counter to traditional arguments that toxic chemicals and waste are the cheapest option for business. In addition, the declining cost of decentralized wind and solar power that has made these energy sources competitive with centralized coal providing another such illustration of deviation from the anticipated results of the status quo.

Amidst inaccurate market predictions of the status quo, Dr. Zimmerman noted that changed thinking prompted by innovative and systemic questions is needed. In her own research aimed at achieving a product's or process's function through more environmentally and socially friendly means, alternative solutions to toxic chemicals were developed by considering all the different means to achieve a function. One example includes DuPont's use of biomimicry to design fluorinated compounds for waterproofing by mimicking the structure of the lotus flower leaf, in which water balls up and rolls off the leaf, allowing for the retention of the function of water repellency without the toxic product associated with it.

Steven Skerlos, co-director of the Program in Sustainable Engineering at the University of Michigan, discussed notions of framing sustainability as a set of necessary conditions to achieve, rather than applying a separate "sustainable" approach to many fields. Dr. Skerlos identified four conditions for any field to achieve a sustainable system: (1) identification and measurement of progress in addressing an important environmental or social challenge, (2) mitigation of potential unintended consequences to where they do not outweigh social and environmental benefits, (3) the self-sustaining adoption of the system by the market, and (4) attainment of balance that allows a system's economic success to not negatively affect other planetary or social systems.

Dr. Skerlos highlighted a set of activities and innovations in automobile industries that indicated sustainability progress in the manufacturing sector. One such activity, adding wear-resistant coatings to the top of crankshafts, showed that automobile companies may reduce millions of pounds of emissions because the coatings increase both the lifespan and speed of the crankshafts. Despite sustainable advances and innovations in the automobile industry, Dr. Skerlos acknowledged that sustainability manufacturing has devoted minimal efforts to address larger questions of the enterprise decision-making process, such as "should fossil fuels continue to power automobiles?" A sustainability context could add significant value to business product, process, and policy decision making by contributing regulated market behavior models that account for unexpected and irrational consumer behavior, life-cycle assessment models from economic and social perspectives in addition to environmental perspectives, and models assessing the local and regional impacts of supply chains.

One National Science Foundation project is attempting to add the sustainability frame to business decision making by applying a framework that measures life-cycle emissions of supply, demand, and market behaviors in the automotive sector following regulations. This consequential life-cycle assessment takes a more holistic approach in informing market-driven decisions by overlaying consumer choices, policy directives, and profit maximizing behavior (Figure 4-2). When addressing market-driven questions such as whether the revised fuel economy standards in 2012 would increase vehicle size, Skerlos's model determined that vehicle size would likely increase contrary to the assertions of many others.

The findings of this study, while insightful, resulted in minimal influence in the decision-making realm; regulators did not change fuel standards, and automobile manufacturers continued traditional practices that may lead to increased car sizes and safety risks. Dr. Skerlos remarked that, overall, many sustainability manufacturing indicators effectively evaluate resource consumption of various activities, but not many metrics and indicators exist that analyze how these activities affect worker health, local and regional ecosystems, and the inner workings of supply chains.

For Dr. Skerlos, developing more holistic indicators and metrics that incorporate all aspects of the triple bottom line of people, prosperity, and planet, requires both more education and development of system-level models industry by industry. Thousands of engineers in the United States are trained each year in isolation from the consumer and may not be capable of applying their methods and life-cycle assessments to decision making, markets, and policy. Education, particularly in the social sciences, could enable these scientists and engineers to add valuable insight and inputs into societal organization and advancement. Finally, the potential and continued evolution of focused system-level models for each industry may offer significant insights to the science and technology decision-making space.

In the question-and-answer session, Dr. Skerlos and Dr. Zimmerman weighed in on the automobile-sharing economy started by such market disruptors as Uber and Lyft, and whether this emerging trend will cause large-scale changes from a sustainability perspective. Dr. Skerlos predicted that these entities would contribute minimal results in mitigating global ecosystem problems of greenhouse gas emissions and water pollution, as many in the automobile industry view the sharing economy as an opportunity to sell cars at a normal or higher rate. Dr. Zimmerman countered Dr. Skerlos's comments by arguing that the sharing economy's high potential to disrupt the future market creates an opportunity, perhaps an obligation, to start designing the sharing economy to benefit sustainability. While the potential for the shared economy to tackle such issues is present, this may only be possible if actors configure the policy landscape to shift the market away from consumption through mechanisms such as a carbon tax.

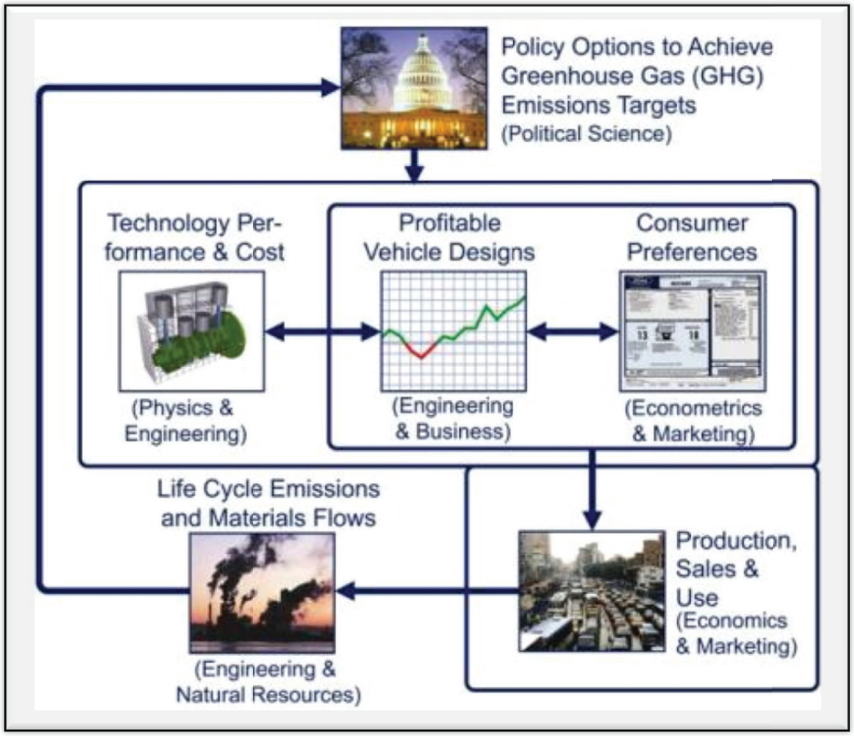

FIGURE 4-2 Consequential life-cycle assessment with market-driven design.
SOURCE: Steven Skerlos, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 14, 2016, Newport Beach, California.

Another question concerned the topic of autonomous vehicles as a possible example for how an emerging economy can create significant sustainable benefits. A hypothetical situation was proposed wherein an immediate transition to 80 percent adoption of autonomous vehicles took place, causing a dramatic decline in cars on the road. The reduced number of cars would reduce the need for roads and parking places while providing an opportunity to transform grey infrastructure into green space, storm-water management infrastructure, and so forth. Dr. Skerlos noted that such a complete transition would likely not take place until 2050, well past the point that climate-change impacts would occur. While autonomous vehicles may offer numerous solutions in the long term, a sense of urgency and principal focus on actions that may be implemented under the shortness of the time frame available would be useful.

5

Sustainable Food Systems

Gerald Nelson, professor emeritus, University of Illinois at Urbana-Champaign, addressed indicators and metrics associated with the transition to sustainable food systems. Dr. Nelson opened his discussion by highlighting progress made globally in reducing hunger and sustaining the demand for food as population has continued to increase. The 2005 Millennium Ecosystem Assessment (MEA) is representative of the advances made in understanding food security. [1] The MEA projected that global agricultural demand will double by 2050, largely driven by population and income growth. Agriculture may be able to meet such demands given the increases in yields for most crops; nevertheless, a number of challenges remain that would affect the projected demand in 2050, including impacts of climate change on crop yields, increased obesity worldwide (i.e., sustainable food systems could address both malnutrition and over nutrition), overuse of antibiotics in agriculture, and expanding "big data" to influence sustainable agricultural management.

Elaborating on the major challenges that would affect projected demand for food in 2050, Dr. Nelson discussed climate change risks to food supply. A number of researchers are working on comprehensive analyses of how food systems may be affected by climate change with advances in models that link biophysical and social systems, along with coordinated efforts to compare agricultural models, such as AgMIP (Figure 5-1).[2] In one study, Dr. Nelson and colleagues examined the effects of climate change on global crop yields by 2050 using nine global economic models linked to both crop yield models and global climate models.[3] On average, crop yields decreased by 17 percent and crop prices increased by 20 percent. There is uncertainty in these models, he said, due to large variability in regions and crops (Figure 5-2). Higher prices lead to adaptive behaviors, such as changes in farm management that increased the area under cultivation by 11 percent, reduced consumption by 3 percent, and moderated effects of the drop in yield such that global supply was only reduced by 11 percent on average.

[1] Millennium Ecosystem Assessment (MEA). 2005. *Ecosystems and Human Well-being: Synthesis*. Washington, DC: Island Press. The Millennium Ecosystem Assessment was initiated by then-UN Secretary Kofi Annan in 2000. From 2001 to 2005, the MEA assessed the consequences of ecosystem change for human well-being, and provided a scientific appraisal of the condition and trends in the world's ecosystems and the services they provide, as well as the scientific basis for action to conserve and use them sustainably.

[2] The Agricultural Model Intercomparison and Improvement Project (AgMIP) is a major international effort linking the climate, crop, and economic modeling communities with cutting-edge information technology to produce improved crop and economic models and the next generation of climate-impact projections for the agricultural sector.

[3] Nelson, G. C. et al. 2014. Climate change effects on agriculture: Economic responses to biophysical shocks. *Proceedings of the National Academy of Sciences* 111(9):3274–3279.

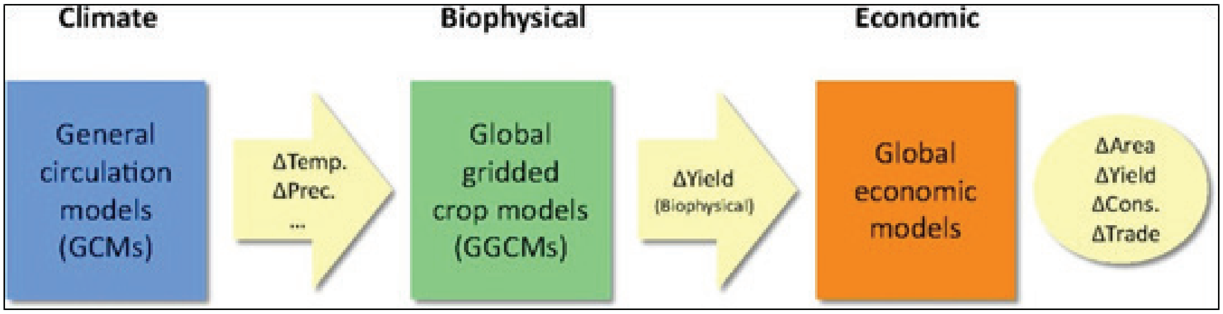

FIGURE 5-1 The impact modeling chain from climate through to crop and economic effects. Abbreviations: Temp = temperature; Prec = precipitation; Cons = consumption.
SOURCE: Nelson, et al. 2014. Climate change effects on agriculture: Economic responses to biophysical shocks. *Proceedings of the National Academy of Sciences* 111 (9):3274–3279.

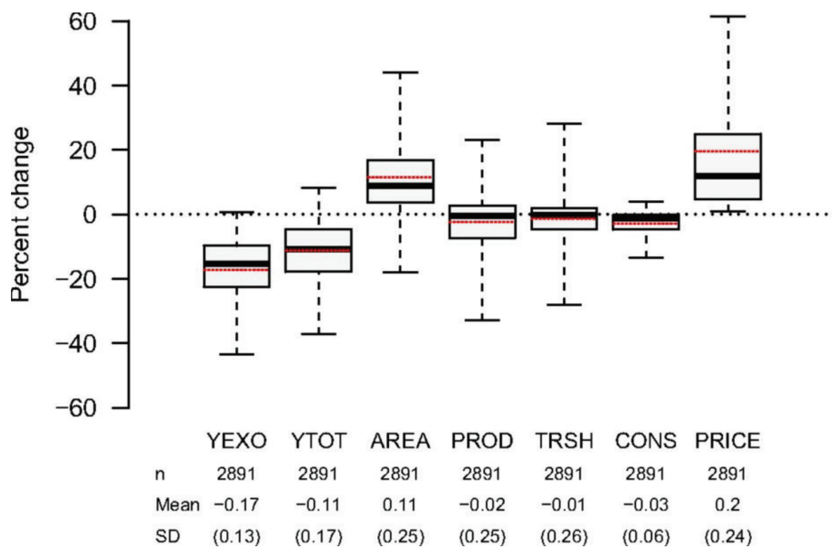

FIGURE 5-2 Variability of key crop and economic model results across crop aggregates (n = 4), models (n = 9), scenarios (n = 7), and regions (n = 13).
NOTE: Box-and-whiskers plots for key crop and economic model results. The variables YEXO (initial shock on yields of coarse grains, oil seeds, wheat, and rice), YTOT (final yields), AREA (crop area), PROD (crop production), CONS (crop consumption), and PRICE (market price effects) are reported as percentage change for a climate change scenario relative to the reference scenario (with constant climate) in 2050. TRSH is the change in net imports relative to reference scenario production in 2050. Boxes represent first and third quartiles, and the whiskers show 5–95 percent intervals of results. The thick black line represents the median, and the thin red dotted line, the mean value. (Nelson, et al. 2014. Climate change effects on agriculture: Economic responses to biophysical shocks. *Proceedings of the National Academies* 111(9) 3274–3279.)
SOURCE: Gerald Nelson, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 15, 2016, Newport Beach, California.

Discussing the remaining needs to address challenges to sustainably feeding the world in 2050, Dr. Nelson noted that while it is important to model issues in agriculture and food systems in an integrated biophysical-social framework, more research is needed to further develop a transition to sustainable food systems. He emphasized a need to look more closely at regional and smaller-scale variations in data. Using recent model results disaggregated by region as an illustrative example, India experiences a much larger price increase than Europe; however, results vary significantly by crop and model (Figure 5-3). Similar types of data help further our understanding of how food systems respond at scales that are relevant to decision makers. In addition, changes in weather extremes and climate variability impact crop yields and food systems more than changes in mean temperature and precipitation. Furthermore, gaps remain in understanding the effects of climate variability and change in fruits and vegetables' nutrient content, factors that are important for human nutrition. There are also gaps in understanding how disease and pest pressure may change with climate change and affect changes in food production and nutrition. Finally, better communication of science to multiple audiences is needed.

Dr. Nelson next turned to metrics and indicators, indicating that complacency, low levels of investment into agricultural research, and low levels of strategic thinking about indicators and metrics are barriers to understanding and addressing threats to food systems. Increasing yields over the last few decades are the consequence of major advances in agricultural research, a growth in the use of biotechnology, and the opening up of commodity markets through free-trade agreements; however, such progress contributed to the perception that food supply is no longer a priority issue, leading to a decline in agricultural research globally. Agricultural trade negotiations have stalled globally and may become more problematic as variability in agricultural production increases because of climate change. Dr. Nelson highlighted a need for increased efforts in advancing biotechnology to address future food security risks. In addition, he stressed the importance of cultivating better strategies for developing goals and indicators for sustainable food systems and improving data collection to support sustainability indicators. Although other researchers argue for a limited number of goals and indicators, a broader set of goals and indicators may be important in order to measure progress for different audiences, sectors, or spatial scales.

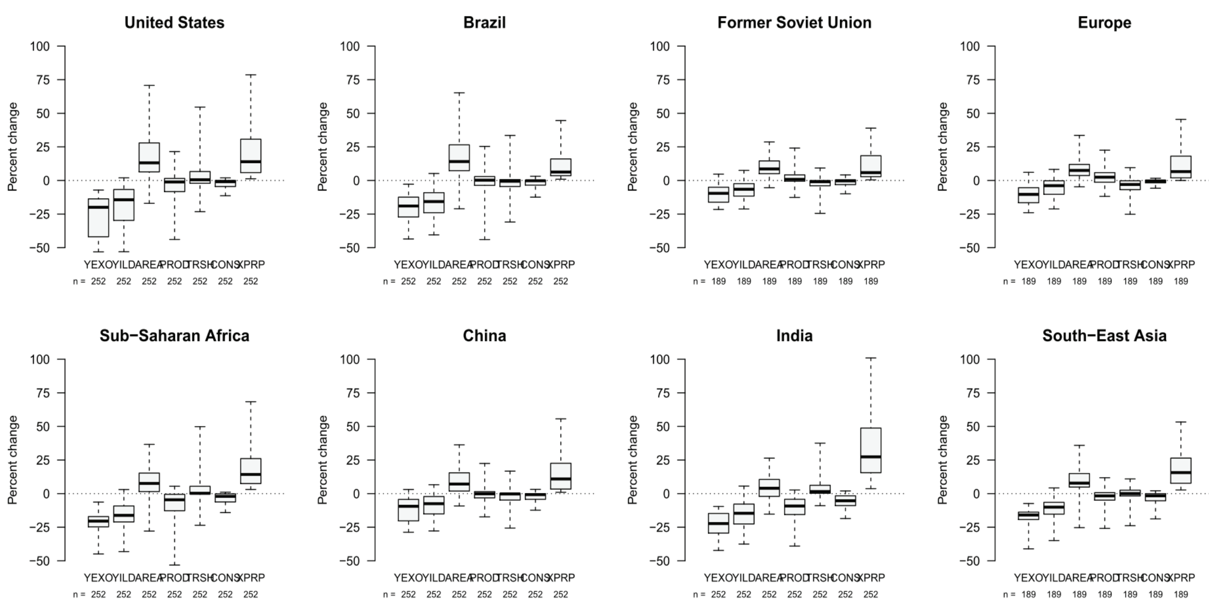

FIGURE 5-3 Distribution of model results by region for all models, scenarios, and crops.
NOTE: Boxes represent first and third quartiles, and the whiskers show the 5–95 percent range of results. The black line represents the median. Abbreviations are the same as in Figure 5-2.
SOURCE: Gerald Nelson, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 15, 2016, Newport Beach, California.

Dr. Nelson concluded by pointing out a large gap in data collection remains and further analysis is needed to develop indicators for sustainability benchmarking, including:

- Data on how crops respond to climate variability and change
- Remotely-sensed data that can be utilized to scale up local observations
- Commonly agreed-upon and widely implemented data collection standards
- A mechanism or platform to report and store data
- Tools to facilitate the development and tailoring of indices
- A transparent system that links calculated indices directly back to data

Mark Howden, chief research scientist at Australia's Commonwealth Scientific and Industrial Research Organisation's Agriculture Flagship and director of the Australian National University's Climate Change Institute, provided insight on progress and barriers to using models to promote the sustainability of agriculture and food systems and how models have been used to inform policy decisions. Dr. Howden said that although there has been progress in using models to support decision making, the modeling community needs to further develop models with the potential to move agriculture toward sustainability. In the late 1980s, the Bruntland Report outlined a number of conditions for research and modeling to better serve food security, including less centralized research, models sensitized to decision makers' priorities and industry/farmer innovations, and improvements engaging the research community with place-based and adaptive research.[4] These challenges are still relevant, Dr. Howden said, noting that the evidence is "patchy" on whether models have delivered on improvements to decision making related to food system sustainability.[5, 6, 7]

One of the overarching reasons for why models fail to meet goals for informing management and policy is that models have historically been developed by researchers to inform research-oriented questions. Although there are engineering-oriented models designed to more explicitly address decision making, much of the modeling effort in the sustainability field over the past few decades was constructed around models designed primarily to self-educate modelers and researchers. Several other reasons current models have fallen short in terms of making desired impacts on decision making include the following:

- Models are an expression of modelers' world views, assumptions, and values
- Models are embedded into the social and institutional processes and contexts in which decisions are made
- Models by definition focus on explicit, codifiable knowledge, rather than tacit knowledge
- Modeling frameworks are designed to address a problem rather than to identify solutions or opportunities
- Models ignore social, cultural, and biological diversity issues
- Model development focused on farm-level production or yields instead of value or value chains
- Models are susceptible to political capture or marginalization
- There are large uncertainties associated with the outputs of many models

Despite these barriers, Dr. Howden highlighted several successful modeling efforts, and drawing from these examples, described a number of success factors. In one example, an integrated pest management framework was used with a pest-monitoring, data-interpretation, and decision-analysis package aggregated into a simulation model. The success of the model was due, in part, to transparency that allowed farmers to see the data and relationships incorporated into the models, which they could eventually utilize in their own soft models of tacit understanding.[8]

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[4] Brundtland, G., et al. 1987. *Our Common Future*. Oxford: Oxford University Press.

[5] Hayman, P. 2004. Decision support systems in Australian dryland farming: A promising past, a disappointing present and uncertain future. In *New Directions for a Diverse Planet: Proceedings of the 4th International Crop Science Congress*, Brisbane, Australia, September 26–October 1, 2004.

[6] Matthews, K. B., et al. 2008. Wither agricultural DSS? *Computers and Electronics in Agriculture* 61(2):149–159.

[7] Carberry, P. S., et al. 2002. The FARMSCAPE approach to decision support: Farmers', advisers', researchers' monitoring, simulation, communication and performance evaluation. *Agricultural Systems* 74(1):141–177.

[8] Hearn, A. B., and M. P. Bange. 2002. SIRATAC and CottonLOGIC: persevering with DSSs in the Australian cotton industry. *Agricultural Systems* 74(1):27–56.

The application of seasonal climate forecasts in Australia also illustrates an example where farmers used model results in scenario planning and "management gaming" to construct action rules for responding to different circumstances.[9] Additionally, nutrient models that inform farm nitrogen budgets have been designed to integrate data from farm and regional models with additional information about compliance levels.[10,11] Dr. Howden noted that an important element in many of these examples is the effort to make sure that "hard" models (e.g., numerical models) are embedded into "soft" models (e.g., systems of tacit understanding). A broader participatory process that addresses salience, credibility, legitimacy, and power is necessary to achieve this integration. In some cases, researchers are the minority knowledge holders and there is evidence that indicates that incorporating user knowledge through such participatory research may expand the range of actionable options.

Dr. Howden stressed that the value in such modeling efforts can serve as a way of convening different groups to discuss potential changes in food systems—these social processes may contribute to more successful models. Dr. Howden said that several "new horizons" in modeling have the potential to further increase the application of models to food systems and sustainability. The effective incorporation of extremes into models, improvements in the treatment of crop pests and diseases and their interaction with biophysical factors, improved quantification of uncertainties, and a focus on nutrition security all encompass potential innovations that can improve sustainable food systems modeling. In addition, Dr. Howden emphasized a need for the development of models promoting innovation and cross-fertilization of ideas, simulation of models that accelerate technological advances, and monitoring and indicators for decision support.

Prabhu Pingali, professor in the Charles H. Dyson School of Applied Economics and Management and founding director of the Tata-Cornell Agriculture and Nutrition Initiative at Cornell University, discussed improvements in the design of sustainability metrics and the path forward in closing remaining data gaps. Dr. Pingali said that without indicators that are relevant to policy decisions, and without sufficient data and data quality to calculate these indices, it will be difficult to transition from knowledge to action on sustainable food systems. A large share of current research efforts focuses on frameworks, methodology, and analysis. In contrast, minimal efforts focus on managing data, improving data systems, or ensuring that indicators are giving the right signals to policy makers. As a result, both data uncertainties and counterproductive metrics may represent the largest challenges to making advances toward food system sustainability.

As an example of counterproductive metrics, Dr. Pingali shared an analysis of the UN Millennium Development Goals (MDGs) on global hunger.[12] According to these metrics, there has been progress made on addressing hunger since 2002. The MDGs articulated a goal of cutting global hunger by half of 1990 levels by 2015; however, the metric used to measure progress toward addressing hunger is misleading, he said. The *number* of hungry people in the world has not dropped nearly as much as the *percentage* of hungry people. Furthermore, some countries have met or almost met the MDG goal despite a number of other sobering statistics on the state of their food security, including increases in the absolute number of people who are hungry, failure to increase food supply at the same rate as population growth, and number of chronic recipients of international food aid (Figures 5-4 and 5-5). The current hunger metric may have led to an overly optimistic message on the state of world hunger.

Dr. Pingali emphasized that any indicator or metric, even if well formulated, is only as strong as the data used to calculate it, and in many cases, the scientific community is far from having sufficient data to accurately measure progress. He gave an example of food balance sheets from the UN Food and Agriculture Organization (FAO) where much of the data used to assess food production and food security was drawn from an FAO database; however, in collecting data, the FAO sends questionnaires to each country every year and enters the results into an FAO database. Although a large number of countries provide information on trade, reporting may be poor for

[9] McCown, R. L., et al. 2012. Farmers use intuition to reinvent analytic decision support for managing seasonal climatic variability. *Agricultural Systems* 106(1):33–45.

[10] Leach, A. M., et al. 2012. A nitrogen footprint model to help consumers understand their role in nitrogen losses to the environment. *Environmental Development* 1(1):40–66.

[11] de Vries, W., et al. 2011. Comparison of land nitrogen budgets for European agriculture by various modeling approaches. *Environmental Pollution* 159(11):3254–3268.

[12] The eight Millennium Development Goals (MDGs) form a blueprint agreed to by all the world's countries and all the world's leading development institutions.

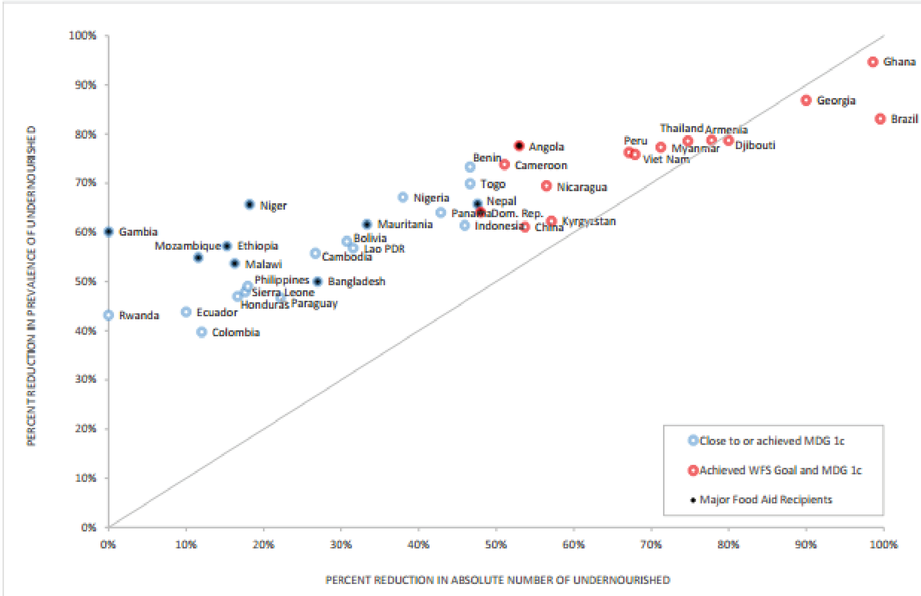

FIGURE 5-4 Countries that have met (red dots) or almost met (blue dots) MDG targets on hunger.
SOURCE: Prabhu Pingali, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 15, 2016, Newport Beach, California. Adapted from: Pingali, P.L. 2016. Opinion: The hunger metrics mirage: there's been less progress on hunger reduction than it appears. Proceedings of the National Academy of Sciences 113(18):4880-4883.

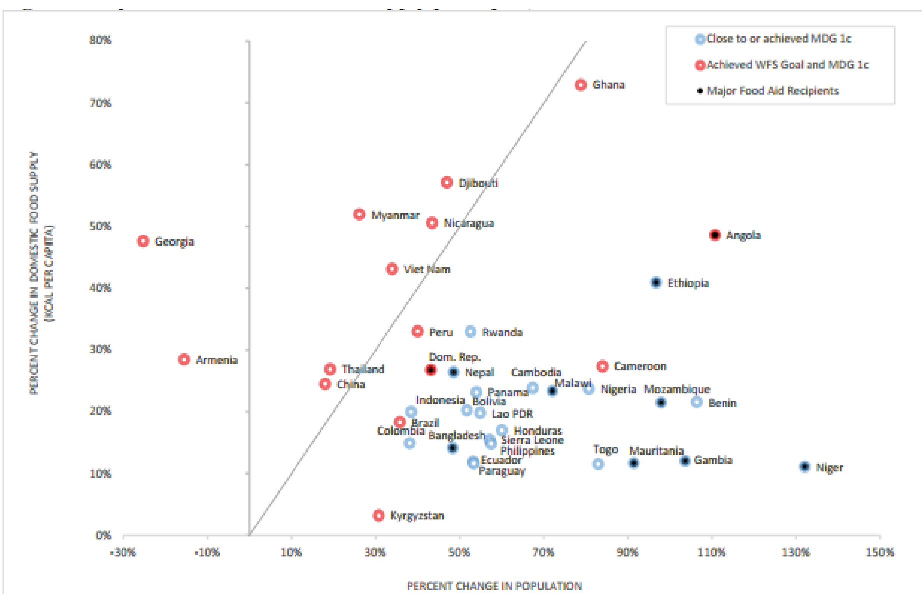

FIGURE 5-5 The same countries as above plotted by population growth and change in food supply.
SOURCE: Prabhu Pingali, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 15, 2016, Newport Beach, California. Adapted from: Pingali, P.L. 2016. Opinion: The hunger metrics mirage: there's been less progress on hunger reduction than it appears. Proceedings of the National Academy of Sciences 113(18):4880-4883.

other important aspects of the food system—for example, only 50 percent of countries report on food production, prices, and land use (Figure 5-6). Nevertheless, the data are aggregated or extrapolated and presented as continuous time series for each country.

Even when data are available, he said, poor data quality can be a major problem. The Intergovernmental Panel on Climate Change included projections about the impacts of climate change on crop production and food supply under different climate-change scenarios, but the data utilized for such estimates are often of poor quality. Data on sorghum production and yields from India, for example, appear to be largely estimated, given the very uneven distribution of these frequencies, and the very high frequency of yields reported at one half, two-thirds and one ton, rather than measured, given the unlikely distribution of yield measurements from India's agricultural districts (Figure 5-7). The meteorological data used to establish a relationship with crop production may be equally as questionable.

Similar discrepancies exist for other types of measurements. In another example, Dr. Pingali compared remote sensing versus government reporting data on Indian water use and irrigation and found a 100 percent difference in the amount of land under irrigation, illustrating the importance of data quality, ground truthing, and data validation. It may be likely that these data gaps and counterproductive metrics are not confined to the agricultural sector or to developing economies. Nonetheless, such gaps could be addressed as the world attempts to develop metrics to measure progress toward the Sustainable Development Goals, which have a much more extensive set of indicators. The benefits of providing better data could be further clarified and communicated, and public education may also be important—knowledge of why data collection and management is important to sustainability could be highly beneficial to the public.

Dr. Pingali lastly addressed leveraging new technologies to improve data collection. Remote sensing may have much potential, but several challenges remain for using remote sensing to estimate crop productivity in different regions. Cheap, local sensors are increasingly available for providing field-level estimates of soils and moisture levels. Crowd-sourcing approaches to estimating prices and access to food may also hold promise, although barriers remain in accessing data that reflect food access by households rather than by men. Other challenges remain in

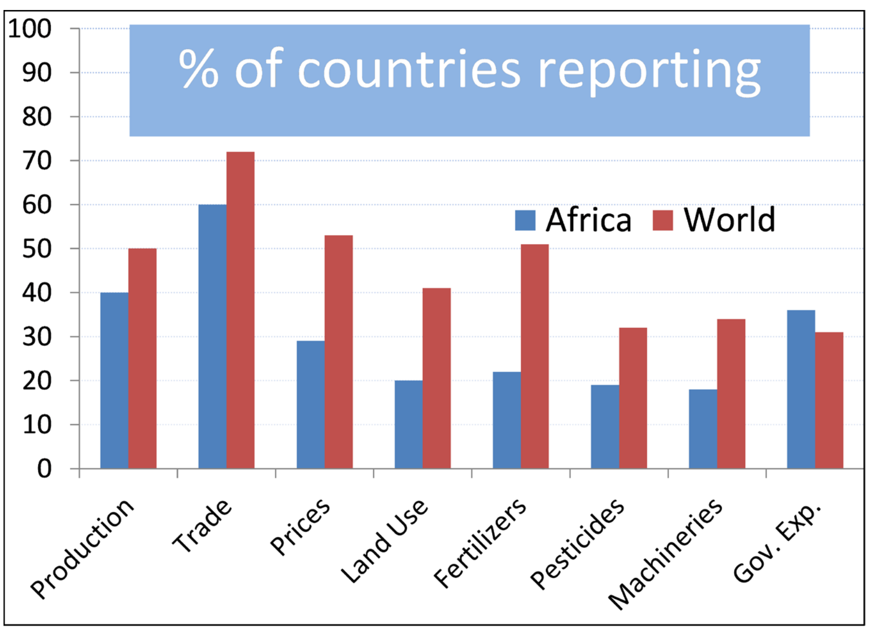

FIGURE 5-6 Percentage of countries contributing data to FAO food sheets (2005–2013) across different data categories.
SOURCE: Prabhu Pingali, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 15, 2016, Newport Beach, California.

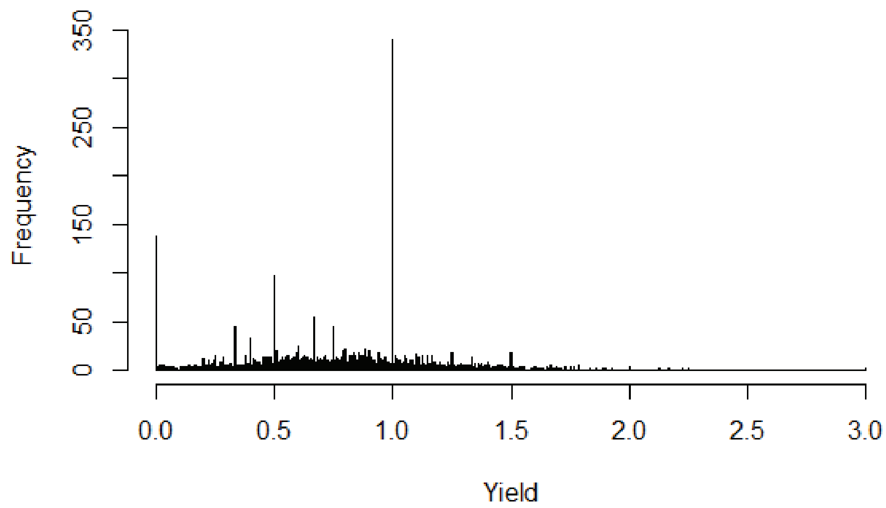

FIGURE 5-7 Frequency distribution of sorghum yields in India for 213 districts during 1980–2009 (n = 5,186).
SOURCE: Prabhu Pingali, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 15, 2016, Newport Beach, California.

scaling up these technologies, such as the difficulty in collecting social data. In his concluding remarks, Dr. Pingali reiterated the need for further progress in data access, data interoperability, and adequate metadata collection.

In the question-and-answer session, Dr. Pingali was asked about how societal data could be aggregated to the same extent as data from the biophysical world. Dr. Pingali responded that data on social topics, such as differences in gender and access to food, are all going to be big challenges. Researchers are still dependent on household surveys for much of that socioeconomic data. The World Bank recently partnered with the Gates Foundation to invest in The Living Standards Measurement Study (LSMS) in order to develop systematic data in Africa at the household level. The goal of the LSMS is to facilitate the use of household survey data for evidence-based policy-making. Participants were interested in crowdsourcing as a way to develop data, but Dr. Pingali commented that there have been some attempts, such as giving farmers rain gauges and having farmers send a text message on amounts of rain each day.

Dr. Howden was asked about participatory modeling and involving stakeholders in the design and construction of the models related to agricultural production. He responded that there have been modeling efforts that engaged stakeholders with a narrow focus, such as the investigation of pesticide application, as well as broad applications that focused on farm tourism and off-farm income. Models serve to help synthesize information about the systems being examined and explore multiple options. The processes of developing these models and research can be taken to other modeling communities and significantly increase the utility and productivity of many models.

6

Ocean Sustainability

Roberta Marinelli, Executive Director of the University of Southern California Wrigley Institute for Environmental Studies, presented an opening reflection on the state of ocean sustainability since *Our Common Journey*[1] was published. She noted that discussions of ocean environmental degradation in *Our Common Journey* focused on pollution and overfishing. However, in the subsequent 15 years, we have grappled with the effects of rising atmospheric carbon dioxide on our ocean ecosystems, contributing to ocean acidification, ocean warming, and the melting of ice sheets. There is a critical need to learn more about the response of ocean ecosystems to these and other anthropogenic activities. The oceans are a broad and complex commons, capable of supporting a vibrant blue economy that includes food and energy production. However, lack of data and poor governance systems hamper the development of sustainable ocean use.

Steven Lohrenz, dean and professor of the School for Marine Science and Technology at the University of Massachusetts Dartmouth, discussed the role of oceans in global sustainability. In addition to serving as a climate and weather engine, oceans provide a variety of ecosystem services, including a depository of greenhouse gases, oxygen, and water; a critical habitat for many organisms; and a coastal safeguard from natural disasters. The multivaried role of oceans has clear implications for security, human health, marine resources, and economic benefits as indicated by the strong coupling between human population and oceans in a United Nations Environment Programme map of coastal population distributions (Figure 6-1). By providing commerce, transportation, and food supply, oceans significantly reduce poverty for many countries. Blue carbon is an emerging concept in carbon management and is the ability of oceans to sequester carbon from fossil fuel sources.

Dr. Lohrenz said that oceans are changing in many ways, including increased ocean temperature and heat content, sea-level rise, ocean acidification, habitat loss, and coastal degradation. These factors further impact ocean circulation and productivity, and reduce the ocean's capacity for greenhouse gas uptake, with significant implications for climate regulation, sea level rise, and land ice decline. Fisheries and ecosystems are also severely degraded by anthropogenic activities. Integrated, comprehensive and sustained ocean observations can support a better understanding and management of these changes with concomitant feedbacks to sustainability. Integrated, comprehensive, and sustained ocean observations can support a better understanding and management of these changes and their implications for sustainability.

[1] National Research Council (NRC). 1999. *Our Common Journey: A Transition Toward Sustainability*. Washington, DC: The National Academies Press.

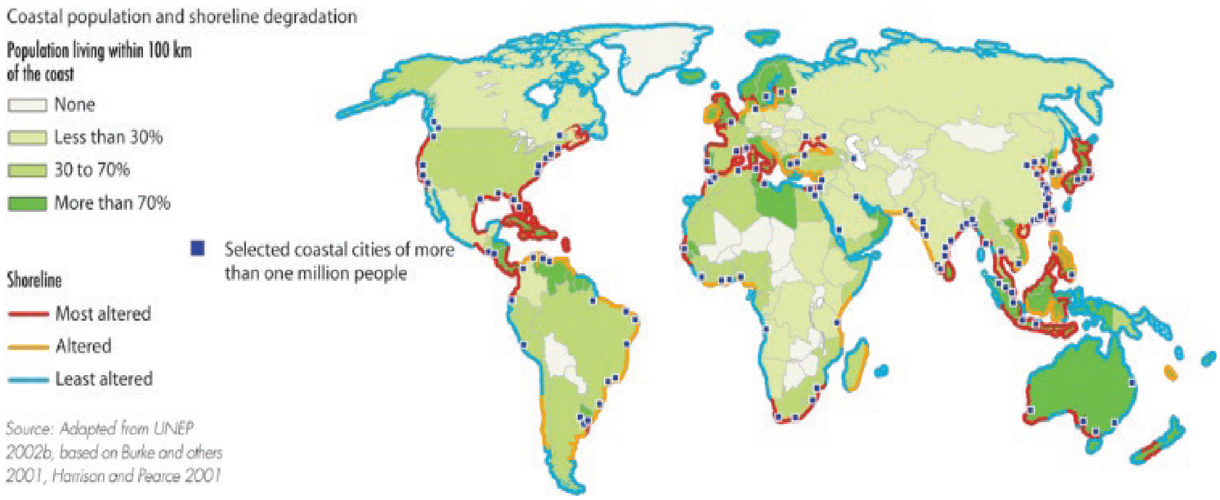

FIGURE 6-1 Population distributions and level of coastal alteration, illustrating the dependence of humans on the coastal ocean.
SOURCE: Steven Lohrenz, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 14, 2016, Newport Beach, California.

SDG 14 aims to "conserve and sustainably use the oceans, seas and marine resources for sustainable development." Dr. Lohrenz highlighted targets associated with Goal 14 that reinforce a number of ocean observation needs for sustainable development. These include prevention of ocean acidification and pollution, strengthening of marine and coastal ecosystems, improved science-based management of fish stocks, and creating more effective sea-level rise and coastal forecasting. Another goal promotes the transfer of marine technology for small island developing states or less developed countries. While this list of proposed needs is comprehensive and perhaps daunting, there are a number of approaches to accomplishing these goals.

The research of Trenberth et al. outlined what is involved with the types of integrated observation systems for long-term climate data.[2, 3] The constant changing of these observation systems creates a challenge of maintaining continuity in the data. Another challenge includes maintaining the continuity of satellites and the instrumentation in the water itself over time. Few ocean time series, such as the Hawaiian Ocean Time-series, the Bermuda Atlantic Time-series Study, and the Carbon Retention in a Colored Ocean Time-series Program, span time periods as far back as 1950.[4]

Other ocean observation efforts include the UN's Global Ocean Observing System (GOOS) that coordinates the gathering of ocean and sea data on an international scale. The GOOS provides a system for processing ocean data and the analytic and prognostic environmental information that would support sustainability and other ocean science. Dr. Lohrenz explained that such integration of global measurements allows for systematic observation of large-scale patterns that can support understanding global change. A UNESCO report outlined a broad-based framework for this approach in terms of decision support.[5] Research by Malone et al. detailed the data needed for

[2] Trenberth, K. E., T. R. Karl, and T. W. Spence. 2002. The need for a systems approach to climate observations. *Bulletin of the American Meteorological Society* 83(11):1593.

[3] Trenberth, K. E., et al. 2013. Challenges of a sustained climate observing system. In *Climate Science for Serving Society*, 13–50. Eds. G.R. Asrar, G.R., and Hurrell, J.W., Springer, Dordrecht, Heidelberg, New York, London.

[4] Church, M. J., M. W. Lomas, and F. Muller-Karger. 2013. Sea change: Charting the course for biogeochemical ocean time-series research in a new millennium. *Deep Sea Research Part II: Topical Studies in Oceanography* 93:2–15.

[5] United Nations Educational, Scientific and Cultural Organization. 2012. *A Framework for Ocean Observing*. By the Task Team for an Integrated Framework for Sustained Ocean Observing. IOC/INF-1284 rev., doi:10.5270/OceanObs09-FOO.

ecosystem-based management of coastal ecosystem services and advocated for observation systems on a localized level where decisions are ultimately made.[6, 7]

Dr. Lohrenz emphasized the amount of effort, capacities, and resources needed for these observation systems by discussing the U.S. Integrated Ocean Observing System (IOOS) conducted in conjunction with NASA and the Jet Propulsion Laboratory. Including all data and observation needs for the various federal agencies and associated satellites, the buildout of the IOOS over the next 15 years required an estimated $54 billion. Some of the various regional Coastal Ocean Observing Systems developed buildout plans based on a process that encompassed stakeholders, decision makers, and data users, which is a useful model for providing data in a collaborative way.

The National Oceanic and Atmospheric Administration (NOAA) Space Platform Requirements Working Group examined various space platforms for observation including a focus on oceans. A second iteration of the National Academies of Sciences, Engineering, and Medicine's decadal survey for Earth Science and Applications from Space is in progress. Entities partially developed an observing network for global ocean acidification, a priority for a large share of the ocean science community, and conducted research on how this network fits a societal benefit decision-making framework (Figure 6-2).

New technologies for ocean observing are improving our understanding of ocean change. Profiling floats and gliders provide information on ocean conditions for ground truthing and satellite observations. Ocean sensors have evolved to fulfill data collection tasks previously executed by water sampling and human observation with a microscope. Examples include the development of sensors to look at plankton communities at the individual species level; the creation of molecular sensors to target specific algal types such as harmful algal blooms; and the development of nutrient sensors. New technologies are increasing observational capability, efficiency and accuracy, and decreasing costs.

Nevertheless, Dr. Lohrenz said challenges remain for ocean observation, including improvements in data computation and data management. As the volume of data increases, the ability to make such data widely available and accessible to a variety of users will become a principal challenge. Examples of data management plans include the IOOS Data Management and Communication Strategy and the data management plan of the Ocean Observatories Initiative. He further explained that beyond having a large volume of usable and accessible data on ocean observations, such data would provide necessary components in the context of an integrated modeling approach. Atmospheric, terrestrial, and aquatic systems that are now being recognized as inherently linked may be beneficial to model at localized scales for decision support. One project associated with the NASA Carbon Monitoring System uses a dynamic land ecosystem model and terrestrial biogeochemical model, which encompasses a variety of different modules, to examine human activity and natural systems. An ocean circulation model within an embedded biogeochemical model couples these variables. This type of integrated modeling allows for practical observations of the linkages among atmospheric, terrestrial, and hydrologic processes, transport of materials to the coast, and their processing within the coastal zone in a coupled physical-biological sense.

Dr. Lohrenz's final comments reiterated that gaps remain in ocean observational research, highlighting the importance of the continuity and consistency of data records. He also emphasized global integration of data as a goal and that localized regional approaches are needed for the application data in a decision-support context. These approaches would include using low-cost, efficient methodologies and innovative technologies coupled with sound data management and integrated modeling to provide decision-support products.

Margaret Leinen, director of the Scripps Institution of Oceanography at the University of California, San Diego, further discussed the importance of oceans for sustainability, the direction the ocean sustainability discussion followed since publication of *Our Common Journey*, and additional needs for achieving ocean sustainability. Since the publication of *Our Common Journey*, research and sustainability work brought oceans "to the table." Terrestrial livelihoods previously dictated most of the discussion when notions of sustainability first appeared in global discourse, and while oceans play a large role in global processes, a large share of the sustainability community did not anticipate the rapid changes that oceans experienced in the last 20 years. Additionally, ocean

[6] Malone, T. C., et al. 2014. A global ocean observing system framework for sustainable development. *Marine Policy* 43:262–272.

[7] Malone, T. C., et al. 2014. Enhancing the global ocean observing system to meet evidence based needs for the ecosystem-based management of coastal ecosystem services. *Natural Resources Forum* 38:168–181, doi:10.1111/1477-8947.12045.

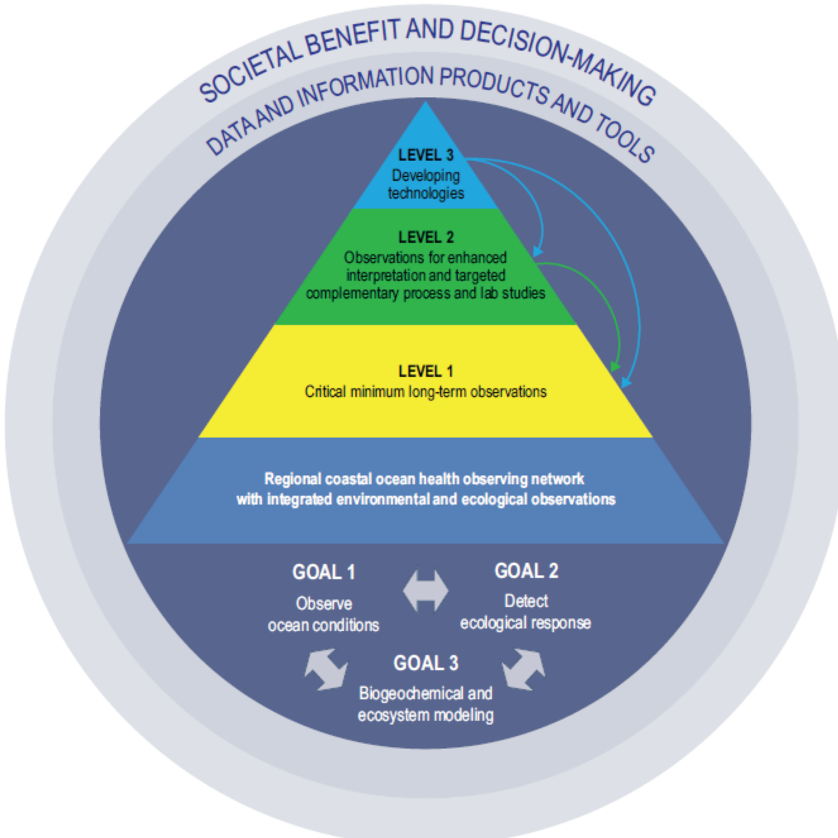

FIGURE 6-2 Schematic diagram of the parts of the Global Ocean Acidification Observing Network.
NOTE: The core goals of the Global Ocean Acidification Network are depicted in the pyramid above, along with the levels at which various activities address the core goals. The outer rings depict the ultimate societal needs that the activities are designed to address. (Alin, S. R., R. E. Brainard, N. N. Price, J. A. Newton, A. L. Cohen, W. T. Peterson, E. H. De Carlo, E. H. Shadwick, S. Noakes, and N. Bednarsek. 2015 "Characterizing the natural system: toward sustained, integrated coastal ocean acidification observing networks to facilitate resource management and decision support. *Oceanography* 28(2):92–107.)
SOURCE: Steven Lohrenz, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January, 15, 2016, Newport Beach, California.

management may require more diffuse responsibility than terrestrial ecosystem management. Though individual countries are responsible for their coastal waters, much of the ocean is considered international waters, resulting in vague frameworks for responsibility and decision making.

Dr. Leinen provided examples of progress in ocean sustainability since *Our Common Journey*. The Intergovernmental Panel on Climate Change transitioned to viewing oceans as not only a climate regulator but also a large factor in the global economy, in decision-support frameworks, and in adaptation and mitigation. Current U.S. indicators largely focus on sea-level rise from water supply impacts in large cities and the influx of large storm systems such as Hurricane Sandy. Other indicators attempted to measure the aragonite saturation state of ocean acidification—one of the most difficult measurements to make in all oceanography. New instruments such as those associated with the XPrize for pH measurements exemplify the difficulty of measuring ocean acidification. For example, scientists deployed one instrument off the coast of Hawaii on Argo floats for 3 weeks of test runs, taking measurements every day in coming up from a depth of 2,000 meters. That instrument took more pH measurements of the ocean in those weeks than during the entire World Ocean Circulation Experiment, a 10-year multination, multicrew effort. Progress has also been made regarding chlorophyll concentration in surface waters as a proxy for primary productivity and coral thermal stress.

Improvement in the development of indicators hearkens back to *Our Common Journey*. However, a number of needs remain, for example, an indicator on fisheries or the state of fisheries is still lacking. This reflects the differences in the ocean science community—there are blue-water oceanography groups who work on large-scale circulation problems and climate problems and then fisheries oceanography groups. Dr. Leinen remarked that the current 85 percent overexploitation rate of global fisheries will require significant attention in the future. She pointed to SDG 14's focus on ocean life and emphasis on fisheries as an example of progress. In addition, from a disconnect between traditional academic oceanography and perceived needs, a call for a world ocean assessment has emerged and researchers responded with a gradual development of the first World Ocean Assessment. Finally, regarding bringing oceans "to the table" in discussions of sustainability, the 2015 Conference of Parties, or COP21, of the UN Framework on Climate Change in Paris added the word *ocean* for the first time to its working documents.

Returning to the subject of fisheries, Dr. Leinen commented that it may be time for the oceans community to reengage on the linkage between fisheries and food security—roughly 40 percent of the world population depends on fish protein. Despite the deployment of additional plant protein, projections for 2050 estimate that about three billion people will depend on seafood protein, the majority of which will constitute the poorest three billion on the planet. Emerging evidence points to commercial and artisanal fishing as unsustainable because overfishing puts traditional fishing species at risk of endangerment or extinction. The discussion now has turned to aquaculture and its substantial share in the production of the United States' fish seafood protein. The issue of aquaculture production and management is controversial for environmental groups, businesses, and governments and is further complicated by the Department of Agriculture overseeing all aquaculture even though NOAA regulates environmental impacts of aquaculture. A new organization, Conservation X, compiles innovative ideas for large prizes in the field of conservation and recently focused on saltwater aquaculture on land, and on illegal, unreported, and unregulated (IUU) fishing. Dr. Leinen remarked that modern technologies can contribute to solutions for both these issues. Already, promising research conducted outside of the United States addressed on-land, in-tank, and saltwater aquaculture. Illegal fishing and ecosystem-damaging fishing practices still occur in the ocean despite a large increase in marine-protected areas over the past 10 years.

Dr. Leinen highlighted estuaries, the Arctic, and deep sea mining as other key issues related to ocean sustainability. Nutrient pollution will exacerbate impacts on ecosystem services given that estimates project that the largest population growth will take place in urban areas, which are predominately upstream of estuaries. Our Global Estuary strives to increase observation of estuaries globally. Fishery and transportation systems will also impact the Arctic beyond the expected ice melt and shifting habitat from climate change. Deep sea mining has expanded without a formal monitoring organization and there have been minimal scientific studies on the impacts. In conclusion, Dr. Leinen emphasized that these issues only represent a sample of the existing gaps in knowledge, observations, and capacity of ocean sustainability.

In the question-and-answer session, the panelists responded to a question about the progress being made for oceans and global cooperation in monitoring, observation, and action. Dr. Leinen responded that much progress has been in observation and monitoring versus governance schemes. Despite challenges regarding management and accessibility of data, structures exist to bridge these gaps, such as the Intergovernmental Oceanographic Commission. Regarding governance, the United Nations Convention on the Law of the Sea does not address many sustainability-related topics. Dr. Leinen said the International Maritime Organization is the only organization that has made efforts to solve these problems. Dr. Lohrenz added that the use of satellite data in international venues contributes tremendously, including data sharing and cooperation in sensor development. Additionally, discussions to develop an ocean acidification framework have shown promise and exhibit a strong international component.

7

Paths Forward

Steve Skerlos, Arthur F. Thurnau Professor of Mechanical Engineering and Civil and Environmental Engineering; co-director, Center for Socially Engaged Design; and director, Sustainability Education Programs at the University of Michigan, reflected on observations of paths forward for sustainability. Sustainability has roots in the environment, but it is more widely recognized now that it is about people. There is a lot of data available for sustainability-related analysis, but it is not enough. There are more integrated models as well, but there are also large gaps between building models and model-driven decision making, partly due to concerns with validating them.

It is widely recognized that recent decisions have created situations that will become challenges in the future, such as increasing carbon dioxide emissions; thus, there is a greater appreciation for interlinked systems, codesign, decision lock-ins, and path dependencies as they relate to sustainability. Education grew but also new knowledge is being gained by moving beyond disciplines—transdisciplinarity is gaining appreciation. Education is a clear imperative at all levels and in every direction, including participatory design. Sustainability actions and claims abound in industry, but they need to be better grounded in sustainability science.

Dr. Skerlos also noted that, looking forward, sustainability is at a stage equivalent to gross measures for human health, such as pulse or blood pressure. The science has not progressed to a point to be able to provide clear metrics or practices for improvement, such as in minutes of exercise, cholesterol targets, and diet for human health. Aiming for human well-being is a notable goal, but it does not yet translate into information usable by an engineer for designing a car. Sustainability engineering is one path forward, which would translate insights from modeling into needed action at national, city, and industrial levels. This application to industry would hold technology innovations to necessary standards. There is a challenge in finding common goals, such as well-being, because of differences in value systems. It may be easier to agree on what should not happen instead of what should happen. For example, not damaging the biosphere (e.g., ocean acidification) may be an easier goal to establish targets for than trying to agree to a vision of well-being.

This perspective is more similar to a perspective of decision making from engineering and design perspectives, indicated Dr. Skerlos, and allows for multiple design problems to be analyzed simultaneously to see where solutions to such problems conflict with each other. The world would then be viewed not as multiobjective, but as a series of interlinked objectives with ecosystem and social constraints (e.g., pH constraints for seawater). The development of metrics would be needed that help in better understanding progress relative to such constraints. This design perspective is useful to the sustainability science community for moving forward with clarity and when interfacing with specific sectors viewed as the cause of certain problems.

Robert Costanza, professor and chair of public policy at the Australian National University's Crawford School of Public Policy, focused his discussion beyond oceans to future challenges of integrating metrics, models, and the vision to transition toward sustainability. He touched on the concept of planetary boundaries and the constraints of an ecological life support system, emphasizing the need for new framing approaches to drive behavior change. Sustainable solutions for these complex problems require the combination of three elements: the development of a new shared vision of sustainability that integrates a range of different disciplines, including not only ecology and economics but also psychology, history, sociology, and anthropology; new analytical tools and techniques that focus on systems thinking; and behavior change through new implementation instruments and "therapies," such as societal therapy.

To construct a new shared vision of sustainability, Dr. Costanza asked, "What does a desirable system look like? How does society prosper within global constraints while producing the elements of well-being and quality of life?" He described the Sustainable Development Goals (SDGs) as significant in bringing together a range of inclusive goals and objectives, but these goals operate in silos. Dr. Costanza called for integration across goals that recognizes the synergies, trade-offs, and interdependencies of the underlying system. The pursuit of an overarching goal may include prosperity and a high quality of life that is both equitably shared and sustainable. Ecological economics provides an example of a transdisciplinary field that attempts to combine these elements into a systems perspective to achieve efficient allocation and fair distribution within the confines of planetary boundaries. Sustainability entails dealing with basic assets. Dr. Costanza presented a refined version of William Clark's social-environmental system model that captures the interactions between four of Dr. Clark's five capital assets: natural, social, built, and human capitals (Figure 7-1). The natural environment and natural capital provide the overarching system, while built, human, and social capitals interact to produce sustainable well-being.[1, 2]

Dr. Costanza suggested not using the maximization of gross domestic product (GDP) as an indicator of well-being and quality of life. To develop appropriate metrics and analytical tools for sustainable well-being, research agendas need to ask questions about how to define and effectively measure a desirable quality of life and well-being. Dr. Costanza outlined recent research on this concept by presenting a diagram with a list of basic human needs that go well beyond subsistence and reproduction for achieving well-being, including security, affection, and participation (Figure 7-2). The list of fundamental human needs had several variations depending on culture, individual, and other factors. From a policy perspective, the objective is to create opportunities for people to meet those needs through varying configurations of built, social, human, and natural capital assets. Positive psychology provides another approach to quality of life by looking beyond income and associating a sense of well-being with positive emotion, engagement, good relationships, meaning and purpose, and accomplishment.

A number of alternative metrics to GDP of national welfare and well-being have been put forward in recent years, including the World Values Survey and Bhutan's Gross National Happiness Survey. Dr. Costanza, however, indicated that these metrics still have flaws, and there remains a need for additional research to develop hybrid, integrated indicators linked to the SDGs. He points to the Genuine Progress Index (GPI) as an example. The GPI adds several elements to the popular GDP metric, including social, human, and natural capital, while subtracting undesirable elements, such as crime or automobile accidents. One analysis that collected national level GPI studies for 17 countries to construct a representative global GPI per capita found that the global GPI per capita rate plateaued while the global GDP per capita rate increased. This result, while not a perfect indicator, reveals the inadequacy of using GDP as an indicator of well-being and the need for the creation of a new quality-of-life approach that builds on the values of a broad group of stakeholders. Several states, such as Maryland and Vermont, made efforts to adopt new well-being approaches, using their own versions of the GPI.

In addition to rethinking the GDP metric, Dr. Costanza advocated for convening natural and social scientists from different fields to collaborate and integrate the modeling of societies to address large questions such as whether transitions to sustainability can occur without major collapses of civilization. Future Earth exemplifies this type of project by bringing together historians, ecologists, and anthropologists to help understand how humanity has evolved.

[1] Costanza, R., et al. 2014. Changes in the global value of ecosystem services. *Global Environmental Change* 26:152–158.

[2] Matson, P., W. C. Clark, and K. Andersson. 2016. *Pursuing Sustainability: A Guide to the Science and Practice*. Princeton, NJ: Princeton University Press.

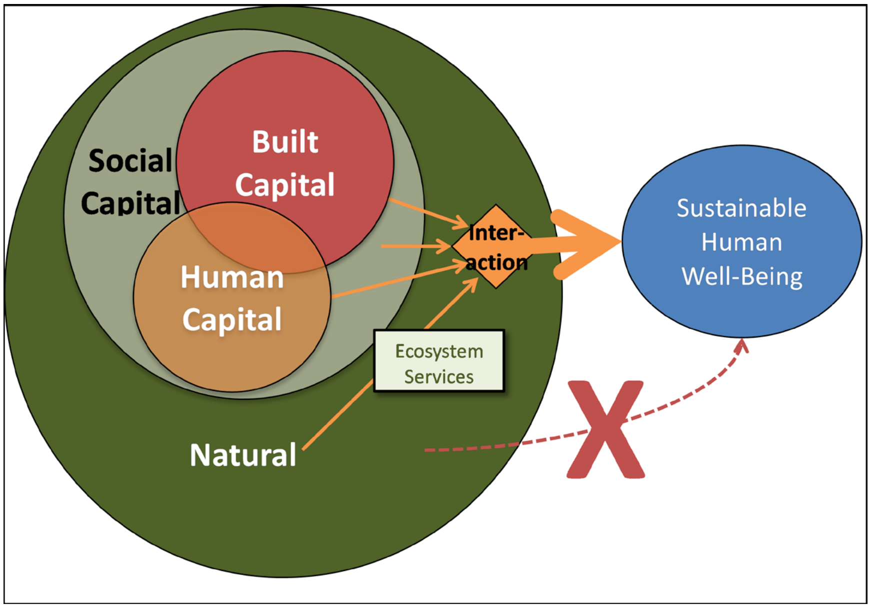

FIGURE 7-1 Four interacting assets that produce sustainable well-being.
SOURCE: Robert Costanza, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 14, 2016, Newport Beach, California.

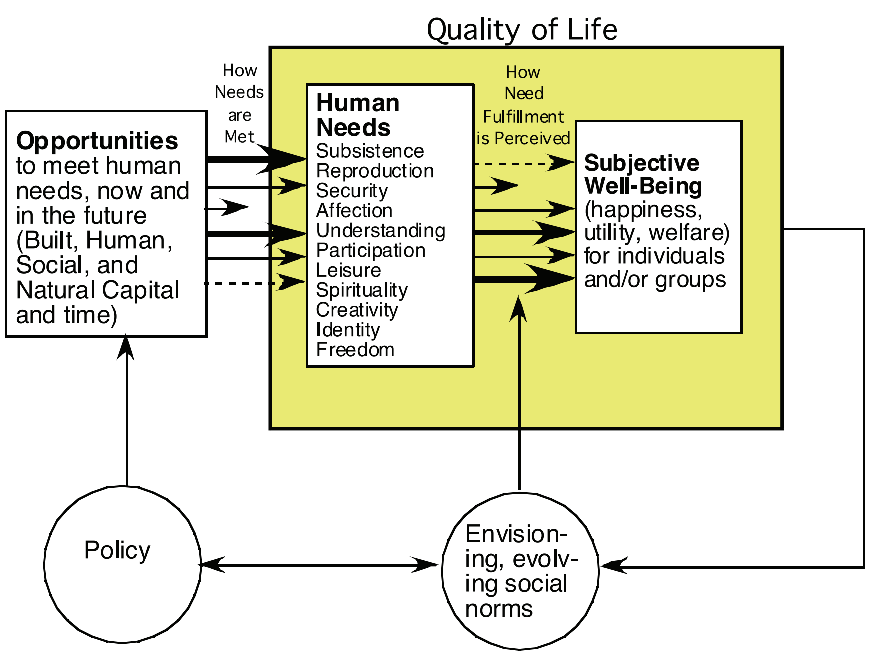

FIGURE 7-2 Quality of life: An approach integrating opportunities, human needs, and subjective well-being.
SOURCE: Robert Costanza, Presentation, National Academies of Sciences, Engineering, and Medicine Workshop, January 14, 2016, Newport Beach, California.

Such work would provide important research and insights going forward. A number of countries and institutions, such as New Zealand and Australia, developed methods that strive for this inclusiveness, because they believe the public can add significant value in developing a new shared vision of sustainability. New Zealand conducted a study that asked the public about their opinion on the current system and its future. Australia recently released a similar scenario planning survey that focused on four possible "futures" for the system. The public trust doctrine provides another approach, which implies that governments have a financial responsibility to respect the commons, thus bringing new elements of legal principles and property rights into the sustainability transition. Finally, Dr. Costanza noted the need for new communication venues to relay these results and solutions in the transition to a more sustainable world.

William Clark, Harvey Brooks Professor of International Science, Public Policy and Human Development at Harvard University, provided insights on paths forward for sustainability science. Policy decisions result from preceding actions and can be illustrated as mechanical gears (Figure 7-3); however, missing from the analogy of mechanical gears is the concept of linkages among data, models, and indicators, which should not be developed independently. Similarly, monitoring needs to be done in connection with experiments, theory, and policy needs. These efforts need to be done in the context of a sustainability framework focused on people, equity, and long-term thinking, he said.

The report committee for *Our Common Journey* used a framework with an anthropocentric view. For example, in such a framework it was determined that whales matter because voters determined that whales were worth protecting. Such values for protection of natural elements of the world (e.g., whales, trees) are incorporated into this framework. This framework, he said, provides an end (i.e., targets, goals) that the means can use to try to accomplish (i.e., capital asset stocks, production-consumption systems).

Dr. Clark said that the means of achieving well-being over the long run is done with (capital) asset management so that resources are not depleted leaving future generations with less than there was before (see Figure 1-2). Models and frameworks of sustainability need to represent such assets, and the factors that result in change with time need to be determined in order to assess its effect on well-being. Not every model needs to be integrated completely; variables can be held constant by making approximation and evaluating changes when you adjust the scenario for a given variable. This provides a conceptual modeling framework. Dr. Clark also said another

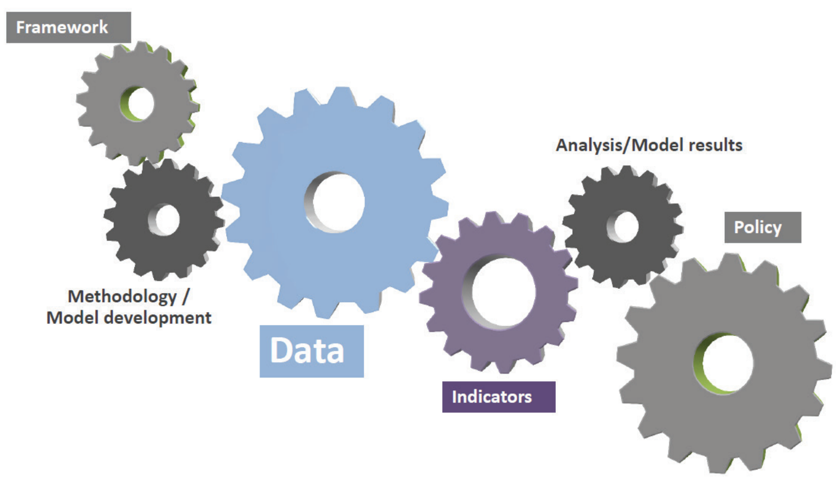

FIGURE 7-3 Policy decisions, which are a result of several preceding moving parts, can be illustrated as mechanical gears in that previous action determines a future response.
SOURCE: Prabhu Phigali, Presentation, National Academies of Sciences, Engineering, and Medicine, January 15, 2016. Newport Beach, California. Adapted by William Clark, for presentation, National Academies of Sciences, Engineering, and Medicine, January 15, 2016. Newport Beach, California.

component of frameworks needed is understanding how people organize activities to cultivate assets and generate well-being (i.e., production-consumption systems). For example, people organize to use land, plant crops, work soil with a tool from manufactured capital, all within the context of a world trade system. There are many different production and consumption systems. Additionally, it needs to be recognized that governments and large industry need to be treated explicitly in a framework because they are main actors in a production and consumption system. They are drivers behind the mechanical wheels in the gear system analogy.

To determine progress toward sustainable development, Dr. Clark said, it is necessary to track all asset stocks from whichever framework is being utilized—meaning all of the variables and indicators that are subsumed under the framework. Then it can be determined if the production-consumption system is working the way it should. Additional indicators are needed for social learning and adaptive management. Data is needed so that models will reflect reality and not imagination. Spillover impacts to other spaces need to be tracked. For example, researchers need to understand how one location does because its pollution was shipped elsewhere. This addresses the challenge of understanding externalities.

There remains a large gap in treating models as though that is how scientists provide advice to decision makers. Models are one component of expert advice, and often inform the expert, who in turn informs the decision maker. More work is needed to understand how models best serve decision makers and fit within systems where scholarly experts are integrating their work with practitioners and stakeholders. Dr. Clark said that social environmental systems are complex adaptive systems, which are not easy to model in order to make projections, and so there are questions about how to deal with innovation, adaptation, and emerging value systems.

Dr. Clark concluded by saying there is a need for community building. In the early days of the Global Change Research Program, there were biogeochemists interacting with physical climatologists and ecosystem ecologists, but there were differences in language and little understanding of the other scientists' fields. There were efforts to increase cross-discipline learning, where scientists would learn about the current state of understanding, datasets, theories, and debates in the others' fields. More efforts like this are needed to move sustainability science forward so that different disciplines truly understand other fields as they relate to sustainability. Publishing in a collective space is a large part of this community building, which is why success with the sustainability science section of the *Proceedings of the National Academy of Sciences* is important to continue. Another option for sharing ideas would be to have an online outlet where a small group of editors from different fields can select a paper published in their respective journals to share as an example of a finding they believe other sustainability scientists should know. That paper and a short abstract could then be posted to the online location. This would not be possible with researchers simply setting up search terms, but would require a small group of experts to nominate a select number of key papers to share.

8

Workshop Synopsis

This workshop brought together leading scientists in the field of sustainability science to further the discussion on sustainability indicators and metrics, models for supporting decision making, and opportunities to inform decision making. The workshop's overarching objectives were to reflect on the last 15 years since *Our Common Journey* was released and identify advances, knowledge gaps, and barriers to progress in

- Sustainability indicators,
- Models for supporting decisions,
- Frameworks for environmental decision making, and
- Efforts needed to address the range of needs and opportunities related to sustainability.

Indicators were discussed throughout the workshop. In her opening remarks, Pamela Matson said much progress has been made in developing metrics and indicators. For example, indicators are increasingly integrative and indicator systems better help decision makers understand trade-offs and gain a fuller understanding of coupled social-environmental systems. In many research areas, however, there is a drive to create new indicators while not giving enough attention to how indicators relate to other indicators. Instead of collecting data on new indicators, some participants said it would be more useful to map existing indicators against ongoing efforts. Others commented that there exists a multitude of metrics for sustainability, yet an individual decision maker can only handle a few at any one time. Paring down the number of indicators to fewer of the most useful ones may better facilitate decision making.

Participants discussed models extensively, and integrated assessment modeling (IAM) in particular, noting that such models have improved the relevance of integrated assessments by incorporating more governance, land, water, and food capabilities into assessments. There is a need, however, some said, to continue addressing gaps in understanding various systemic linkages, feedbacks, and uncertainties in models. Additionally, despite progress made in integrating human and physical earth systems in assessments, there is a lack of social indicators such as equity, connectedness, culture, and health. Participants discussed remaining barriers to IAMs and other models, such as large scale ones not being used regularly for decision making and having a limited set of topics and focus. Models often have a single focus on the effect of a single intervention, and a number of participants observed that ecology and socials systems, except for economics, are often missing from models.

Several frameworks for environmental decision making were presented during the workshop, including the World Health Organization's operational framework that helps decision makers build better climate-resilient health systems. Urban systems over the last 15 years have been an increasingly research-intense area for indicator and framework development. Many participants noted that observations and models of urban systems, however, lack sophistication compared to models of climate systems that have progressed not only spatially but also in complexity. Urban research needs to progress from models that only analyze interactions within a city to a global model that incorporates global hinterlands and feedbacks across multiple levels. In the urban context, participants discussed shared socioeconomic pathways (SSPs) as a framework for considering development and progress toward sustainability. Frameworks were also discussed as a key component to transitioning to sustainable food systems. As some participants noted, that is important to model issues in agriculture and food systems in an integrated biophysical-social framework. Regardless of the sustainability topic, participants said that indicator and model development efforts need to be done in the context of a sustainability framework focused on people, equity, and long-term thinking.

Although many participants provided examples of progress made on sustainability indicators and metrics, models for supporting decision making, and opportunities to inform decision making, there were many remaining research gaps identified that would need to be filled in order to address the range of needs and opportunities related to sustainability. For example, well-being was discussed throughout the workshop as a key component to sustainability. It was noted by some, however, that although aiming for human well-being is a notable goal, it does not translate easily into quantifiable information for scientists and decision makers to use. There was ensuing discussion on how future research should focus on different metrics and indicators of well-being, along with the importance of interdisciplinary research and of engaging and clearly communicating research efforts and results to non-technical audiences and policy makers.

Appendix A

Workshop Agenda

Transition Toward Sustainability after 15 Years:
Where Do We Stand in Advancing the Scientific Foundation?
A Workshop
Hyatt Regency Newport Beach
Newport Beach, CA

JANUARY 14, 2016

9:00 AM **Welcome from the National Academies of Sciences, Engineering, and Medicine**
Ralph J. Cicerone, National Academy of Sciences

9:10 AM **Introductions and Meeting Goals**
David Dzombak (Chair) (NAE), Carnegie Mellon University, Committee Chair
Jerry Miller, National Academies of Sciences, Engineering, and Medicine

9:30 AM **Keynote Remarks – Sustainability Science: Overview of the State of the Field**
Pamela Matson (NAS), Stanford University

10:15 AM **A Brief Update on the Sustainability Roundtable 2015 Sessions on Sustainability Indicators and Metrics**
David Dzombak (NAE), Carnegie Mellon University, Roundtable Co-chair

10:30 AM BREAK

10:45 AM **Panel I: Sustainability and Economic and Population Growth**
Moderator: Susan Trumbore (NAS), Max Planck Institute for Biogeochemistry
John Weyant, Stanford University
Joseph Arvai, University of Michigan
Wolfgang Lutz, International Institute for Applied Systems Analysis

11:45 AM **Q&A and Discussion**

12:15 PM LUNCH

1:15 PM **Panel II: Urban Systems and Resource Sustainability**
Moderator: Stephen Polasky (NAS), University of Minnesota
John Crittenden (NAE), Georgia Institute of Technology
William Solecki, Hunter College
Karen Seto, Yale University

2:15 PM **Q&A and Discussion**

2:45 PM BREAK

3:00 PM **Panel III: Sustainable Manufacturing**
Moderator: Thomas Graedel (NAE), Yale University
Anthony Ku, GE Global Research
Julie Zimmerman, Yale University
Steven Skerlos, University of Michigan

4:00 PM **Q&A and Discussion**

4:30 PM **Summary Discussion**
David Dzombak (NAE), Carnegie Mellon University

5:00 PM **Adjourn**

JANUARY 15, 2016

9:00 AM **Welcome and Re-Cap from Previous Day**
David Dzombak (NAE), Carnegie Mellon University

9:15 AM **Panel IV: Sustainable Food Systems and Diet**
Moderator: Prabhu Pingali (NAS), Cornell University
Gerald Nelson, University of Illinois, Urbana-Champaign
Mark Howden, Commonwealth Scientific and Industrial Research Organisation
Prabhu Pingali (NAS), Cornell University

10:15 AM **Q&A and Discussion**

10:45 AM BREAK

11:00 AM **Panel V: Ocean Sustainability**
Moderator: Roberta Marinelli, University of Southern California
Robert Costanza, Australian National University
Steven Lohrenz, University of Massachusetts Dartmouth
Margaret Leinen, University of California, San Diego

12:00 PM **Q&A and Discussion**

12:30 PM LUNCH

1:15 PM **Panel VI: Integrated Analysis**
Moderator: Kristie Ebi, University of Washington
Elena Bennett, McGill University
Thomas Dietz, Michigan State University

2:15 PM **Q&A and Discussion**

2:45 PM BREAK

3:00 PM **A Path Forward: The State of Sustainability Science: Future Needs and Opportunities**
Moderator: David Dzombak (NAE), Carnegie Mellon University
Steve Skerlos University of Michigan
William Clark (NAS), Harvard University

4:15 PM **Summary Remarks**
David Dzombak (Chair) (NAE), Carnegie Mellon University

4:30 PM **Workshop Conclusion**

Appendix B

Workshop Participants

David Dzombak (Chair) (NAE)
Hamerschlag University Professor and Department Head
Carnegie Mellon University

Joseph Arvai
Max McGraw Professor of Sustainable Enterprise and Director
University of Michigan

Elena Bennett
Associate Professor
School of Environment
McGill University

Blair Bowers
Caset Associates, Ltd

Ralph J. Cicerone (NAS)
President
National Academy of Sciences

William Clark (NAS)
Harvey Brooks Professor of International Science, Public Policy and Human Development
Harvard University

Robert Costanza
Professor and Chair in Public Policy
Australian National University

John Crittenden (NAE)
Director, Brook Byers Institute for Sustainable Systems
Georgia Institute of Technology

Steven Davis
Assistant Professor
Department of Earth System Science
University of California, Irvine

Thomas Dietz
Professor of Sociology and Environmental Science and Policy
Michigan State University

Kristie Ebi
Professor, Department of Global Health
University of Washington

Thomas Graedel (NAE)
Clifton R. Musser Professor of Industrial Ecology
Yale University

Marilu Hastings
Vice President, Sustainability Program
Cynthia and George Mitchell Foundation

Alan Hecht
Director for Sustainable Development Office of Research and Development
U.S. Environmental Protection Agency

Mark Howden
Chief Research Scientist
Commonwealth Scientific and Industrial
Research Organisation

Lek Kadeli
Acting Assistant Administrator
Office of Research and Development
U.S. Environmental Protection Agency

Anthony Ku
Senior Engineer
Manufacturing and Materials Technologies
GE Global Research

Margaret Leinen
Vice Chancellor for Marine Sciences
Director of Scripps Institution of Oceanography
University of California, San Diego

Steven Lohrenz
Dean and Professor
School for Marine Science and Technology
University of Massachusetts Dartmouth

Wolfgang Lutz
Director, World Population Program
International Institute for Applied Systems Analysis

Alison Macalady
Associate Program Officer
The National Academies of Sciences, Engineering, and Medicine

Roberta Marinelli
Executive Director
Wrigley Institute for Environmental Studies
University of Southern California

Pamela Matson (NAS)
Chester Naramore Dean, School of Earth, Energy & Environmental Sciences
Stanford University

Jerry Miller
Director, Science and Technology for Sustainability Program
The National Academies of Sciences, Engineering, and Medicine

Gerald Nelson
Professor Emeritus
University of Illinois, Urbana-Champaign

Dusan Pejakovic
Program Officer, Science
Gordon and Betty Moore Foundation

Marty Perreault
Director, President's Circle
The National Academies of Sciences, Engineering, and Medicine

Prabhu Pingali (NAS)
Professor, Charles H. Dyson School of Applied Economics and Management
Cornell University

Stephen Polasky (NAS)
Fesler-Lampert Professor of Ecological/Environmental Economics
University of Minnesota

Yasmin Romitti
Research Assistant
The National Academies of Sciences, Engineering, and Medicine

Karen Seto
Associate Dean of Research
Professor of Geography and Urbanization
Yale University

Steven Skerlos
Arthur F. Thurnau Professor, Mechanical Engineering
University of Michigan

William Solecki
Professor and Founder Director, Emeritus CUNY Institute for Sustainable Cities
Hunter College

Susan Trumbore (NAS)
Director
Department Biogeochemical Processes
Max Planck Institute for Biogeochemistry

John Weyant
Professor of Management Science and Engineering
Stanford University

Julie Zimmerman
Professor, Green Engineering
Yale University

Appendix C

Biographies of Planning Committee, Speakers, and Staff

DAVID DZOMBAK (NAE) (Planning Committee Chair) is the Hamerschlag University Professor and Head of the Department of Civil and Environmental Engineering at Carnegie Mellon University. The emphasis of his research and teaching is on water resources and water quality engineering, and energy-environment issues. Dr. Dzombak is a member of the National Academy of Engineering, a registered professional engineer in Pennsylvania, and a board-certified environmental engineer by the American Academy of Environmental Engineers and Scientists. His professional service activity has included the U.S. Environmental Protection Agency (EPA) Science Advisory Board (2002–present); the U.S. Department of Defense Strategic Environmental Research and Development Science Advisory Board (2013–present); the EPA National Advisory Council for Environmental Policy and Technology, Environmental Technology Subcommittee (2004–2008); the National Research Council (various committees, 2000–present); Editorial Advisory Board for *Sustainable Chemistry & Engineering* (2012–present); associate editor of *Environmental Science & Technology* (2005–2012); chair of committees for the American Academy of Environmental Engineers and Scientists, American Society of Civil Engineers, Association of Environmental Engineering and Science Professors, and Water Environment Federation; and advisory committees for Allegheny County and the Commonwealth of Pennsylvania. Dr. Dzombak received his Ph.D. in civil engineering (environmental engineering focus) from the Massachusetts Institute of Technology in 1986. He also holds an M.S. in civil engineering (1981, environmental engineering focus) and a B.S. in civil Engineering (1980) from Carnegie Mellon, and a B.A. in mathematics from Saint Vincent College (1980).

RYAN ANDERSON is a Christine Mirzayan science and technology policy fellow at the National Academies of Sciences, Engineering, and Medicine. He also works for the Chicago-based environmental nonprofit the Midwest Pesticide Action Center as a program and communications manager, where he educates and trains urban residents on the practices to reduce synthetic lawn pesticide and fertilizer use. Prior to joining the National Academies, Mr. Anderson completed a master of sustainable solutions at Arizona State University. During his time at Arizona State, he collaborated on carbon mitigation planning with the city of Indianapolis, contributed to research on corporate social responsibility at the Asia Global Institute, and led the online, academic journal *The Sustainability Review* during its transition to a video format. Mr. Anderson also holds a dual bachelor's degree in biology and electronic journalism from Butler University.

JOSEPH ARVAI (Planning Committee Member) is the Max McGraw Professor of Sustainable Enterprise and the director of the Erb Institute for Global Sustainable Enterprise at the University of Michigan. He is jointly appointed between the School of Natural Resources and Environment, and the Ross School of Business. Prior to joining the University of Michigan, Dr. Arvai was Svare Professor and Chair in Applied Decision Research at the University of Calgary. Dr. Arvai is an internationally recognized expert in the risk and decisions sciences; his research has two main areas of emphasis: First, Dr. Arvai and his research group conduct experiments focused on advancing our understanding of how people process information and make decisions, with a specific emphasis on how people make trade-offs. Second, Dr. Arvai and his team conduct research focused on developing and testing decision-aiding tools and approaches that can be used by people to improve decision quality across a wide range of environmental, social, and economic contexts. Dr. Arvai's research is applied, and accounts for decision making by a broad spectrum of public and stakeholder groups, as well as by technical experts, business leaders, and policy makers. His work also focuses on choices made by people individually, and when working in groups. Likewise, he conducts his research across a wide range of contexts, ranging from environmental risk management, to consumer choice and policy making. In addition to Dr. Arvai's academic work, he is a member of the U.S. Environmental Protection Agency's Chartered Science Advisory Board, and is a member of the U.S. National Academy of Sciences' Board on Environmental Change and Society.

ELENA BENNETT is an associate professor in the Department of Natural Resource Sciences at the McGill School of Environment. Dr. Bennett attended Oberlin College as an undergraduate, where she studied biology and environmental studies. She earned her M.Sc. in land resources from the University of Wisconsin in 1999, and her Ph.D. in limnology and marine sciences in 2002. As a postdoc, she helped coordinate the Scenarios Working Group for the Millennium Ecosystem Assessment. Dr. Bennett started working at McGill in 2005. Her research interests include sustainable use and management of ecosystem services; human impacts on biogeochemical cycles; human perturbation of ecosystem processes; management of trade-offs among ecosystem services, especially agricultural production and water quality; land-use change and water quality; urban ecology; communicating science; and scenarios.

RALPH J. CICERONE (NAS) is the president of the National Academy of Sciences and chair of the National Research Council. His research in atmospheric chemistry, climate change, and energy has involved him in shaping science and environmental policy at the highest levels nationally and internationally. Dr. Cicerone has received a number of honorary degrees and many awards for his scientific work. Among the latter, the Franklin Institute recognized his fundamental contributions to the understanding of greenhouse gases and ozone depletion by selecting Dr. Cicerone as the 1999 laureate for the Bower Award and Prize for Achievement in Science. In 2001 he led a National Academy of Sciences study of the current state of climate change and its impact on the environment and human health, requested by President Bush. The American Geophysical Union awarded Dr. Cicerone its James B. Macelwane Award in 1979 for outstanding contributions to geophysics by a young scientist and its 2002 Roger Revelle Medal for outstanding research contributions to the understanding of Earth's atmospheric processes, biogeochemical cycles, and other key elements of the climate system. In 2004 the World Cultural Council honored him with the Albert Einstein World Award in Science. In addition to the National Academy of Sciences, Dr. Cicerone is a member of the American Academy of Arts and Sciences, the American Philosophical Society, the Accademia Nazionale dei Lincei, the Russian Academy of Sciences, and the Korean Academy of Science and Technology. He has served as president of the American Geophysical Union. Dr. Cicerone was educated at the Massachusetts Institute of Technology (B.S. in electrical engineering) and the University of Illinois at Champaign-Urbana (M.S., Ph.D. in electrical engineering, with a minor in physics). Immediately prior to his election as Academy president, Dr. Cicerone served as chancellor of the University of California, Irvine, from 1998 to 2005.

WILLIAM C. CLARK (NAS) is the Harvey Brooks Professor of International Science, Public Policy and Human Development at Harvard University's John F. Kennedy School of Government. His research focuses on sustainability science: understanding the interactions of human and environmental systems with a view toward advancing the goals of sustainable development. He is particularly interested in how institutional arrangements affect the linkage between knowledge and action in the sustainability arena. At Harvard, he currently codirects the Sustainability Science Program. He is coauthor of *Adaptive Environmental Assessment and Management* (Wiley, 1978), *Redesigning Rural Development* (Hopkins, 1982), and *The Global Health System: Institutions in a Time of Transition* (Harvard, 2010); editor of the *Carbon Dioxide Review* (Oxford, 1982); coeditor of *Sustainable Development of the Biosphere* (Cambridge, 1986), *The Earth Transformed by Human Action* (Cambridge, 1990), *Learning to Manage Global Environmental Risks* (MIT, 2001), and *Global Environmental Assessments* (MIT, 2006); and cochaired the U.S. National Research Council's study *Our Common Journey: A Transition toward Sustainability* (NAP, 1999). He serves on the editorial board of the *Proceedings of the National Academy of Sciences*. Dr. Clark is a member of the National Academy of Sciences and a fellow of the American Association for the Advancement of Science. He is a recipient of the MacArthur Prize, the Humboldt Prize, the Kennedy School's Carballo Award for excellence in teaching, and the Harvard College Phi Beta Kappa Prize for Excellence in Teaching.

ROBERT COSTANZA is a professor and chair in public policy at the Australian National University's Crawford School of Public Policy. Prior to this, he was distinguished university professor of sustainability in the Institute for Sustainable Solutions at Portland State University; Gund Professor of Ecological Economics and founding director of the Gund Institute for Ecological Economics at the University of Vermont; professor at the University of Maryland and at Louisiana State University; and a visiting scientist at the Beijer Institute for Ecological Economics in Stockholm, Sweden, and at the University of Illinois Natural History Survey. Dr. Costanza is also currently a senior fellow at the National Council on Science and the Environment, Washington, D.C.; a senior fellow at the Stockholm Resilience Center, Stockholm, Sweden; an affiliate fellow at the Gund Institute for Ecological Economics at the University of Vermont; and a deTao Master of Ecological Economics at the deTao Masters Academy in Shanghai, China. Dr. Costanza received B.A. and M.A. degrees in architecture and a Ph.D. in environmental engineering sciences (systems ecology with economics minor), all from the University of Florida. Dr. Costanza's transdisciplinary research integrates the study of humans and the rest of nature to address research, policy, and management issues at multiple time and space scales, from small watersheds to the global system. Dr. Costanza is cofounder and past president of the International Society for Ecological Economics, and was chief editor of the society's journal, *Ecological Economics*, from its inception in 1989 until 2002. He is also founding editor-in-chief of *Solutions*, a unique hybrid academic/popular journal. Dr. Costanza is the author or coauthor of more than 500 scientific papers and 27 books. His work has been cited in more than 17,000 scientific articles, and he has been named as one of the Institute for Scientific Information's Highly Cited Researchers since 2004.

JOHN CRITTENDEN (NAE) is director of the Brook Byers Institute for Sustainable Systems and Hightower Chair/Georgia Research Alliance Eminent Scholar in Environmental Technologies at Georgia Institute of Technology. His current research focus is working with other academics and institutions on the challenge of sustainable urban infrastructure systems. The goal of this effort is to connect public policy with the design of urban form in the context of varied urban development scenarios and their potential local, regional, and global environmental impacts. Topics of interest in this work include regional development, energy use, alternative energy technologies, sustainable materials, advanced modeling of urban systems, and sustainable engineering pedagogy. Dr. Crittenden received his Ph.D. and M.S.E. in civil engineering and his B.S.E. in chemical engineering from the University of Michigan, Ann Arbor.

THOMAS DIETZ is a professor of sociology and environmental science and policy and assistant vice president for environmental research at Michigan State University (MSU). He is also codirector of the Great Lakes Integrated Sciences and Assessment Center. He holds a Ph.D. in ecology from the University of California, Davis, and a bachelor of general studies from Kent State University. At MSU he was founding director of the Environmental Science and Policy Program and associate dean in the Colleges of Social Science, Agriculture and Natural Resources, and Natural Science. Dr. Dietz is a fellow of the American Association for the Advancement of Science, and has been awarded the Sustainability Science Award of the Ecological Society of America; the Distinguished Contribution Award of the American Sociological Association Section on Environment, Technology and Society; the Outstanding Publication Award from the American Sociological Association Section on Environment, Technology and

Society; and the Gerald R. Young Book Award from the Society for Human Ecology. He has served as chair of the U.S. National Research Council Committee on Human Dimensions of Global Change and the Panel on Public Participation in Environmental Assessment and Decision Making, and as vice chair of the Panel on Advancing the Science of Climate Change of the America's Climate Choices study. Dr. Dietz has also served as secretary of Section K (Social, Economic, and Political Sciences) of the American Association for the Advancement of Science and is the former president of the Society for Human Ecology. He has coauthored or coedited 13 books and more than 130 papers and book chapters.

KRISTIE L. EBI (Planning Committee Member) is a professor in the Department of Global Health and in the Department of Environmental and Occupational Health Sciences, University of Washington; a guest professor at Umea University, Sweden; and consulting professor at Stanford University and George Washington University. She conducts research on the impacts of and adaptation to climate change, including on extreme events, thermal stress, foodborne safety and security, waterborne diseases, and vectorborne diseases. Her work focuses on understanding sources of vulnerability and designing adaptation policies and measures to reduce the risks of climate change in a multistressor environment. She has worked on assessing vulnerability and implementing adaptation measures in Central America, Europe, Africa, Asia, the Pacific, and the United States. She is cochair with Tom Kram (PBL, the Netherlands) of the International Committee on New Integrated Climate Change Assessment Scenarios (ICONICS), facilitating development of new climate change scenarios. She was executive director of the International Panel on Climate Change (IPCC) Working Group II Technical Support Unit from 2009 to 2012. She was a coordinating lead author or lead author for the human health assessment for two U.S. national assessments, the IPCC *Fourth Assessment Report*, the Millennium Ecosystem Assessment, and the International Assessment of Agricultural Science and Technology for Development. Dr. Ebi's scientific training includes an M.S. in toxicology and a Ph.D. and M.P.H. in epidemiology, and postgraduate research at the London School of Hygiene and Tropical Medicine. She has edited 4 books on aspects of climate change and has published more than 150 papers.

THOMAS GRAEDEL (NAE) (Planning Committee Member) is the Clifton R. Musser Professor of Industrial Ecology, professor of chemical engineering, and director of the Center for Industrial Ecology at Yale University. Previously, he was a distinguished member of the technical staff at AT&T Bell Laboratories. He cochaired the National Academies of Sciences, Engineering, and Medicine's Roundtable on Science and Technology for Sustainability from 2008 to 2014. He is the author or coauthor of 13 books and more than 350 technical papers in various scientific journals. Dr. Graedel received his B.S. (chemical engineering) from Washington State University in 1960, his M.A. (physics) from Kent State University in 1964, and his M.S. and Ph.D. (astronomy) from the University of Michigan in 1967 and 1969, respectively.

MARK HOWDEN is a chief research scientist with the Commonwealth Scientific and Industrial Research Organisation Agriculture Flagship and an honorary professor at Melbourne University, School of Land and Food. He is also the interim director of the Climate Change Institute at the Australian National University. Dr. Howden's work has focused on how climate impacts on, and innovative adaptation options for, systems we value: agriculture and food security, the natural resource base, ecosystems and biodiversity, energy, water, and urban systems. He has also developed the national (NGGI) and international (IPCC/OECD) greenhouse gas inventories for the agricultural sector and assessed sustainable methods of reducing net greenhouse gas emissions from agriculture. Dr. Howden has worked on climate variability, climate change, innovation, and adoption issues for more than 27 years in partnership with farmers, farmer groups, catchment groups, industry bodies, agribusiness, urban utilities and various policy agencies via both research and science-policy roles. Dr. Howden has more than 390 publications of different types. He has been a major contributor to the Intergovernmental Panel on Climate Change (IPCC) Second, Third, Fourth, and Fifth Assessment reports and various IPCC special reports, sharing the 2007 Nobel Peace Prize with other IPCC participants and Al Gore. Recently, Dr. Howden sat on the U.S. Federal Advisory Committee for the Third National Climate Assessment, and he participates in several other international science and policy advisory bodies.

ANTHONY KU is a senior engineer in the Manufacturing and Materials Technologies organization at GE Global Research, with interests in advanced materials and material systems development. Since joining GE, Dr. Ku has worked on a range of projects in support of GE's Water, Energy, Aviation, and Healthcare businesses. He has led several projects centered on the themes of energy, water, and materials sustainability, with experience in advancing technology from TRL 1 through 6. He is currently supporting the introduction of advanced cores for blade casting and ceramic matrix composites into GE's new jet engines. Dr. Ku is also interested in the interface between materials development and system design, and recently joined with several colleagues to start a new scientific journal, *Sustainable Materials and Technology*, to promote technical dialogue in this area. Dr. Ku served as chair of the National Academies of Sciences, Engineering, and Medicine's committees on Energy Sustainability: A Meeting Series. He received his Ph.D. degree in chemical engineering from Princeton University and his M.S. degree in chemical engineering practice from Massachusetts Institute of Technology in 2004 and 1997, respectively.

MARGARET LEINEN is the director of Scripps Institution of Oceanography at the University of California, San Diego, and also serves as the University of California, San Diego's vice chancellor for marine sciences and dean of the School of Marine Sciences. Prior to joining Scripps, she served as vice provost for marine and environmental initiatives, and executive director at Florida Atlantic University's Harbor Branch Oceanographic Institute from 2011 to 2013. She is the founder and served as president of the Climate Response Fund from 2009 to 2011 and was the Chief Science Officer of Climos, Inc., from 2007 to 2008. From 2000 to 2007, she was the assistant director for geosciences and coordinator of environmental research and education at the National Science Foundation. Dr. Leinen was vice provost for marine and environmental programs and dean of the Graduate School of Oceanography at the University of Rhode Island from 1991 to 2000. She is president-elect of the American Geophysical Union. Dr. Leinen serves on numerous boards, including the Oceanography Society, the National Council for Science and the Environment, International Geosphere-Biosphere Programme, Atmospheric and Hydrospheric Science Section of the American Association for the Advancement of Science, and Research Board of the Gulf of Mexico Research Initiative. She previously served on the board for the National Ecological Observatory Network and the Global Change Research Program of the National Research Council/National Academy of Sciences. Dr. Leinen received her doctorate in oceanography from the University of Rhode Island, her master's degree in geological oceanography from Oregon State University, and her bachelor's degree in geology from the University of Illinois.

STEVEN LOHRENZ assumed the position of dean and professor of the School for Marine Science and Technology at the University of Massachusetts Dartmouth in July 2011. Prior to that, he served as chair of the University of Southern Mississippi Department of Marine Science, located at the NASA John C. Stennis Space Center. Dr. Lohrenz received a Ph.D. in biological oceanography in 1985 from the Massachusetts Institute of Technology–Woods Hole Oceanographic Institution Joint Program. He currently serves on the Board of Directors of the Northeast Regional Association Coastal Ocean Observing System and is a member of the NASA Geostationary Coastal and Air Pollution Events Satellite Mission Science Working Group and the NASA Ocean Carbon Monitoring System Scoping Team. He served on the University of Southern Mississippi Oil Spill Response Team and a statewide Mississippi oil spill response committee during the Deepwater Horizon oil spill. His research interests include phytoplankton ecology and physiology, cycling of nutrients and carbon, and the application of optics and remote sensing for characterizing water quality and biogeochemical processes in coastal waters. Dr. Lohrenz is currently involved in research on detection and characterization of harmful algal blooms, distribution and fate of the oil from the Deepwater Horizon oil spill, and land-ocean interactions in the Mississippi River basin and northern Gulf of Mexico.

WOLFGANG LUTZ is founding director of the Wittgenstein Centre for Demography and Global Human Capital (a new collaboration between the International Institute for Applied Systems Analysis [IIASA], the Austrian Academy of Sciences, and the Vienna University of Economics and Business [WU]). He joined IIASA in October 1985, where he is program director of the World Population Program. Since 2002 he is also director of the Vienna Institute of Demography of the Austrian Academy of Science, and since 2008, full professor of applied statistics (part time) at the WU. He is also professorial research fellow at the Oxford Martin School for 21st Century Studies. Dr. Lutz studied philosophy, theology, mathematics, and statistics at the Universities of Munich, Vienna, and Helsinki and holds a Ph.D. in demography from the University of Pennsylvania (1983) and a second doctorate (habilitation) in statistics from the University of Vienna. He has worked on family demography, fertility analysis, population projection, and the interaction between population and environment. He has been conducting a series of in-depth studies on population-development-environment interactions in Mexico, several African countries, and Asia. He is the author of the series of world population projections produced at IIASA and has developed approaches for projecting education and human capital. He is also principal investigator of the Asian MetaCentre for Population and Sustainable Development Analysis. Dr. Lutz is author and editor of 28 books and more than 200 refereed articles, including 7 in *Science* and *Nature*. In 2008 he received an ERC Advanced Grant, in 2009 the Mattei Dogan Award of the International Union for the Scientific Study of Population and in 2010 the Wittgenstein Prize, the highest Austrian science award. He is elected full member of the Austrian Academy of Sciences and of the German National Academy Leopoldina as well as a member of the Committee on Population of the U.S. National Academy of Sciences.

ALISON MACALADY (Staff) is an associate program officer for the Board on Atmospheric Sciences and Climate at the National Academies of Sciences, Engineering, and Medicine. Dr. Macalady grew up in Colorado and holds a B.A. in geology, a master's degree in forestry, and a Ph.D. in geography from the University of Arizona. Her dissertation research focused on understanding how climate variability and change influence forest ecosystems, and in particular on how drought coupled with high temperatures can increase tree mortality rates, insect outbreaks, and wildfires. Prior to pursuing her Ph.D., Dr. Macalady spent several years working as a reporter and radio producer, covering environmental issues in the American West. She also worked for a variety of nonprofit organizations on issues related to forest conservation and management.

ROBERTA MARINELLI (Planning Committee Member) is the executive director of the University of Southern California (USC), Wrigley Institute for Environmental Studies. She plays a leadership role in planning and implementing an expansion of academic and research programs in environmental studies at USC's University Park Campus and at the Philip K. Wrigley Marine Science Center on Santa Catalina Island. She also oversees the George and Mary Lou Boone Center for Science and Environmental Leadership, a nexus where scientists and policy makers can meet to resolve environmental disputes and address marine science concerns. Her research interests include the ecology and geochemistry of seafloor communities, and coupled human-natural interactions in marine environments. Dr. Marinelli was a program officer the National Science Foundation's Antarctic Sciences section, where she contributed to building collaborative programs across the foundation, including the International Polar Year, Climate Research Investments, and SEES (Science, Engineering and Education for Sustainability). She was previously on the faculty of the University of Maryland's Center for Environmental Science, and the Skidaway Institute of Oceanography, where she received a National Science Foundation Early Career Award. She is a member of the American Geophysical Union and the American Society for Limnology and Oceanography. Dr. Marinelli received her Ph.D. in marine science from the University of South Carolina.

PAMELA MATSON (NAS) is the Chester Naramore Dean of the School of Earth, Energy and Environmental Sciences, Richard and Rhoda Goldman Professor in Environmental Studies, and senior fellow at the Woods Institute for Environment at Stanford University. A MacArthur fellow and elected member of the National Academy of Sciences and the American Academy of Arts and Sciences, Dr. Matson is an internationally recognized interdisciplinary Earth scientist, academic leader, and organizational strategist. Her research addresses a range of environment and sustainability issues, including sustainability of agricultural systems; vulnerability of particular people and places to climate change; and environmental consequences of tropical land-use change and global change in the nitrogen and carbon cycles. With multidisciplinary teams of researchers, managers, and decision makers, she has worked to develop agricultural approaches that reduce environmental impacts while maintaining livelihoods and human well-being. Dr. Matson is the author of numerous scientific publications and books, including the recently published *Seeds of Sustainability*, and the National Research Council volumes *Our Common Journey: A Transition Toward Sustainability* and *America's Climate Choices*. She is the founding cochair of the National Academies of Sciences, Engineering, and Medicine's Roundtable on Science and Technology for Sustainability, and serves on the boards of the Foundation for Food and Agriculture Research, World Wildlife Fund, and Climate Works Foundation. She is a past president of the Ecological Society of America, past lead author for the Intergovernmental Panel on Climate Change, and was a member of the science leadership committee for the International Geosphere-Atmosphere Programme. Dr. Matson received her B.S. in biology from the University of Wisconsin–Eau Claire; her M.S. in environmental science from Indiana University; and her Ph.D. in forest ecology from Oregon State University.

JERRY MILLER (Staff) was appointed director of the Science and Technology for Sustainability Program at the National Academies in February 2015. A senior executive with expertise in science and resource management policy, Dr. Miller is the Academies' senior scientist driving policy and program direction on sustainability-related issues. Previously, Dr. Miller served as president of Science for Decisions, a consulting practice he founded to ensure that solid science is available to inform policy and management decisions that impact natural resources and the livelihoods that depend upon them. From 2009 until 2013, Dr. Miller served as assistant director for ocean sciences at the White House Office of Science and Technology Policy (OSTP). During his time at OSTP, Dr. Miller was instrumental in the creation of the nation's first National Ocean Policy and the development of its foundational science priorities. He was founding codirector of the National Ocean Council Office and later served as its deputy director for science and technology. Before taking on his role at OSTP, Dr. Miller was technical director and director of research at the Consortium for Oceanographic Research and Education (now the Consortium for Ocean Leadership), where he had management and oversight responsibilities for the program offices of the U.S. National Oceanographic Partnership Program, the national and international Census of Marine Life programs, and other community-wide activities. As associate director for ocean, atmosphere, and space sciences at the Office of Naval Research's global office in London, he built international programs in ocean and atmosphere modeling as well as remote sensing. Dr. Miller has published widely in peer-reviewed literature and has made significant contributions to several major federal policy documents. His work has been recognized with awards both in the United States and abroad, including with a Distinguished Career Achievement Award from the University of Rhode Island. Dr. Miller received his B.S. in marine science from the University of South Carolina, his M.S. in oceanography from the University of Rhode Island, and his Ph.D. in meteorology and physical oceanography from the University of Miami.

GERALD NELSON is professor emeritus, University of Illinois, Urbana-Champaign. Dr. Nelson was the principal author of the report *Advancing Global Food Security in the Face of a Changing Climate*, released by the Chicago Council on Global Affairs in May 2014. He most recently served as a senior research fellow at the International Food Policy Research Institute in Washington, D.C., where he coordinated its climate change research, led the policy analysis activities of the Consultative Group for International Agricultural Research Program on Climate Change, Agriculture, and Food Security, and was the principal investigator on major projects on food security and climate change issues funded by the Bill and Melinda Gates Foundation, and the German and British aid agencies. His research includes global modeling of the interactions among agriculture, land use, and climate change; consequences of macroeconomic, sector, and trade policies and climate change on land use and the environment using remotely sensed geographic and socioeconomic data; and the assessment of the effects of genetically modified crops on the environment. Dr. Nelson was the coordinating lead author of the "Drivers of Ecosystem Change" chapter of the Millennium Ecosystem Assessment Scenarios work. Previously, he was professor in the Department of Agricultural Consumer Economics at the University of Illinois, Urbana-Champaign, served as visiting scholar at the Economic Research Service at the U.S. Department of Agriculture, and was specialist and visiting assistant professor at the University of the Philippines.

PRABHU PINGALI (NAS) (Planning Committee Member) is a professor in the Charles H. Dyson School of Applied Economics and Management and the founding director of the Tata-Cornell Agriculture and Nutrition Initiative at Cornell University. Prior to joining Cornell in June 2013, he was the deputy director of the Agriculture Development Division of the Bill and Melinda Gates Foundation, based in Seattle, Washington, from 2008 to May 2013. Dr. Pingali was elected to the U.S. National Academy of Sciences as a foreign fellow in May 2007, a fellow of the American Agricultural Economics Association (AAEA) in 2006, and a fellow of the International Association of Agricultural Economists (IAAE) in 2009. He served as the president of IAAE from 2003 to 2006, and was named the 2010 Outstanding Alumnus of North Carolina State University. He has received several international awards for his work, including the Research Discovery Award from the AAEA. Dr. Pingali has more than 3 decades of experience working with some of the leading international agricultural development organizations as a research economist, development practitioner, and senior manager. He was the director of the Agricultural and Development Economics Division of the Food and Agriculture Organization of the United Nations from 2002 to 2007, and the director of the Economics Program at the International Maize and Wheat Improvement Center (CIMMYT), Mexico, from 1996 to 2002. Prior to joining CIMMYT, he worked at the International Rice Research Institute at Los Banos, Philippines, from 1987 to 1996 as an agricultural economist, and at the World Bank's Agriculture and Rural Development Department from 1982 to 1987 as an economist. Dr. Pingali has written 10 books and more than 100 referred journal articles and book chapters on food policy, technological change, productivity growth, environmental externalities, and resource management in the developing world.

STEPHEN POLASKY (NAS) is the Fesler-Lampert Professor of Ecological/Environmental Economics at the University of Minnesota. He received a Ph.D. in economics from the University of Michigan in 1986. He previously held faculty positions in the Department of Agricultural and Resource Economics at Oregon State University (1993–1999) and the Department of Economics at Boston College (1986–1993). Dr. Polasky was the senior staff economist for environment and resources for the President's Council of Economic Advisers (1998–1999). He was elected into the National Academy of Sciences in 2010. He was elected as a fellow of the American Academy of Arts and Sciences in 2009 and a fellow of the American Association for the Advancement of Science in 2007. His research focuses on issues at the intersection of ecology and economics and includes the impacts of land use and land management on the provision and value of ecosystem services and natural capital, biodiversity conservation, sustainability, environmental regulation, renewable energy, and common property resources. He has served as coeditor and associate editor for the *Journal of Environmental Economics and Management*, as associate editor for the *International Journal of Business and Economics*, and is currently serving as an associate editor for *Conservation Letters*, *Ecology and Society*, and *Ecology Letters*, and on the editorial board of the *Proceedings of the National Academy of Sciences*.

YASMIN ROMITTI (Staff) is a research assistant for the Science and Technology for Sustainability Program at the National Academies of Sciences, Engineering, and Medicine. Ms. Romitti has previous experience with the United Nations Environment Programme, working on workshops and roundtables pertaining to climate change, biodiversity conservation, various environmental treaties and conventions, and the Sustainable Development Goals. Ms. Romitti earned a B.A. in international relations with a minor in biology at Boston University and a master of advanced international studies at the Diplomatic Academy of Vienna in Austria.

KAREN SETO is professor of geography and urbanization and associate dean of research at the Yale School of Forestry and Environmental Studies. Prior to joining Yale University, she was on the faculty at Stanford University for 8 years. Dr. Seto's research is on the human transformation of land and the links between urbanization, global change, and sustainability. She is an expert in urbanization dynamics, forecasting urban growth, and examining the environmental consequences of urban expansion. She has pioneered methods using satellite remote sensing to reconstruct historical patterns of urbanization and to develop projections of future urban expansion. She specializes in China and India, where she has conducted urbanization research for more than 15 years. Dr. Seto serves on a number of international and national scientific advisory committees, including as coordinating lead author for the Intergovernmental Panel on Climate Change Fifth Assessment Report, coordinating lead author for the United Nations Convention on Biodiversity Cities and Biodiversity Outlook, and cochair of the International Human Dimension Programme on Global Environmental Change Urbanization and Global Environmental Change Project. She also currently serves on the National Research Council (NRC) Committee to Advise the U.S. Global Change Research Program (USGCRP), the NRC Geographical Sciences Committee, and the U.S. Carbon Cycle Scientific Steering Group. She is the executive producer of *10,000 Shovels: Rapid Urban Growth in China*, a documentary film that integrates satellite imagery, historical photographs, and contemporary film footage to examine the urban changes occurring in China. Dr. Seto is a recipient of a NASA New Investigator Program (Career) Award, a National Science Foundation CAREER Award, and a National Geographic research grant. She was named an Aldo Leopold Leadership fellow in 2009. Dr. Seto received her B. A. in political science from the University of California, Santa Barbara (1991) and her M.A. in international relations and resource and environmental management (1995) and Ph.D. in geography (2000) from Boston University.

STEVEN SKERLOS is Arthur F. Thurnau Professor at the University of Michigan and is a tenured faculty member in the Departments of Mechanical Engineering and Civil and Environmental Engineering. He also serves as a University of Michigan distinguished faculty fellow in sustainability. Dr. Skerlos is director of the University of Michigan's Program in Sustainable Engineering and codirector of the Engineering Sustainable Systems Program. He is chairman of the board and founder of Fusion Coolant Systems. In 2015 he colaunched the Insitu Center for Socially Engaged Design. He has also served as director of Sustainability Education Programs for the College of Engineering since 2012. Dr. Skerlos has gained national recognition and press for his research and teaching in the fields of technology policy and sustainable design. He has cofounded two successful start-up companies (Accuri Cytometers and Fusion Coolant Systems), cofounded BLUElab, served as director of the Graduate Program in Mechanical Engineering (2009–2012), and served as associate and guest editor for four different academic journals. From 2005 to 2012, he served as principal investigator for a $2 million National Science Foundation Award to study Greenhouse Gas Policies in the Automotive Sector. Dr. Skerlos received his Ph.D. in industrial engineering and his B.S. in electrical engineering from University of Illinois, Urbana-Champaign, in 2000 and 1994, respectively.

WILLIAM SOLECKI is a professor in the Department of Geography at Hunter College-City University of New York (CUNY). Dr. Solecki's research focuses on urban environmental change, resilience, and adaptation transitions. From 2006 to 2014, he served as the director of the CUNY Institute for Sustainable Cities at Hunter College. He also served as interim director of the Science and Resilience Institute at Jamaica Bay. He has colead several climate impact studies in the greater New York and New Jersey region, including the New York City on Panel on Climate Change. He recently was a lead author of the Intergovernmental Panel on Climate Change, Working Group II, Urban Areas chapter (Chapter 8) and a coordinating lead author of the U.S. National Climate Assessment, Urbanization, Infrastructure, and Vulnerability chapter (Chapter 11). He is a cofounder of the Urban Climate Change Research Network, coeditor of *Current Opinion on Environmental Sustainability*, and founding editor of the *Journal of Extreme Events*. He holds a B.A. in geography from Columbia University and an M.A. and Ph.D. from Rutgers University.

AMANDA STAUDT directs the Board on Atmospheric Sciences and Climate (BASC) and the Polar Research Board at the National Academies of Sciences, Engineering, and Medicine. Dr. Staudt leads strategic planning, guides project development, and provides institutional oversight for both boards. From 2007 to 2013, she was a senior climate scientist at the National Wildlife Federation. In this role, she focused on communicating climate science and impacts with key decision makers and the general public, developing the intellectual and practical foundation for climate-informed conservation, and advancing climate change science education. She served on the steering committee for Impacts of Climate Change on Biodiversity, Ecosystems, and Ecosystem Services: Technical Input to the 2013 National Climate Assessment, and was an editor of *Climate-Smart Conservation: Putting Adaptation Principles into Practice*, a 2014 guidance produced by an expert workgroup including representatives from government, nonprofits, and academia. Prior to her time at the National Wildlife Federation, Dr. Staudt was a senior program officer for BASC, where she directed the Climate Research Committee and a number of high-profile studies, including the fast-track review of the U.S. Climate Change Science Program Strategic Plan, and studies on weather research for surface transportation and radiative forcing effects on climate. She also spearheaded the development of the Academies' first booklet on climate change targeted to public audiences. Dr. Staudt received her B.A. cum laude in environmental science and engineering from Harvard College and her Ph.D. in atmospheric sciences from Harvard University.

SUSAN TRUMBORE (NAS) (Planning Committee Member) has been a director of the Department Biogeochemical Processes at Max Planck Institute for Biogeochemistry since 2009. She is also professor of earth system science at the University of California, Irvine, and honorary professor in the faculty of chemistry and geology at the Friedrich Schiller University of Jena. Her main research contribution is the application of radiocarbon to study the dynamics of carbon cycling in plants and soils. In 2014 she became the editor-in-chief of *Global Biogeochemical Cycles*. She is a member of the speaker team for the Collaborative Research Centre AquaDiva and a member of the German Centre for Integrative Biodiversity Research. Dr. Trumbore received her B.S. in geology from the University of Delaware and her M.A., M.Phil., and Ph.D. in geochemistry from Columbia University.

JOHN WEYANT is professor of management science and engineering, director of the Energy Modeling Forum, and deputy director of the Precourt Institute for Energy Efficiency at Stanford University. He is also a senior fellow of the Precourt Institute for Energy and the Freeman-Spolgi Institute for International Studies at Stanford. Dr. Weyant earned a B.S./M.S. in aeronautical engineering and astronautics, M.S. degrees in engineering management and in operations research and statistics, all from Rensselaer Polytechnic Institute, and a Ph.D. in management science with minors in economics, operations research, and organization theory from the University of California, Berkeley. He was also a National Science Foundation postdoctoral fellow at Harvard's Kennedy School of Government. His research focuses on analysis of global climate change policy options, energy-efficiency analysis, energy-technology assessment, and models for strategic planning. He has been a convening lead author or lead author for the Intergovernmental Panel on Climate Change (IPCC) for chapters on integrated assessment, greenhouse gas mitigation, integrated climate impacts, and sustainable development, and most recently served as a review editor for the climate change mitigation working group of the IPCC's *Fourth Assessment Report*. He is a member of the California Air Resources Board Economic and Technology Advancement Advisory Committee (ETAAC), which is charged with making recommendations for technology policies to help implement Assembly Bill 32, the state Global Warming Solutions Act of 2006. Dr. Weyant was awarded the U.S. Association for Energy Economics' 2008 Adelmann-Frankel award for unique and innovative contributions to the field of energy economics. Dr. Weyant was honored in 2007 as a major contributor to the Nobel Peace Prize awarded to the IPCC and in 2008 for contributions to ETAAC on AB 32.

JULIE ZIMMERMAN is the Donna L. Dubinsky Associate Professor of Environmental Engineering jointly appointed to the Chemical and Environmental Engineering Department of the School of Engineering and Applied Sciences and the School of Forestry and Environmental Studies. She is the associate director for research at the Yale Center for Green Chemistry and Green Engineering. Dr. Zimmerman's research interests broadly focus on green chemistry and engineering with specific emphasis on green downstream processing and life-cycle assessment of algal biomass for fuels and value-added chemicals as well as novel bio-based sorbents for purification of drinking water and remediation of industrial wastewater. Other ongoing focus areas include the design of safer chemicals from first principles and the implications of nanomaterials on human health and the environment. Further, to enhance the likelihood of successful implementation of these next-generation designs, Dr. Zimmerman studies the effectiveness and impediments of current and potential policies developed to advance sustainability. Together, these efforts represent a systematic and holistic approach to addressing the challenges of sustainability to enhance water and resource quality and quantity, to improve environmental protection, and to provide for a higher quality of life. Dr. Zimmerman previously served as an engineer and program coordinator in the Office of Research and Development at the U.S. Environmental Protection Agency (EPA), where she managed sustainability research grants and created EPA's P3 (People, Prosperity, and the Planet) Award program. She received a joint Ph.D. from the University of Michigan in environmental engineering and natural resource policy.