Can Earth's and Society's Systems Meet the Needs of 10 Billion People?: Summary of a Workshop

DETAILS

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AUTHORS

Maureen Mellody, Rapporteur; Board on Environmental Change and Society; Committee on Population; Division of Behavioral and Social Sciences and Education; Board on Life Sciences; Division on Earth and Life Studies; National Research Council

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SUMMARY OF A WORKSHOP

Maureen Mellody, *Rapporteur*

Board on Environmental Change and Society

and

Committee on Population

Division of Behavioral and Social Sciences and Education

Board on Life Sciences

Division on Earth and Life Studies

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Acknowledgment of Reviewers

This workshop summary has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published summary as sound as possible and to ensure that the summary meets institutional standards for objectivity, evidence, and responsiveness to the charge. 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 workshop summary: F. Stuart (Terry) Chapin, III, Emeritus, Institute of Arctic Biology, University of Alaska; Eugenia Kalnay, Department of Atmospheric and Oceanic Science, University of Maryland, College Park; and Hassan Virji, Director, International START Secretariat, Washington, DC.

Although the reviewers listed above have provided many constructive comments and suggestions, they did not see the final draft of the workshop summary before its release. The review of this summary was overseen by Kristie L. Ebi, ClimAdapt, LLC, Los Altos, California. Appointed by the National Research Council, she was responsible for making certain that an independent examination of this summary was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this summary rests entirely with the author(s) and the institution.

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Introduction

The Earth's population, currently 7.2 billion, is expected to rise at a rapid rate over the next 40 years. Current projections state that the Earth will need to support 9.6 billion people by the year 2050, a figure that climbs to nearly 11 billion by 2100 (United Nations, 2012). At the same time, most people envision a future Earth with a greater average standard of living than currently exists—and, as a result, greater consumption of planetary resources. How can this population growth be achieved in a manner that is sustainable from an economic, social, and environmental perspective?

The Presidents' Committee of the National Academies, concerned that the social and natural sciences communities may not be working in concert to address these important questions, sponsored a multidisciplinary workshop to explore how the human population of the world might increase to 10 billion in a sustainable manner while simultaneously increasing the well-being and the standard of living for that population. In sponsoring this project, the presidents hoped that other sponsors would step forward for subsequent, in-depth examination of topics surfaced at this introductory workshop. To develop the workshop, three groups within the National Academies—the Board on Environmental Change and Society, Committee on Population, and Board on Life Sciences—established a planning committee to identify workshop topics and agenda items, speakers, and invited guests. The planning committee's role was limited to planning and convening the workshop. A statement of task,

BOX 1-1
Workshop Statement of Task

An ad hoc committee appointed under the auspices of the Division of Behavioral and Social Sciences and Education (Board on Environmental Change and Society and Committee on Population) working together with the Division on Earth and Life Studies (Board on Life Sciences) will plan and conduct a public workshop that will feature invited presentations and discussions directed at a careful empirical examination of the key issues in the science of sustainability that are related to overall human population size, population growth, aging populations, migration toward cities, and differential consumption, land use change, etc., by different subpopulations, as viewed through the lenses of both social and natural science.

The committee will develop the agenda for the workshop, select and invite speakers and discussants, and moderate the discussions. In defining the agenda, the committee will take into account recent empirical literature on the topics of interest, and explicitly emphasize the research questions that need to be addressed in order to achieve sustainability for a larger human population, incorporating considerations of the carrying capacity of the Earth, and climate change adaptation and mitigation.

A rapporteur-authored summary of the workshop will be produced, and opportunities for public outreach will be explored collaboratively with the Koshland Science Museum. The workshop will also be organized so as to induce participants to prepare scientific papers of a quality appropriate for publication in the *Proceedings of the National Academy of Sciences* Sustainability Science section.

outlining the details and scope of the proposed workshop, is shown in Box 1-1.

The workshop was held at the National Academy of Sciences Building, 2101 Constitution Ave., NW, Washington, DC, September 30 and October 1, 2013.[1] Approximately 40 participants, including speakers, members of the planning committee and parent boards and committees, invited guests, and members of the public, participated in the workshop. Appendix B lists the attendees. The views contained in the report are those of individual workshop participants and do not necessarily represent the views of all workshop participants, the planning committee, or the National Research Council (NRC).

The workshop was designed as a venue to explore issues, not to reach consensus. It was organized into six sessions, focusing on the following concepts:

[1]More information, including archived webcasts of the workshop sessions and prepared slides from the presenters, can be found at http://sites.nationalacademies.org/DBASSE/BECS/CurrentProjects/DBASSE_072678 [March 2014].

- The Human-Earth System
- Challenges to the Earth System: Character and Magnitude of the Challenges in 2050
- Challenges to the Earth System: Consequences for the Earth System
- Extreme Events
- Resource Distribution and Global Inequality
- Interaction Between Earth and Societal Systems

Each section consisted of one to three presentations, followed by general discussion among all workshop participants.

During the course of the workshop, several themes recurred in presentations and discussions; all are issues that cut across the many disciplines and topics of study involved in sustainability science. These themes, which are described in the following section, were identified for this summary by the rapporteur, not by the workshop participants.

Following the section below on rapporteur-identified recurring themes, the remainder of this report summarizes the presentations and discussions for each of the workshop sessions; it was prepared by the workshop rapporteur as a factual summary of what occurred at the workshop. Appendix A shows the workshop agenda, Appendix B lists the workshop participants, and Appendix C defines acronyms used in the report. Appendix D provides short biographical information of each of the workshop presentation authors.

RECURRING THEMES

The following six theme areas were identified from the workshop and are described in more detail below:

1. *Demographic variables that influence sustainability.* A frequently discussed topic at the workshop related to understanding the impact of different demographic variables on future projections of population, climate, well-being, biodiversity, health, and the overall state of the Earth system.
2. *Economic and policy variables that influence sustainability.* Workshop participants explored financial incentives, land use, technology use, and other policies and concepts that have the potential to alter the future Earth system.
3. *Suitable metrics.* Some workshop participants noted the lack of suitable metrics to measure such quantities as overall human well-being, the impact of climate change on the human population, environmental impact, and inequality.

4. *Carrying capacity.* Originally one of the organizing principles of this workshop, some presenters did not consider the concept of carrying capacity a useful framework for evaluating the Earth system and sustainability.
5. *Integrating social and natural sciences.* Also one of the organizing principles of the workshop, several participants pointed out the need to enhance the interaction between the social and natural sciences.
6. *Structuring a research agenda.* The workshop's charge included a request to consider future research needs. Participants suggested ways to move forward with a set of focused research ideas, spanning the relevant disciplines.

DEMOGRAPHIC VARIABLES THAT INFLUENCE SUSTAINABILITY

Much of the workshop focused on identifying demographic variables that influence sustainability, along with attempting to identify the relative importance of each variable. The variables most widely discussed were education, fertility and aging, urbanization, and migration.

Education

The importance of education was discussed by numerous speakers, and education was perhaps the most frequently recurring theme throughout the discussion. Wolfgang Lutz, in his presentation, stated that the Intergovernmental Panel on Climate Change (IPCC) has determined that education is the third most important demographic variable, following age and gender. The workshop's discussion of education focused on identifying statistical relationships between increased education and other metrics that indicate improvement to human well-being; it did not focus on challenges associated with access to education or areas of needed research. Some of the key benefits of education discussed included the following:

- *Overall impact of education on society.* Brian O'Neill stated that increased education results in a substantial improvement to the Human Development Index. Lutz also pointed out that education enhances life in many ways, including enhancing cognitive skills; inclining people toward less risky behavior; extending personal planning horizons; enabling for better learning from past damage; providing better access to relevant information; providing improvements to health and physical well-being; and promoting higher incomes at the individual, household, and national level. Overall, Lutz linked a more educated population with decreases in disaster mortality and increases in the population's adaptive capacity to respond to climate change.

- *Relationship between maternal education and population growth.* Lutz showed a strong relationship between maternal education and slowed population growth, focusing on South Korea as an example. He referred to studies that have provided evidence for causation: A more educated population leads to a lower fertility rate.
- *Relationship between education and intergenerational mobility.* Intergenerational mobility—the likelihood of rising out of poverty, expressed as the probability of escaping the lowest quintile of income—was discussed, along with its relationship to education. Branko Milanović stated that the correlation between parent and child income in the United States is quite high, around 0.5. In European countries, this number is closer to 0.3. Lutz pointed out that by far the most important path to upward social mobility is education in every country in the world. The Nordic countries have high-quality public education and a correspondingly high level of social mobility. In countries where the best education is private, mobility is significantly lower.
- *Time lag between education and its positive effects.* Lutz stated that there is a large time lag—as much as 40 years—before the benefit of the educational effect on fertility can be observed. This indicates that an age-specific education approach may be needed to increase the societal benefits of education.

Fertility and Aging

Data presented by John Bongaarts show a clear bifurcation in population: Fertility rates are high in many developing nations, while, at the same time, fertility rates are becoming low in many developed nations (leading to an aging population). The challenges are therefore different in the two populations:

1. *High fertility.* Parfait Eloundou-Enyegue examined many variables associated with inequality in high-fertility settings, and differential fertility was the greatest contributing factor to income. Lutz discussed in detail that increased education for women and girls leads to significant decreases in fertility rates. Bongaarts stated that fertility rates dropped significantly in nations with a comprehensive, national family planning program that included widespread access and choice, pointing to Mexico and Iran as

models in this area. He also suggested investing in family planning programs and in human capital (i.e., the education of girls) as the primary keys to reducing high fertility rates.

2. *Aging populations.* Bongaarts postulated in his presentation that fertility rates lower than 1.7 or so births per woman result in a demographic imbalance, with an aging population that puts stress on the economy and society; this imbalance is among the biggest challenges facing the United States and Europe in the next two to three decades. He suggested that solutions could include modifying the pension system; encouraging a larger labor force, including working later in life; encouraging increased childbearing; and encouraging increased immigration. Peter Marcotullio and Andrew Jorgenson noted infrastructure and energy consumption are affected by aging populations. Eloundou-Enyegue, in his presentation, examined variables that correlate to income inequality in low-fertility settings. In those settings, family structure (marriage rates and premarital fertility rates) are the largest contributing factors to inequality.

Urbanization

Urbanization was discussed in depth by Marcotullio, who argued that urban areas benefit from an economy of scale in production and consumption: In highly developed nations, urbanization can lower carbon emissions per capita through consolidation. In less developed nations, however, cities provide avenues to consumption absent elsewhere, potentially increasing per capita carbon emissions. Urbanization generally leads to increased emissions overall; as O'Neill and Marcotullio explained, urbanization leads to an increase in labor productivity, additional amenities, increased advancements in technology and innovation, and reduced transportation emissions. However, Stephen Polasky noted that urban land use is a small fraction (<1 percent) of total land use, and changes in urbanization have little to no effect on land use distributions.

Migration

Milanović informed the group that currently about 3 percent of the population migrates, but 8 percent of the population would like to do so; thus, he said, there is a pent-up demand for migration. Within a nation, there is a general migration trend from rural to urban areas. Milanović said that migration is a tool that has the potential to significantly reduce inequality. Bongaarts stated that migration currently has only a small impact in population estimates overall, but there are strong localized effects, such as in South America. Recently there have been examples of rapid migration in Europe and, to a certain extent, in North America, and the populations that immigrate tend not to integrate quickly into their new society.

Many speakers agreed that migration is not well understood or modeled. Marcotullio and Jorgenson noted that identifying a person's location is a difficult task, and that spatial distribution of population is a new demographic area that needs additional work, particularly because it may be important in understanding environmental change.

ECONOMIC AND POLICY VARIABLES THAT INFLUENCE SUSTAINABILITY

While the size of the human population exerts a strong and obvious influence on the Earth system, the workshop also addressed economic and policy variables that can have a strong impact on sustainability. As James Edmonds noted, it is not surprising that in a world with 10 billion people, what will matter is how much they are doing, how they are doing it, and what policies there are for regulating what they do. While a number of ideas were brought up, the workshop participants discussed the following topics most frequently.

Economic Incentives

Several workshop participants discussed a number of economic incentives that might promote behaviors that could lead toward greater sustainability. Some of these included the following:

- *Demographic dividend.* The demographic dividend is a "natural" (but temporary) incentive that occurs as the result of changing demographics in a society. In his presentation, Bongaarts discussed the concept of a demographic dividend, which is a 20- to 30-year financial benefit that results when a high-fertility population shifts its average age through drops in fertility rates and increases in life expectancy, leading to a larger fraction of its population in the working age group. He said that to an economist, the demographic dividend is good, as it results in a decline of poor populations and motivates governments to help decrease fertility rates. The downside is that the effect lasts for only a few decades, and then it shifts to the demographic burden of an aging population.
- *Incentives for ecosystem services.* Polasky suggested adding financial incentives for ecosystem services to increase output of goods

and services without a negative impact on natural capital. He described how ecosystem services related to food production, which see a financial reward, have seen a net increase over time. The remaining ecosystem services do not deliver financial rewards to those people responsible for them, and, as a result, the future of those services is in doubt.

- *Discount rate.* A discount rate is the converse of an interest rate: While an interest rate expresses how something today will be valued in the future, a discount rate expresses how something in the future would be valued in today's terms. The discount rate concept was explored in the workshop discussion as a potential avenue to incentivize responses to climate change. A participant pointed out that the IPCC has a long list of possible climate change interventions, but they are expensive to implement. No action is being taken, in part because there is no way to value making things better for the future. Several participants speculated that a discount rate, even a small one, might make some difference in actions taken today.
- *Understanding return on investment.* Polasky stated that the sustainability consequences of various investment possibilities are known, and he suggested the need to evaluate the return on investment of different scenarios to understand what action leads to a benefit somewhere else. The scenarios proposed would take into account different time frames and the various beneficiaries to develop an incentive structure. Another participant argued that society currently has an overemphasis on individual value systems and individual returns, and interconnections should be considered. Several participants also discussed education as an example of an area that needs additional investigation into the return on investment. William Rouse said that, when discussing the economics of investing in people, the economic valuation depends on who lives with the consequences of not investing.

Food: Costs and Consumption Habits

Several participants discussed the importance of global consumption habits and their influence on environmental sustainability. In general, they noted, as countries move toward increased affluence, they also increase their intake of refined, rather than whole grains, as well as of larger livestock. During a discussion session, Siwa Msangi said that there is still little understanding of the impact of livestock, particularly with respect to livestock intensively fed with grains. He said reducing the need for grain as livestock feed, however, would take pressure off of the production system, but the stresses on animal productivity and animal growth (such as heat, water, stocking density, and food) need to be better understood.

Several workshop participants also considered the issue of rising food prices. Msangi provided projections of the cost increases for maize, rice, and wheat under different assumptions about climate change, income growth, and population growth. It is likely that these rising prices will increase overall levels of inequality, he said.

Land Use

Land use and land use policy were mentioned by several speakers as variables that should be modeled and included in future emissions projections. Edmonds indicated that land use policy is an important variable to consider when modeling the Earth system, but that it is not currently well studied. Land use was only discussed in detail in Polasky's presentation. He divided land use history into five stages: (1) presettlement, (2) frontier, (3) subsistence, (4) intensifying, and (5) intensive. The intensifying stage is marked by huge changes, as ecosystem use transitions to intensive agriculture and urban areas. He stated that establishing financial incentives for preservation or enhancement of ecosystem services to increase output of goods and services without a negative impact on natural capital may be a route to increasing sustainability.

Technological Change

The impact of technology on sustainability can be complex, as noted by several presenters. Rouse stated that, on the one hand, technological advances can help alleviate environmental impact by improving efficiency and ameliorating some of the by-products or effects of consumption. On the other hand, increased technology use can lead to increased energy consumption. Both Polasky and Msangi discussed technological improvements and their influence on productivity increases in crop production and more efficient water usage, although that trend is not likely to continue domestically.

Rouse also explained that the adoption of an innovative technology is a highly selective process, and those who embrace a technology or innovation first will experience it very differently from subsequent adopters. While the adoption of a technology usually leads to an aggregate increase in human well-being, ultimately it usually also leads to increases in inequality, because early adopters tend to receive the greatest benefit. He noted that near-term technology tends to benefit those who least need the improvement.

SUITABLE METRICS

Many participants and speakers questioned how to quantify some of the topics discussed. In some cases, the ideal metric is understood although perhaps difficult to obtain; in other cases, there does not appear to be agreement on the best metric to use to understand a particular phenomenon. B.L. Turner II said metrics are critical to the discussion of sustainability, or it will be impossible to assess different options.

Some metrics that were discussed included the following:

- *Overall human well-being.* A participant pointed out that the community tends to use increasing gross domestic product (GDP) and life expectancy as indicators of "success," but a different set of metrics might be able to capture the intent, rather than just measuring the throughput. One person recommended a "gross national happiness" product. Another participant proposed that it would be important to measure not just current well-being, but also the impact on future well-being. He urged an understanding of how the present may be compromising or improving the future, and GDP and measures of happiness do not account for the future. John Casti used financial markets as a measure of collective beliefs; he acknowledged that this metric was frequently questioned, but that it was an important first step toward measuring group beliefs. Lutz argued in support of a figure of merit that is static across time that could incorporate aggregate indicators of well-being, which would not decline over time or for any subpopulation. The figure of merit, he said, should also include the depletion of natural stock and how that depletion feeds back to the future well-being of humankind. He used metrics such as life expectancy at birth and the Human Development Index, acknowledging that these metrics have limitations but are a good first step. Lutz said that the community needs to identify a broad metric that can assess improvements to intergenerational inequality.
- *Indicators of environmental change, including tipping points and boundaries.* Turner said that it may be important to understand the structure and function of tipping points and planetary boundaries, and to have a tipping point time scale as one kind of metric. Jorgenson indicated that the ecological footprint may not be the appropriate metric when considering environmental change, although it can be a useful tool for discussion.
- *The impact of climate change on humans.* Lutz stressed the importance of understanding how dangerous climate change is to human well-being. Without an analytic answer to that question, he said the world cannot respond appropriately to climate change.

- *Demographic changes.* Lisa Berkman's talk highlighted the importance of examining population distributions, not just a single variable (such as a mean) to represent the distribution. A more sensitive measure would provide information about both the center of the population and the variation out to the extremes.
- *Return on investment.* Several participants noted that it could be useful to better understand how to use return on investment as an incentive for action. However, several workshop participants pointed out that measuring and quantifying return on investment is another challenge for the community.

CARRYING CAPACITY

Based on the statement of task (Box 1-1), the workshop was originally asked to address the concept of carrying capacity as a possible framework within which to consider the burgeoning human population of the Earth. Carrying capacity, a concept originated in animal ecology, refers to the maximum population size of a species that the environment can sustain indefinitely, to which it is able to provide an appropriate supply of food, water, habitat, and other natural resources. However, to some workshop participants, the concept of carrying capacity did not seem to be a useful framework for human populations and sustainability. In other words, although carrying capacity was expected to be a recurring theme of this workshop, it was not. Turner noted that the more built up the environment is, the more difficult it becomes to apply the concept of carrying capacity, which assumes natural limitations (such as disease or starvation through drought) on animal species that are not technologically countered by that species. Because the human species manipulates and converts its habitat and can counter the natural limits on its population (such as by vaccinating for disease or providing emergency food to drought-struck areas), the conceptual basis of carrying capacity breaks down when considering people. Turner stated that carrying capacity should be only a heuristic device, and he cautioned against calculating specific values for the human-environment system. He stated that carrying capacity has been "largely abandoned" in the social and policy sciences.

INTEGRATING SOCIAL AND NATURAL SCIENCES

In the discussion, several participants explored the motivation for the workshop, given that one of the stated workshop goals was to enhance the interaction of the social and natural sciences. Turner said that such integration is taking place, but he emphasized the need to think of the whole Earth as a system of systems. In that context, he said, social and natural scientists need to understand that the regimes of the Earth system are changing in a fundamental way and those regime shifts have interrelated consequences. He also postulated that there is room for additional interactions among the sciences, and he singled out urbanization as one area in which this would be particularly useful. Rouse stated that no one person could leave the workshop and address the questions posed; rather, it would require a group, consensus-driven effort.

Berkman said that it was her perception that researchers in environmental issues remain mostly separated from population scientists. In addition, she said there is a need for highly skilled demographers to work on issues related to climate science. She pointed to an overall need for more nuanced thinking, rather than a black-and-white interpretation that population is ruining the world or that the world is ruining population; population and the environment are too closely intertwined to make such a distinction, she said.

STRUCTURING A RESEARCH AGENDA

The workshop discussion sessions focused in part on identifying elements of a research agenda for sustainability science moving forward. Specific research topics are addressed in the themes above. However, additional comments were made about the structure and focus of a research agenda; these were pragmatic ideas that spanned the range of topics and disciplines. Some of the salient suggestions offered by individual participants included the following:

- Catalogue the current state of knowledge, so that gaps in understanding can be addressed. Research would then target these gaps.
- Understand potential future impacts, using detailed, evidence-based scenarios to understand the possible outcome from each set of actions. This would help identify what can be put into place now for easier adoption later.
- In addition to looking at the most plausible scenarios, investigate possible, though unexpected, shocks that would disrupt these scenarios, including how to eliminate or mitigate these possible shocks.
- Consider how to implement small changes within the poorest nations, such as improvements to education and family planning programs, which would make the most impact.
- Consider a long-term framework (out to 2050), but focus on the next 5 years, because it is easier to attract attention to short-term needs, and thereby start reversing dangerous trends. An example suggested by one participant might be to help address China's

short-term pollution problems within a larger emissions framework. Identify multiple possible research agendas; from them, develop a broad agenda but select certain elements for deeper focus.

- Try to understand how and when a particular scenario might shift from possible to inevitable. For instance, one participant asked, how much of the reality of 2050 will be "locked in" by 2030?
- Try to understand the determinants of risk, looking across different socioeconomic and demographic variables and spatial distributions.
- Consider not just the science, but also the policy, including ideas for implementation.

2

The Human-Earth System

The opening session of the workshop was chaired by William Rouse (Stevens Institute of Technology and the chair of the workshop steering committee). B.L. Turner II (Arizona State University and steering committee member) and Rouse gave presentations during this session, followed by discussion with the participants.

UNDERSTANDING POPULATION IN HUMAN-ENVIRONMENT RELATIONSHIPS: SCIENCE SHAPED BY WORLD VIEWS OR EVIDENCE?

B.L. Turner II
Gilbert F. White Professor of Environment and Society,
School of Geographical Sciences and Urban Planning,
Arizona State University

B.L. Turner II began his presentation by explaining that he would address the history of how population and carrying capacity have been applied to impacts on the Earth system and human well-being. He pointed out that there is little debate over the data and empirical evidence, especially in regard to population and environmental change; the debate revolves around the interpretation of those data. Interpretations, he said, say as much, if not more, about the world views of the interpreter as they do about the data and analytics.

Turner described three foundational models of the human-environment relationship during the course of his presentation—Malthus, Boserup, and Geertz—as well as two contemporary viewpoints—Cassandra and Cornucopia—linked to them. (See Box 2-1 for a description of each model and viewpoint.) He began with the model of Malthus. Thomas Malthus (1798) attempted to explicate the repercussions of the population growth of cities resulting from a huge influx of rural peasants in the late 18th century in the United Kingdom and focused on how this rapid urban growth could lead to negative outcomes (crises) for society at large. He said that there would be discrepancies between the growth rates of the population and of food supply sufficiently large to lead to a crisis, thereby inferring that technology is outside the demand-production system. While a Malthusian crisis is hypothetically possible, Turner stated that it is difficult to find in the historical evidence a "true" Malthusian

BOX 2-1
Models and Viewpoints of Human-Environment Interactions

Malthus Model. Thomas Malthus postulated that population growth, when unchecked, will surpass the food ceiling and generate a negative impact on the human-environment relationship, i.e., demand leads to crisis (Malthus, 1798).

Boserup Model. Ester Boserup stated that population increase, and the pressures that result from it, will increase the food ceiling; i.e., demand stimulates growth (Boserup, 1965).

Geertz Model. Clifford Geertz postulated the theory of agricultural involution in which a unit of labor (input) yielded a unit of production, a case of stagnation in which the population is fed but surpluses are absent (Geertz, 1963).

Cassandra (also referred to as neo-Malthusian). The Cassandra viewpoint is concerned about stresses from human demands placed on environment and resources over the long run. The Cassandra model accounts for all factors generating demand, not just population; it includes such drivers as affluence and entitlements (Dasgupta and Ehrlich, 2013; Ehrlich and Holdren, 1988). Most global indicators signal major declines in the states and function of the Earth system.

Cornucopia (also referred to as Technology Fix or Pollyanna). The Cornucopian viewpoint states that increases in population (demand) lead to technological innovation and substitution. This in turn leads to an increase in access to and decline in relative price of materials (Simon, 1988). Almost all indicators of human well-being have increased, but there is some recognition of the negative consequences on the environment.

BOX 2-2
What Is Carrying Capacity?

In ecology, carrying capacity is the maximum number of individuals of a species that the environment can sustain indefinitely, given the food, habitat, water, and other necessities available. In population biology, carrying capacity is defined as the environment's maximal load.

Carrying capacity in regard to human beings refers to the maximum population size that the use of environment can sustain indefinitely while providing an appropriate supply of food, water, habitat, and other natural resources; it also encompasses many additional factors, such as governance, technology, and knowledge systems.

SOURCE: Adapted from presentation by B.L. Turner II.

crisis. Constraints on food production may be one potential factor that could escalate a crisis (i.e., famine), but access to food (i.e., entitlements) proves to be more robust in explaining famine and other crises. Turner noted that W.A. Dando (1980) put forward the idea that humans induced food shortages in the food supply system because of variables unrelated to production level. Dando's work was, however, eclipsed by the development of entitlement theory (famine linked to entitlements) by Sen (1982), who received the Nobel Prize in economics for this work.

Turner then discussed carrying capacity (defined in Box 2-2), noting that its antecedents are found in the works of Malthus but modern development and use of the term emerges largely from the ecology of nonhuman biota. He pointed out that the more the environment is manipulated or constructed by people, the more difficult it becomes to apply the concept of carrying capacity because technology and management are important determinants of sustainable production. It is possible that carrying capacity might be applicable at the global level; hypothetically, the Earth system could be treated as a "closed" human-environment system with the single exogenous input of incoming solar radiation. In this view, human appropriation of the world's net primary productivity (HANPP),[1] which has been estimated to have been between 23-45 percent around the year 2000, serves as a limiting factor (Haberl et al., 2007). Turner stated that beyond such hypotheticals, carrying capacity is useful only as a heu-

[1]Human Appropriation of Net Primary Productivity (HANPP) is an indicator of the amount and intensity of land use by humans. It is measured as a percentage of total potential vegetation, which in turn is a measure of the incoming solar radiation.

ristic device, and he cautioned against calculating specific measures for it with regard to human-environment systems. He told the workshop that carrying capacity has been largely abandoned as a concept in social and policy sciences.

Turner then turned to the Boserup model, which was initially developed to explain subsistence farmers' responses to land pressures occasioned by population increases, but it was ultimately expanded to agricultural systems in general. Ester Boserup (1965) explained that the level of agricultural intensification (food production) was not set by some technological maximum but by the level of land pressure confronting farmers. As these land pressures increase, so does intensification, which raises the food ceiling. This process can take place because changes to techno-managerial inputs are considered as coming from within the system, rather than from outside (as in the Malthusian view). This model has been empirically demonstrated in many studies (e.g., Pingali et al., 1987), including production systems that are transitioning from subsistence to commercial farming.

Turner then briefly explained that the Geertz model (Geertz, 1963) is essentially a state of equilibrium; the change in output is equal to the change in input. This is also known as agricultural involution.

Are Malthus and Boserup, and by comparison, the Cassandra and Cornucopian viewpoints that draw on them, irreconcilable? Turner explained that the Boserup model, often considered to be an "anti-Malthusian" thesis, was intended to expand upon themes raised by Malthus while searching for an understanding in which economic growth rather than crises might follow from increases in population. He noted that demographer and economist Ronald D. Lee has demonstrated that Malthus and Boserup could, to a certain extent, be reconciled (Lee, 1986). Using phase-space models, Lee concluded that in Boserup's model, space is the limiting condition, while Malthusian forces tend to view the system as the limiting condition. Turner and Ali (1996), in turn, have traced how increasing population and other demand factors push population-environment relationships into Boserup-, Geertz-, and Malthus-like conditions, in which the Boserup conditions tend to prevail in most systematic examinations. Understanding agricultural change sufficiently to predict outcomes, however, has proven difficult because human-environment systems operate as complex adaptive systems.

Turner then turned to a comparison of the Cassandra and Cornucopian viewpoints of population and environment as world views linked to Malthus and Boserup. He pointed out that the history of the human species is marked by both increasing the material well-being of humankind and increasing changes and degradation of the environment. The Cassandra view focuses on the consequences for the environment, whereas the

Cornucopian view focuses on human well-being. These foci, and drawing on either Malthus- or Boserup-like arguments, lead to different interpretations of the base relationship in question.

The Cassandra viewpoint (Ehrlich and Holdren, 1988) begins with the notion that the environment is ultimately unable to sustain services provision to humans under conditions of long-term degradation. It is guided by the IPAT equation (identity):

$$I = P \cdot A \cdot T$$

in which I = human impact on the environment, P = population, A = affluence, and T = technology. Turner argued that over the long term and at the global scale, resource use and environmental change correlate with the PAT variables more than any others; he said that few people question the use of IPAT as an identity. It is often used to infer causation, however, and this use is hotly debated and criticized as being too superficial, diverting attention from deeper causes of the observed correlations. And, at meso- to micro-spatiotemporal scales, Turner observed, PAT variables commonly do not track well with environmental change.

Turner then explained the Cornucopian view, which holds that increasing population leads to innovation and techno-managerial change, reflected in resource substitution (for example, fiber optics for copper wiring). As a result, over time the access to and production of raw materials increases in efficiency, lowering prices to the benefit of society. Because it is focused on resources and substitutes for them, the Cornucopian view de-emphasizes damages to the environment and emphasizes innovative ways to deal with damages.

Turner went on to discuss "the bet" made in 1980 between Paul Ehrlich and Julian L. Simon (the champions, in the public view, of the Cassandra and Cornucopian viewpoints, respectively) and the subject of the book *The Bet* (Sabin, 2013), to illustrate divergences in the two views of population and environment. Simon publicly bet that Ehrlich could pick any five minerals and that 10 years later, after considerable population growth worldwide, they would all be cheaper in constant dollars (Cornucopian view) as opposed to more expensive (Cassandra view). Simon won the bet, although subsequent economic analysis showed that had the period of assessment been other than the particular decade 1980 to 1990, Ehrlich would have won the majority of the time. In fact, Turner argued that the bet was a stunt, because market force complexities involve much more than simple demand emanating from population numbers. Simon wagered that over the following 10 years, all indicators of human well-being would increase. Ehrlich, together with eminent climatologist Steve Schneider, countered that all indicators of the state of the environment would decrease (Sabin, 2013). Turner reasoned that this dichotomy in the new proposed wagers not only illuminated distinctions in the two world views, but also it marked the reshaping of the Cassandra viewpoint to focus less on resource economics and more on the condition of the environment and Earth systems' capacity to function as the sustainable biosphere that life (including human life) requires.

Turner pointed out that the two world views still persist in population-environment and resource assessments discussions. Cassandra followers treat population as one important factor among others that generate demand on nature; this viewpoint is increasingly observable in such global issues as climate change, loss in biodiversity, and possible planetary boundaries. On the other hand, Cornucopian-like assertions often underpin the positions of, for example, climate change naysayers or advocates of technological capacity to confront climate change through geoengineering. These positions in public debate have become politicized, as documented in *The Bet* (Sabin, 2013).

Turner ended by saying that emphasis in analysis and discussion on the role given to human population size, food supply, or any other environmental resource or service depends on the world view of the interpreter as much as it does on the actual evidence. Population is embedded within a complex system of factors that includes environmental change, food production, and sustainability. He stated that the world revisits these questions on decade-plus time scales; the questions are never resolved, but each time, new information is added.

EARTH AS A SYSTEM

William Rouse
Alexander Crombie Humphreys Chair in Economics of Engineering, School of Systems and Enterprises, Stevens Institute of Technology

William Rouse began by explaining that he approaches the sustainability question from an engineering perspective, and he seeks to understand the effect of population on the Earth using systems engineering principles. He said his workshop presentation goals were to better understand the impact of the human population on the Earth and how population interacts with other attributes of the Earth, and he posed four questions to participants:

1. How does the Earth respond to population changes? What do we, as researchers, know and still need to learn about its response?
2. What can we, as a general population, do to influence the future of the Earth?

3. What information can be leveraged from the physical, social, and behavioral sciences communities?
4. What should be the research agenda for activities that would have an impact and enhance our ability to understand and act?

Rouse stated that the Earth is a single self-regulating system that exhibits multiscale temporal and spatial variation.[2] He pointed out that human activities are influencing the Earth's environment in a manner equivalent to the greatest forces of nature. He stated that there are cascading effects throughout the system, and system dynamics are characterized by critical thresholds and abrupt changes. Human activity on Earth may be shifting the Earth system to alternative modes of operation; this shift may be irreversible and may result in a planet less hospitable to humans. The Earth has moved well outside the realm of natural variability when considering environmental factors. Rouse stated that the Earth can even now support more than 10 billion people, but the quality of the lives of those people is a concern. He cited Glaeser (2011), who described how 10 billion people would fit within the state of Texas if the entire state were covered in townhomes. However, Rouse asked what the quality of life would be, and what impact those people would have on Earth.

Rouse explained that the Earth can be considered as a collection of different systems on different scales. (See Figure 2-1 for a schematic.) Loosely speaking, four systems are interconnected: environment, population, industry, and government. In this notional model, population consumes resources from the environment and creates by-products. Industry does the same, but it also produces employment. The government collects taxes and produces rules; the use of the environment is influenced by those rules. Each system component has a different associated time constant. In the case of the environment, the time constant is decades to centuries. The population's time constant can be as short as a few days. Government's time constant may be a bit longer, thinking in terms of years. Industry is longer still, on the order of decades. These systems can be represented at different levels of abstraction and/or aggregation, he said, although a hierarchical representation does not capture the fact that this is a highly distributed system, all interconnected. It is difficult to solve any one part of the problem, because it affects other pieces. Rouse pointed out that by-products are related to population size, so one way to reduce by-products is to moderate population growth. Technology may help to ameliorate some of the by-products and their effects, but it is also possible

[2] See http://www.colorado.edu/AmStudies/lewis/ecology/gaiadeclar.pdf for more information [April 2014].

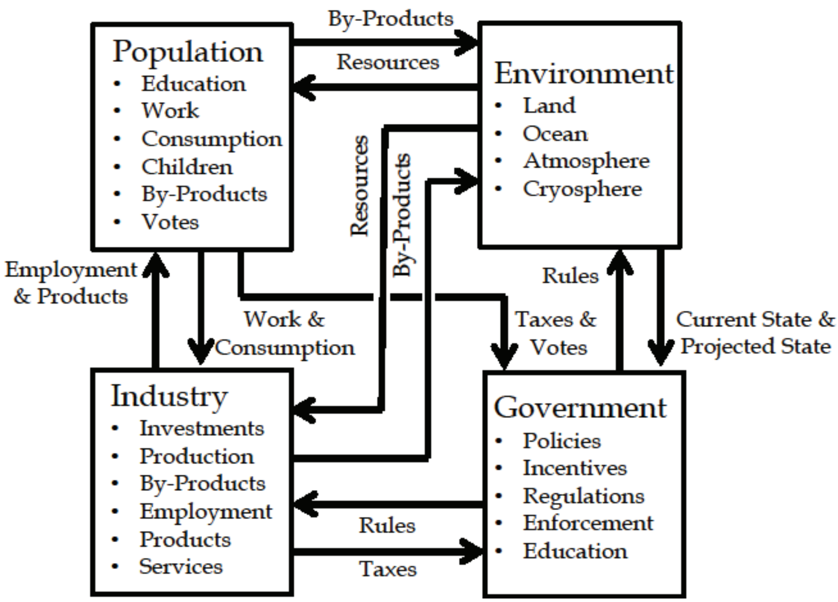

FIGURE 2-1 A schematic diagram of the Earth as a system, looking at four primary system components (population, environment, industry, and government).
SOURCE: Rouse presentation, slide 12.

that technology could exacerbate the effects. Clean technologies lower by-product rates but tend to increase overall use, for instance.

Rouse then defined a "system of systems" as a collection of purposeful systems, each one of which is designed to do something different from the overall intent of the collection. The end result of a system of systems is a new, more complex system whose performance can be greater than the sum of the individual constituents. Each constituent system in the collection has its own agenda. In the Earth system, population and government are the sentient parts of the system. The environment, Rouse pointed out, is nonsentient—one cannot influence the environment through persuasion. How, therefore, can the alignment of goals among constituent systems be motivated? Rouse stated that it is important to identify information and incentives so that short-term benefits from lower-level system activities improve the long term and support long-term system goals.

He then pointed out that support for decisions will depend upon the credibility of the predictions of behavior, at all levels in the system. He stressed the importance of shared "space value" and "time value" discount rates: Consequences that are closest in space and time matter the most, and attributes more distributed in time and space are discounted accordingly. He also pointed out that people will also try to "game" the system. The way to deal with that tendency is to make the system transparent enough to understand the game being played. Sometimes, he said, gaming the system is actually innovation.

Rouse identified three elements that he said are necessary to move forward:

1. Information sharing: Broadly sharing credible information helps all stakeholders understand the situation.
2. Incentive creation: Development of long-term incentives will enable long-term environmental benefits while maintaining short-term improvements.
3. An experiential approach: An interactive visualization of models will enable people to see the results. (Rouse referred to this as a "policy flight simulator.")

He noted people have difficulty buying into a model until they can take the controls, try options, and see the results (Rouse, 2014).

DISCUSSION

A participant asked about Rouse's proposed "policy flight simulator," asking whether an inventory of models could be shared. Rouse responded that there is an effort to compile such an inventory. Problems arise when the models cannot be audited to see how they work. Those models that are explicitly defined and published in the formal literature are well suited to be part of an inventory, but others cannot be inspected properly and they may not be suitable for inclusion. It is also difficult to develop compatible data representations.

The discussion then turned to tensions between the Cassandra and Cornucopian models. Rouse pointed out that the argument is less about the merits of the two approaches and more about the consequences of agreeing or finding middle ground. Turner agreed that the literature shows far less about the reconciliation of the two positions than their differences. He said that older researchers often developed an initial position in the discussion and now feel compelled to defend their decisions. Younger researchers, on the other hand, have more incentive to explore reconciliation. Turner postulated that Cassandra and Cornucopian supporters would not disagree on the factual basis of operation, as they have the same (reliable) population and growth numbers. The difference is that one group classifies them as a problem, the other as an opportunity.

In a discussion of the IPAT model, a participant pointed to increasing analytical work that shows statistically significant relationships between environmental and societal factors. However, in the participant's view, this work may not resonate with social scientists who are more interested in the causes of increases in population, affluence, and technology development. Further, the IPAT model assumes that the population is homogeneous, when in fact consumption and vulnerability vary widely within a population. The participant commented that the picture becomes much richer when considering heterogeneity. For example, populations with greater levels of education are less vulnerable to environmental changes.

Several participants discussed social justice. The conversation began with a discussion of technology adoption. Rouse explained that the adoption of an innovative technology is a highly selective process, and those who embrace a technology or innovation first will experience it very differently from subsequent adopters. He posited that early adopters tend to receive the greatest benefit. While this leads to an aggregate increase in human well-being, ultimately it will also lead to increases in inequality. He suggested that the nature of innovation and its adoption be reconciled, using electricity as an example: Its technology adoption took many decades in the United States and required a huge change in infrastructure to have an impact on the population as a whole. He suggested electricity as an example in which near-term technology benefits those who least need the improvement. Turner then linked this to social justice. He proposed developing a charter vision about social justice and whether it is needed to move forward. Rouse pointed out the possibility that improvements to social justice could have negative environmental consequences.

The discussion also focused on the topic of metrics. A participant said that the world community tends to use gross domestic product (GDP) and life expectancy as indicators of success. A different set of metrics may be able to capture the intent, rather than just measuring the throughput. One person recommended a "gross national happiness" product. Turner pointed out that metrics are critical to the discussion to assess different options, but said he was not certain if a "right" metric exists. Another participant said that it would be important to measure not just current well-being, but also the impact on future well-being to understand how the present may be compromising or improving the future. Turner postulated that it may be important to understand the structure and function of tipping points and planetary boundaries and to have a measure of a tipping point time scale. Robert Hauser (National Research Council) informed the group that a National Research Council committee released a report on measuring well-being, with potentially useful information on metrics (National Research Council, 2013).

3

Challenges to the Earth System: Character and Magnitude of the Challenges in 2050

The second session of the workshop was chaired by steering committee member W.G. Ernst (Stanford University). It included presentations by John Bongaarts (The Population Council), Andrew Jorgensen (University of Utah), and Peter Marcotullio (Hunter College). Their presentations are summarized here, followed by the discussion that ensued.

DEMOGRAPHIC TRENDS AND THEIR CONSEQUENCES

John Bongaarts
Vice President and Distinguished Scholar, Population Council

John Bongaarts noted the extraordinary demographic changes in recent history. The most obvious is the rise in population numbers (an increase of 5 billion since 1950), but he identified other important trends. There has been a revolution in the area of reproduction and fertility; the global fertility rate has been cut in half since 1950. People are also living longer and healthier lives; life expectancy is rising rapidly in almost all countries. Migration flows are expanding as well, as people move away from rural areas and venture across country borders in search of a better life. Also, populations in general are aging. Bongaarts focused on population trends in his presentation.

According to Bongaarts, world population was 1.6 billion in 1900, 2.5 billion in 1950, and has exploded (primarily due to a decline in the

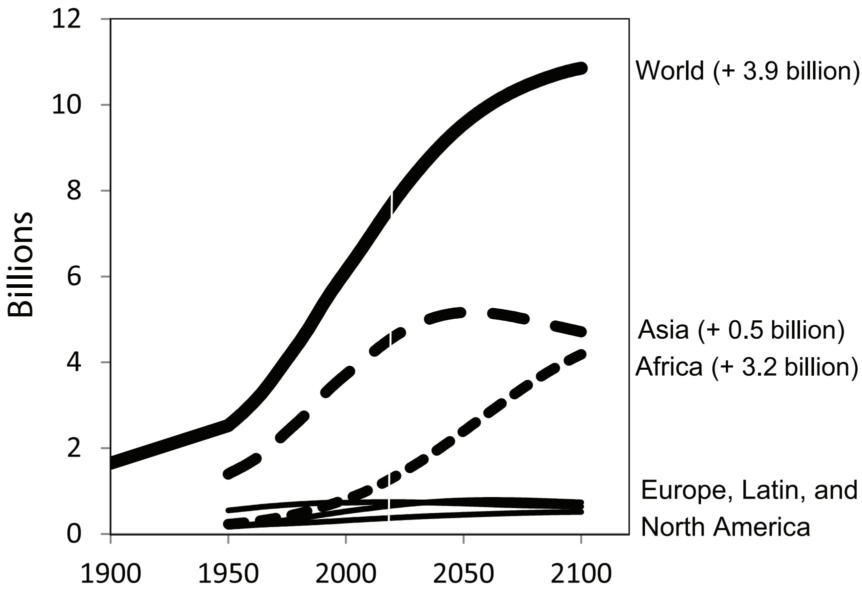

FIGURE 3-1 Population estimates and projections from 1900 to 2100.
SOURCE: Bongaarts presentation, slide 3.

death rate) to 7.2 billion today. Current projections show that population is expected to reach just below 11 billion around 2100. (See Figure 3-1 for a plot of population by continent.)

Asia, which has tripled in population size since 1950, dominates this growth, but Africa is currently the most rapidly growing region and will be the largest contributor to population growth in this century. Europe's population is expected to decline overall, with declining European nations outpacing growing ones. Bongaarts pointed out that the United Nations produces high-, medium-, and low-variant projections by changing the assumptions about future fertility rates. The population estimates may change in the different projections, but the overall percentages by region remain more or less the same. Figure 3-1 represents the medium values from the United Nations, and there is an uncertainty of 2 to 3 billion people associated with those total numbers.

Looking at the populations of each country, Bongaarts pointed to high growth in Africa and parts of the Middle East. In contrast, in North American and European countries, population growth is slow or declining. The main driver is variation in fertility. Over time, nations tend to move from high fertility and high growth to low fertility and low growth.

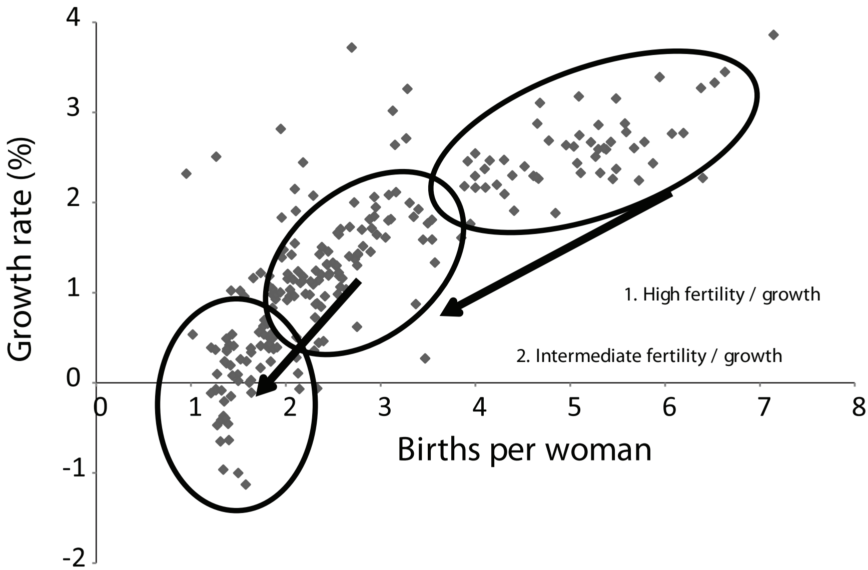

FIGURE 3-2 Scatter plot of nations' growth rate as a function of fertility rate. SOURCE: Bongaarts presentation, slide 3.

Bongaarts showed a scatter plot of growth and fertility levels (see Figure 3-2) and divided nations into one of three groups:

- Group 1: Characterized by rapid population growth and a young age structure. In sub-Saharan Africa, almost 70 percent of the population is under age 25. (In the developed world, by contrast, 30 percent of the population is under age 25.) Group 1 nations tend to experience depletion of natural resources; increased pollution; high unemployment; high maternal and infant mortality; lagging government investments in education, health services, and infrastructure; and rising political unrest and crime due in part to the unemployment of young people.
- Group 2: Characterized by lower fertility rates, lower population growth rates, and fewer young people. They are reaping a temporary "demographic dividend"—an economic boost from a rising proportion of workers. Bongaarts explained Group 2 nations tend to experience increased consumption, leading to increased pollution; rapid economic growth; declining maternal and infant health problems; government investment in education, health, and infrastructure; and rising inequality among their populations.

- Group 3: Characterized by low fertility rates, near-zero population growth, and a rapidly aging population. Bongaarts said Group 3 nations tend to experience high greenhouse gas emissions, the result of high levels of consumption; slower economic growth; slower gross domestic product (GDP) growth; lower growth in worker productivity; unsustainable pension costs; rising deficits; and rising voting power of the elderly.

These groups show distinctly different problems with different solutions; for example, Group 1 has problems due to high fertility, while in Group 3, problems are associated with aging. In high-fertility nations, Bongaarts indicated that the need is to invest in family planning programs and in human capital (particularly the education of girls). In aging nations, Bongaarts said the solution likely resides in a combination of modifying the pension system; encouraging a larger labor force, including working later in life; encouraging childbearing; and encouraging immigration.

DEMOGRAPHIC AND ECONOMIC DRIVERS OF CONSUMPTION AND ENVIRONMENTAL CHANGE

Andrew Jorgenson, Professor and Director of Graduate Studies, Sociology Department, University of Utah (presenter), and
Juliet Schor, Professor, Sociology Department, Boston College (co-author)

Andrew Jorgenson began by asking two questions: (1) What are the planetary boundaries and thresholds that would, if crossed, lead to unacceptable environmental change, and (2) What are the human drivers of consumption and environmental change that are pushing the population to and over the planetary boundaries? He said he would focus primarily on population and affluence.

Jorgenson defined drivers as the demographic, economic, and other social factors that put direct and indirect pressures on the environment. Drivers can be nested and aggregated. Jorgenson then looked at resource consumption and environmental change. To measure resource consumption, one can focus on direct consumption measures (such as food or other natural resources) or use a measure of consumption-based environmental demand (such as ecological footprint). Jorgenson said he likes the ecological footprint measure because it is measured in area units, not economic terms. Three possible metrics, each of which reveal something different, can measure carbon emissions: total carbon emissions, emissions per capita, and emissions per GDP. Depending on the stakeholder, the focus is on one measure over another. Jorgenson pointed out that scale-level outcomes are likely the most critical to issues of sustainability. He showed time series figures to assess emissions in different points in time.[1] In the early 1960s, the majority of nations had a per capita ecological footprint below the globally sustainable threshold. By 2003, more than half of them were above the sustainability threshold, although the distribution had broadened. In other words, in 2003, some nations were still underconsuming, despite the overall increased trend toward overconsumption.

Jorgenson then discussed affluence, noting that the traditional IPAT literature does not cover much discussion of heterogeneity in the effects of affluence or population size. He showed elasticity coefficients that result from statistical modeling of carbon dioxide emissions from the burning of fossil fuels, looking at the population effects on emissions. He used a two-way fixed effect model, which can be useful for hypothesis testing. In Asia, the elasticity coefficient[2] is decreasing over time, dropping from 1.49 to 1.28 between 1960 and 2005. In Africa, the elasticity coefficient has also decreased long term, moving from 1.0 to 0.81. In the high-income countries, the elasticity coefficient is stable and large (around 2). As a result, any population growth in these countries could have a large effect on emissions. Jorgenson pointed out that the results are roughly equivalent when considering the ecological footprint instead of carbon emissions; the correlation factor between the two is around 0.9, but with both regional and temporal variation. He also considered the effect of GDP per capita on emissions by splitting countries into two categories (22 countries were considered developed, 64 less developed). He found very strong temporal stability in the elasticity coefficient for the less developed countries, but a slight decoupling between GDP and emissions for the developed countries beginning in around 1985. He speculated that this could be the result of technology improvements, as well as the influence of expanded global production and trade networks. However, he posited that it is difficult to measure and determine how such mechanisms might shape the relationship between emissions and affluence.

Jorgenson suggested that it would be helpful to have sustainability research that examines how to reduce the ecological or carbon intensity of human well-being in an integrated way. Ecological intensity of well-being is the level of environmental stress (for example, ecological footprint per capita) per unit of human well-being (for example, average life expectancy). The carbon intensity of well-being is the level of anthropogenic

[1]For Jorgenson's presentation, see http://sites.nationalacademies.org/DBASSE/BECS/CurrentProjects/DBASSE_072678 [March 2014].

[2]The elasticity coefficient is the estimated percentage change in the dependent variable associated with a 1 percent increase in the independent variable, controlling for all other factors in the model. In this case, the independent variable is population and the dependent variable is carbon emissions.

carbon emissions per unit of human well-being. These two measures may be useful to provide a more integrative approach to the study of sustainability. Jorgenson showed data from a small sample of 14 high-income and 31 developing nations. Developed nations showed a sharp increase in the estimated effect of GDP on ecological intensity of well-being between the 1960s and 1980s, with the elasticity coefficient crossing from negative to positive around 1970. (He pointed out that, from a sustainability perspective, a negative elasticity coefficient when measuring the effect of GDP on the ecological intensity of well-being is desired.) The lower-income nations also saw an increase in the estimated effect of GDP on ecological intensity of well-being from the 1960s to the 1980s, but the overall value still remained near or slightly below zero. He stressed examining regional effects, but said the overall increasing trend between GDP and ecological intensity of well-being was a troubling one.

Jorgenson recognized the growing environmental concern among individuals in nations throughout the world and asked how to convert that concern into behaviors and actions, both individual and collective, to help address broader sustainability issues. He said that integrative approaches to sustainability studies are part of a critical path forward.

URBANIZATION IN THE 21ST CENTURY: CHALLENGES AND OPPORTUNITIES FOR ENVIRONMENTAL SUSTAINABILITY

Peter Marcotullio, Associate Professor, Department of Geography, Hunter College of the City University of New York (presenter), and
Karen C. Seto, Professor of Geography and Urbanization, Yale School of Forestry and Environmental Studies, Yale University (co-author)

Peter Marcotullio began his presentation by making five statements: (1) Urbanization is a "mega-trend" for the 21st century; (2) there are challenges associated with environmental sustainability and urbanization; (3) there are many opportunities to gain efficiencies; (4) despite these opportunities, the scale of the issues is overwhelming; and (5) humans have the potential to create biophilic, resilient, livable cities in the future.

Marcotullio noted global urban population is increasing and will continue to do so throughout the coming century. By 2050, rural populations will be stable or decreasing around the world. He pointed out that there are many estimates of current urban land use. One estimate finds that in 2000, 73 million hectares of land was urban; by 2030, those numbers may more than triple, to an estimated 225 million hectares (Seto et al., 2012). The change, both in land use and population, has a direct impact on the environment, including lost habitat, lost agricultural land, and alteration of natural resources. It also has an impact on consumption of resources (wood, iron, etc.) to build cities. Indirect impacts from this growth are related to increased consumption and associated waste and emissions. Marcotullio said analysts often conflate increased consumption with urbanization itself, but he suggested considering these two issues separately. Energy consumption, he noted, varies as urbanization patterns evolve. Studies suggest a period of high growth and associated high-energy consumption early in the development process, followed by a period of slowing growth and associated decrease in energy use growth. He reported this pattern happened early in the United States and Japan. China is still in the initial growth period, although the trend in China may be tempered slightly; China's energy intensity is already dropping, whereas during the same level of economic development in the United States, energy use was still increasing.

For the years 2005–2050, Marcotullio predicted enormous increases in consumption of certain materials (particularly metals), with a direct impact on populations as nations look outside their own borders to obtain needed materials. He projected rapid urbanization without the accompanying necessary basic infrastructure development (i.e., water and sanitation) in some parts of the rapidly developing world, noting 20 percent of the global urban population does not currently have access to an adequate water supply. The developed world will likely experience growing infrastructure deficits as older systems deteriorate. For example, the American Society of Civil Engineers released a report card about America's infrastructure in 2013 (American Society of Civil Engineers, 2013) that examined such infrastructure categories as water, sanitation, dams, bridges, roads, and schools. The overall assessment was very negative with a "D+" grade.

Marcotullio stressed a number of opportunities along with the challenges. These opportunities include the following:

- "Agglomeration economies" in production and consumption.
- Lower energy emissions per capita through consolidation. Marcotullio explained that this has been true in the United States, but not necessarily yet true around the world. In some cases, cities provide additional access to energy systems, which enhance consumption as compared to rural areas, which overwhelms the efficiency effects of density (Marcotullio et al., 2013).
- Scale economies in production and consumption.
- Increases in labor productivity.
- Consumption amenities.

- Increase in technology and innovation. Marcotullio showed that there is a disproportional increase in patents and other measures of innovation with increasing city size;
- Reduced transportation emissions. Increased residential density lowers transportation emissions anywhere from 5 to 25 percent, and the benefit tends to increase over time. Marcotullio stated, for example, that bicycle sharing can be a successful model; in New York, for example, 100,000 customers signed up in the first 10 days of the program.

Marcotullio cautioned that, at the same time, efficiency gains may be overshadowed by the scale of urban expansion, as seen in the "rebound effect" in the United States after the 1970s oil shortages. During the late 1970s and early 1980s, transportation figures demonstrated that motor vehicle drivers dramatically reduced fuel consumption through higher efficiency cars and reduced driving. However, these gains were lost over time, and by around the turn of the century, motor vehicle fuel consumption per capita had reached new highs. Any gains from greater fuel economy were lost as more people drove more miles. More directly, Güneralp and Seto (2012) pointed out that in the Pearl River Delta, China, efficiencies gained in energy consumption from dense settlement are overwhelmed by the absolute scale of urbanization. Marcotullio ended on a note of both optimism and urgency, pointing to the opportunity to make cities more environmentally benign (i.e., biophilic, resilient, low carbon, and livable) because 65 percent of the global urban environments (defined by urban land cover) predicted to be developed by 2030 have yet to be built.

DISCUSSION

The discussion session opened with the topic of population targets. A participant pointed out that demography is not destiny, and there is an uncertainty range associated with the various demographic projections. Another asked if there is a desired, or target, world population for 2050, and if there is an optimal level of fertility to help counteract the effect of aging populations. Bongaarts responded that he would be very concerned to see very low fertility rates (1.5 or below). He suggested that something near 1.8 is optimal for societal stability, but government intervention may be necessary to attain such a value. Bongaarts stressed that aging societies remain a huge demographic problem. While working later and postponing retirement is part of the solution, he said these actions alone cannot resolve the large imbalances in social security and health that would occur with an aging population. He said aging populations are among the biggest policy and economic challenges facing the United States and Europe in the next two to three decades. Marcotullio discussed the dividend-burden movement; infrastructure is often built when population growth is taking place, and builders do not think about the future needs of an aging population. For instance, Tokyo is built with many stair steps needed to cross a street, something the elderly can have difficulty using. Jorgenson also stated an increased-age population structure has an impact on energy consumption.

Another participant asked about the differences across nations in birth rate reduction, such as the drastic decline in Mexico. Bongaarts said two things are needed to reduce birth rates: an educated population and access to contraception. Iran, for example, made a large investment in schooling, but the fertility rate remained around 6 births per woman. In 1989, the Iranian government examined projections of infrastructure requirements needed to support its burgeoning population and realized that a crisis was looming. The Iranian government instituted a family planning program that provided many options and was accessible to rural populations. Fertility rates in Iran dropped from 6 to 2 within a decade. Bongaarts said Mexico similarly developed a strong national program in health and family planning. He pointed out that the strength of the economy does not influence fertility rates in a significant way. Nigeria, for example, has a healthy economy but still maintains very high fertility rates. A participant asked about the different impacts of the role of women in the workforce. Bongaarts replied that the child-bearing and child-rearing years can take up the entire life of a typical African woman: She can have children from ages 18–40 and would be 60 before the youngest children left her home. A German woman, by contrast, more likely has two children very close together in age. She would be absent from the workforce for only a few years.

A participant asked about the quality of migration models. Bongaarts responded that migration is modeled rather poorly. He said migration is a minor factor in most population estimates, but it is very important to small, focused regions, particularly some areas in South America. United Nations models assume that migration will go to zero in a few decades, but he said he does not find that to be a realistic assumption and predicted the topic will increase in importance. Recently, there have been examples of rapid migration in Europe and, to a certain extent, in North America, and he said populations that immigrate tend not to integrate quickly into their new society.

Marcotullio postulated that identifying a person's location is a difficult task, and that spatial distribution of population, including migration, is a new demographic area that needs additional work. Jorgenson pointed out that migration may be important in understanding environmental change; a recent task force on climate change is showing that migration is a key knowledge gap. However, Bongaarts said he does not consider migration to be a factor in which large or surprising outcomes are likely. He said that instead there might be more room for variation in mortality rates and health improvements. On the other hand, he noted, a large airborne virus could have surprising outcomes on population. The population projections in the 1990s did not include the significant drops in fertility rates since observed. Overall, however, Bongaarts expressed confidence in current median projections of population.

Several participants asked about the definition of "urban" and whether to revisit that definition. One participant pointed to a division of the term into two definitions: an entity-based definition (population, density, land use, etc.) and a quality-based definition (the "urbanness" of the life experience). Marcotullio said he used an entity-based definition in his presentation. However, population densities are decreasing, and the question arises at what density an area is no longer considered "urban." Turner also asked about differentiation and urbanization by level of development. Marcotullio responded that the economics of agglomeration hold true, but the impact on the environment will differ by the level of development. In developed nations, such as the United States, emissions per capita are lower in cities because of agglomeration. Per capita emissions are higher in cities in other nations, particularly developing nations where there is a disparity in access to resources between urban and rural populations. As resources diffuse across populations, per capita emissions in cities are likely to be lower than per capita emissions overall.

A participant turned the discussion to economics, asking about the demographic dividend and its relationship to consumption and other demographic variables. Bongaarts said, to an economist, the demographic dividend was only positive because it results in a decline of the poor populations and motivates governments to help decrease fertility rates. The downside is that the effect lasts for only a few decades, and then it shifts to the demographic burden of an aging population. A participant asked whether the demographic dividend is actually an education dividend. Bongaarts said that a boost in education tends to be the result of a population decline; it is easier to educate fewer students.

Another participant asked about the robustness of the ecological footprint as an indicator, suggesting it might be useful to correlate to carbon dioxide emissions, but not for other variables. Jorgenson agreed it is right to be skeptical of the ecological footprint as an indicator and said he employs it increasingly less often. He noted he likes to use it for group discussions and in classroom settings, as the ecological footprint concept brings the issues to the table in an understandable way.

The topics of livestock and food behaviors were brought up (also discussed in the context of resource distribution in a later session). A participant posited that demographers tend to be concerned with drivers of emissions that include methane, so livestock is considered from that rather narrow perspective. However, another participant referred to a 2006 report by the Food and Agriculture Organization (FAO) of the United Nations, which stated that the total environmental impact of livestock is larger than that of the transportation industry (Steinfeld et al., 2006). Providing protein sources to a large population may be an important topic, the participant said.

4

Challenges to the Earth System: Consequences for the Earth System

In the third session, steering committee member Henry Harpending (University of Utah) chaired a session that included presentations by Stephen Polasky (University of Minnesota), Siwa Msangi (International Food Policy Research Institute), and James (Jae) Edmonds (Pacific Northwest National Laboratory), followed by discussion with participants.

BIODIVERSITY AND ECOSYSTEM SERVICES IN A WORLD OF 10 BILLION

Stephen Polasky, Fesler-Lampert Professor of Ecological/Environmental Economics and Regent's Professor, Department of Applied Economics, University of Minnesota

Stephen Polasky noted that the previous sessions focused on population, whereas his session focused on the links between population, human actions, and ecosystems (including variables such as land use, water use, and land management), as well as how those variables feed into human well-being. He used the term "ecosystem services" to describe the benefits the ecosystem provides to people. Polasky then identified two challenges to society: (1) economic development to alleviate poverty and malnourishment, and (2) conservation of natural capital to maintain biodiversity and ensure that humanity fits into the Earth's system.

Polasky stated that to support 10 billion people in 2050, the world gross domestic product (GDP) would need to increase by a factor of eight.

(This number also assumes an overall increase in affluence in that time period.) In comparison, the world economy grew by a factor of 40 from 1900 to 2000. However, Polasky reasoned that, in today's world, attaining an eight-fold increase would be difficult and questioned if, while building up economic capital in the form of manufactured and human capital, humans are simultaneously eroding natural capital by not sufficiently considering environmental issues. He defined "natural capital" as the natural assets that provide ecosystem services, possibly multiple ecosystem services, such as a forest (natural capital) that provides ecosystem services (timber production, carbon storage, water regulation, habitat, and tourism). According to the Millennium Ecosystem Assessment (2005), which considered the status of and trends in biodiversity, ecosystems, and biodiversity are both essential for human well-being, and the ecosystem-services concept provides a central theme and organizing principle. The assessment looked at each ecosystem service and evaluated whether it was increasing or decreasing over time. In general, services related to food (such as livestock and food production) are increasing, but all other ecosystem services show a decreasing or level trend. Thus, according to the assessment, while living standards are increasing around the world, natural capital is on the decline (Millennium Ecosystem Assessment, 2005).

Polasky then discussed biodiversity in more detail. The Millennium Ecosystem Assessment documented that the natural historic rate of species extinction is between 0.1 and 1.0 per thousand species per millennium; recent extinction rates, however, are two to three orders of magnitude higher, and future rates are projected to be higher still. These numbers are based on models, not observations, resulting in a large error range (Millennium Ecosystem Assessment, 2005). He proposed that biodiversity and ecosystems have a symbiotic but strained relationship. Biodiversity, he explained, is an attribute, and while it contributes to ecosystem services, it is not an ecosystem service in and of itself. During the Millennium Ecosystem Assessment development, there was some tension in the community about the increased use of ecosystem services over biodiversity, as maintenance of biodiversity can be seen as a goal of its own. Most drivers of change in both ecosystem services and biodiversity are based in human activity, such as changes in land use, climate, and the nutrient cycle; pollution; and the movement of biota (i.e., invasive species).

Analyzing one of those human activities—land use—in more detail, Polasky divided land use history into five stages: pre-settlement, frontier, subsistence, intensifying, and intensive. The intensifying period was marked by huge changes, as the world's ecosystem use transitioned to intensive agriculture and urban areas. He pointed out that people often use the word "loss" when describing this land use transition (harking back to Turner's description of the Cassandra viewpoint), but, more neutrally, humans should be thought of as change agents, converting habitat from one form to another. He said a debate has emerged about peak land use—will expanding the land use base result in more conversion of habitat, or has peak conversion already been reached? He showed that crop land use in the United States declined from 1950 to 2000, as increases in yield offset increases in demand. Technology has been the dominant force in land use transition in the United States recently, but Polasky cautioned the trend was not likely to continue domestically.

Polasky explained that ecosystem services are what economists might call "public goods"; in other words, it is difficult for private companies or landowners to receive payment or reward for the natural benefits of their land. As a result, he said, landowners have little incentive to maintain the natural capital of their land. For example, adding nitrogen and phosphorus is of personal benefit to a farmer, but not to the overall natural resources of the land and the surrounding and downstream areas. Maintaining ecosystems services, Polasky said, has received significant interest recently among scientists and governments (for example, in the United States and China), and it will require a multidisciplinary effort to do so. He identified three tasks to mainstream the maintenance of ecosystem services: (1) understand the provision from the ecosystem, (2) understand the value (such as creating benefits and affecting human well-being), and (3) create incentives via policy.

Polasky then provided an extensive example of land use in a study of the Willamette Basin in Oregon, which looked at the impact of alternate land use patterns on biodiversity and ecosystem services (Polasky et al., 2008). The study combined a biological model (focusing on terrestrial species) with an economic model (focusing on the value of agriculture, timber, and housing development). The study considered nine different land use alternatives to maximize species as a function of land for a given economic score—in other words, the study attempted to assess the best one could do for biodiversity from the landscape. The study found a steep curve: Species conservation can be increased at little cost initially, but it becomes increasingly expensive later in the development phase. The study showed how well it is possible to perform if multiple benefits from the landscape are taken into account.

A second study of the same area (Nelson et al., 2009) considered multiple ecosystem services and trade-offs among them, including services such as water quality, flood control, soil conservation, carbon sequestration, species conservation, and market commodities. Rather than solve a multidimensional optimization problem, the study worked with groups in the Willamette Basin to predict likely changes through time to develop three possible future scenarios: plan trend (or "business as usual"), development, and conservation. Polasky posited that the relative ranking of the scenarios would depend on the set of ecosystem services most valued; however, the conservation scenario showed the most improvement across the scenarios for all ecosystem services outputs, with the exception of market value. He suggested that if the value of certain ecosystem services were included—for instance, if landowners were compensated for carbon sequestration—there would be no significant trade-offs across the different scenarios, and the conservation scenario would become more attractive. The failure to incorporate the value of ecosystem services and biodiversity in planning, however, results in poor outcomes. Polasky postulated that the real challenge is one of integrated thinking—simultaneously integrating development and conservation to both spur economic development and enhance natural capital.

Polasky referred to his earlier statement that GDP needs to experience an eight-fold increase to support 10 billion people by 2050, noting that simply scaling up "business as usual" cannot produce enough for a population of 10 billion. He called for improved technology (better output per unit input), as well as improved institutions and incentives to increase output of goods and services without a negative impact on natural capital. He noted economists frequently write about the importance of incentives, paraphrasing a 2011 *Science* article (Kinzig et al., 2011) that "you get what you pay for and you don't get what you don't pay for." Because ecosystem services are currently supplied for free and without reward, they may soon not be supplied at all. Returning to the list in the Millennium Ecosystem Assessment (2005) that shows the change in various ecosystem services through time, Polasky noted a clear and systematic distinction between those services that increased and those that declined: the increased services (all in food production) are compensated for that production, while those who control the declining services do not receive a tangible benefit for their production. He stated that although a full understanding of the system dynamics at play is not in hand, enough is known to improve on current performance and characterized the integration of decisions about natural capital into societal decision making as a good beginning.

FUTURE DEMAND AND SUPPLY PRESSURES ON WATER: IMPLICATIONS FOR AGRICULTURE AND OTHER SECTORS

Siwa Msangi, Senior Research Fellow,
International Food Policy Research Institute

Siwa Msangi began his presentation by stating that there is a pressing need for additional provisioning of food to preserve nutrition and well-being as the Earth's population expands. He said that the challenge presented by climate change—specifically, the impact of climate change on water availability—affects the ability to meet current and future food production needs. Water scarcity, one of the greatest challenges associated with climate change, is already a widespread problem, encompassing both quantity (how much water is available) and timing (when the water is available). With increasing global temperatures, crop evapotranspiration requirements are likely to increase. He postulated that it is important to understand the role of investments in maintenance and management of water irrigation systems, such as water storage, efficiency improvements, and systems to prevent loss.

Agriculture is currently the single largest use of water globally, Msangi explained, and it is likely to remain that way for the foreseeable future. As a result, water-related technologies are important to food production. Irrigation is the largest user of water, accounting for 70 percent of global water withdrawal and 90 percent of global water consumption (Shiklomanov, 2000). He said that agriculture, despite its large water use, is considered a residual claimant on water. In other words, the agricultural sector has access to water after other users. Higher value sectors tend to use water first, as they have a greater ability to pay for it. In the future, agriculture is likely to receive a smaller fraction of the water available, so the need for efficiency becomes more pressing.

Msangi posited that food security challenges are important and pressing as well. As the global population increases, income growth is also likely to increase in developing countries, causing an increased demand for high-value food (such as meat, fish, fruit, and vegetables). Msangi said that water resource distribution is uneven over aggregate regions of the world. Regions with large amounts of available water (such as Latin America) do not irrigate; they rely upon rain sources instead. Investors in irrigation technologies tend to be in the regions less endowed with water, such as South Asia, North Africa, and the Middle East.

Msangi then looked at irrigation water supply reliability under climate change predictions for 2050. He showed results from several different models, indicating that the ratio of supply to required water is decreasing because of both reduced availability and increased demand. The water reliability index is correspondingly decreasing. There is some variation in the model results, but in general, yield for crops of maize, rice, and wheat are all projected to decline in most regions of the world—in some cases, quite significantly. Growth in both income and population size drives food prices higher. Higher prices are the result of increased demand from the larger population, as well as the increased per-capita consumption that follows income growth. Msangi showed projections of crop price increases from 2010–2050 ranging from around 25 percent for wheat and rice to over 50 percent for maize (Nelson et al., 2010). Using the mean effect from four different climate scenarios, those price increases double when adding the impact of climate change (Nelson et al., 2010).

Msangi then showed how variation to economic and population scenarios may impact crop prices. In an optimistic scenario (high income growth and low population growth), the price of rice increases the least, as Asian demand for rice falls with increasing income. In the most pessimistic scenario (low income growth and high population growth), the price of maize increases the most, as food demand rises in this socioeconomic scenario. In general, socioeconomic uncertainties contribute to price variations as much as the climate uncertainties. Critical uncertainties he pointed to include the following:

- *Models used.* There is significant variation in the outputs across models; climate outcomes are very different depending upon the model used. This includes region-specific variations in the effects.
- *Socioeconomic and income growth.* This growth is a key determinant for future food and water demand and price formation. Broad socioeconomic and well-being outcomes are also not clear. The best way to measure this is still under discussion, but higher food and water prices tend to lead to worse outcomes for the human population overall.
- *Natural science and hydrology*. An integrative approach linking the natural sciences with food and water sciences is needed.
- *Land cover.* Future land cover is uncertain, in terms of urbanization and livestock and land use change.
- *Technology change.* Technological improvements can determine productivity increases in food production and water efficiency.

Msangi stated it is important to better quantify the effects of climate change, particularly in its effect on the interrelationship between water and food supply.

ENERGY, LAND, AND WATER ON A 10-BILLION-PERSON PLANET: AN INTEGRATED PERSPECTIVE

James A. (Jae) Edmonds,
Chief Scientist and Battelle Laboratory Fellow,
Pacific Northwest National Laboratory

James A. Edmonds used an integrated assessment perspective to provide a view of what a 10-billion-person planet may look like in 2050. He began by showing the results from scenarios developed for the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment report, for which working groups are beginning to prepare their findings. He said the scenario work was first used in the early 1990s to launch climate change assessments. They used representative concentration pathways (RCPs), which were landmark scenarios that were organized by the researchers. The second installment was organized by the community itself, which developed what are referred to as shared socioeconomic pathways (SSPs). Five SSP scenarios have been created designed to help understand the climate assessment problem (O'Neill et al., 2012):

- *SSP1: Sustainability.* It is easy to adapt to and mitigate climate change impact.
- *SSP2: Middle of the road.* Adaptation and mitigation are moderate challenges.
- *SSP3: Fragmentation.* It is difficult to adapt to and mitigate the effects of climate change. This is likely the world currently inhabited.
- *SSP4: Inequality*. It is difficult to adapt to but easy to mitigate climate change.
- *SSP5: Conventional development.* It is easy to adapt to but hard to mitigate challenges with climate change.

The SSPs are then used in an integrated assessment model, which uses information about population, labor, technology, and policies to provide quantified projections about prices, carbon emissions, energy supply, land use, livestock, and other economic and ecosystem variables. Edmonds explained the Global Change Assessment Model (GCAM) is technically complex and not optimized in any way—it gives results based purely upon the assumptions provided to it.

Edmonds then looked at the SSP assumptions for population, GDP, and technology. In terms of population, only SSP3 (fragmentation) actually has the population rise to 10 billion by 2050. The other models give rise to a population closer to 9 billion by that time. For GDP, the SSPs use International Development Association (IDA) labor productivity numbers to develop estimates. The GDP numbers are quite different based on the SSP chosen: SSP5 (conventional development) gives overall high GDP numbers, while SSP3 (fragmentation) yields the lowest GDP, and SSP4 (inequality) results in the greatest disparity in income. Regarding technology, the model includes assumptions about quality of life (such as energy demands and renewable technologies). Edmonds said that the technology assumptions also include information about crop yield improvement technologies; while this is a critical model assumption, it is not well studied. He indicated that land use policies also are important but not well studied.

Edmonds then showed some preliminary results for the different SSPs that assume no additional mitigation policies put into place. He showed radiative forcing (W/m^2), a correlate of carbon dioxide emissions, for each SSP. SSP3 (fragmentation), the most likely current path, is on the high end of the scale; SSP5 (conventional development) results in a lower population but also in the highest radiative forcing, putting pressure on the climate system. The world of SSP5 is rich, with a lot of economic activity and a continued high use of fossil fuels. Edmonds showed the energy forms as a function of time for each scenario. There is a compositional change and variation across SSPs; however, the world is still dominated by fossil fuels in 2050 for all scenarios, particularly SSP5.

Looking at land use among the SSPs, Edmonds showed that there is little difference by percentage in land usage. Because urban land usage is such a small fraction relative to crops, forest, and biomass, it did not show up on his graphs.

Edmonds then introduced mitigation to the models. The mitigation information needs to specify the order in which countries implement the mitigation strategies; in general, wealthier nations start first, though some nations (Russia, Middle East) never begin mitigation implementation. Edmonds referred to this as the "delayed accession scenario." The mitigation information also needs to specify whether there is policy in place for land use change; in other words, if there is no charge for indirect land use emissions (such as cutting down a tree). The introduction of mitigation plays out very differently in the five scenarios, which has implications for water demands.

Edmonds closed by stating that population can exert strong pressure on the Earth's climate system, but economic activity, technology availability, and land use policies are also very important in determining the final impact on climate. In a world with 10 billion people, he stated, what matters is how much they are doing, how they are doing it, and what policies are in place to regulate activities.

DISCUSSION

The discussion period began with a question related to food consumption habits and the possible impact of changed food habits—for instance, increased demand for grass-fed beef. Msangi said the impact of livestock, particularly with respect to livestock intensively fed with grains, is not well understood. Grass-fed herds are not particularly well optimized; farmers in Brazil and Argentina say that they can increase herd densities, yet that is not included as a variable in any model. Reducing the need for feed grains, however, would take pressure off the production system. However, the stresses (such as heat, water, stocking density, and food) on animal productivity and animal growth need to be better understood.

The discussion then moved to how rising food prices could affect inequality and the differences between urban and rural poor consumers. Msangi said his models do not take variations in the consumer into account. A more nuanced answer likely can come from the World Bank models, he suggested, which take into account different producer and consumer characteristics. In a more detailed case, milk producers in Latin America tend to benefit from higher food prices, though the benefit is not realized everywhere. In general, price increases are good for farmers in locations where land access is plentiful.

A participant expressed surprise that the price of rice is expected to rise only by 50 percent over the next 40 years. Msangi pointed out that this projected increase is in worldwide market prices, with greater price increases for domestic supply. The most striking price increase will occur in sub-Saharan Africa, and the effect is likely to spread to wheat as well.

A participant stated that current GDP growth is projected to be only four-fold by 2050, not the eight-fold increase referred to by Polasky. Polasky responded that he was not advocating for an eight-fold GDP increase, but rather provided a thought experiment to understand the numbers. He suggested turning the question around: Given an eight-fold increase in GDP cannot be attained, what should be done?

A participant asked about the importance of land grabbing, in which transnational governments, businesses, or individuals purchase land in large quantities, most commonly in developing countries (particularly in tropical regions). Edmonds said land grabbing is not typically assessed, but he does not believe it is an important consideration for the models, most of which look at the forces shaping land use, irrespective of ownership. Msangi pointed out that the model would need to include economic impacts; in that case, land grabbing may be more important because the profits are being expatriated. Land grabbing is a phenomenon documented by the World Bank and others, and the data are just now getting to the point where the phenomenon can be assessed analytically rather than anecdotally.

A participant brought up the topic of crop yield and productivity, asking about any easy ways to increase crop productivity, particularly in sub-Saharan Africa. Polasky responded that it is possible to increase food supply via intensification alone, but farmers have little incentive to do so. While not the case in the United States, he said, farmers are more likely to extend into undeveloped land than increase yield of their currently used land in Africa and tropical areas. Edmonds stated that there is a feedback effect against incentivizing increasing yield. Increasing the supply will not increase demand. Polasky also pointed to time lags in the system; changes in the stock of natural capital (such as land use) take a while to have observable effects. For instance, looking at climate change, it is possible that enough emissions have been introduced to the point of irreversible damage, but the time lag in the system is so great that the negative impact will be felt only by future generations.

5

Special Presentation: Extreme Events

As a special evening presentation, William Rouse introduced John Casti, author of the books *X-Events: The Collapse of Everything* (Casti, 2012) and *Mood Matters: From Rising Skirt Lengths to the Collapse of World Powers* (Casti, 2010). His presentation was followed by a discussion among all participants.

X-EVENTS AND HUMAN PROGRESS (OR, WHY THE TREND IS NOT YOUR FRIEND)

John Casti, Senior Research Scholar,
International Institute for Applied Systems Analysis

John Casti noted a number of the previous presentations used a "trend-following" principle—in other words, the presenter identified a trend and explored its ramifications for various periods of time. He said this principle ties in with his topic about how trends end. He said extreme events (referred to as X-events) will encompass these endings.

Casti then posed a simple paradox: Surprises happen, but no one particular surprise ever happens. In other words, most people acknowledge that surprises occur, but, if presented with a specific surprise scenario, they would say that particular surprise is impossible. Casti then pointed out that trends always end with either a "bang" or a "whimper." In his observation, most go out with a "bang." He pointed out that the time horizon for trends can be very different, ranging from several days to many centuries. He listed several historical trends and their time horizons: dinosaurs (137 million years), the Roman Empire (677 years), the global financial boom (32 years), and the current popular culture fad of vampires (5 years or so).

Casti explained the trajectory of a trend by looking at a typical time series (reproduced in Figure 5-1). If one were to pick an ordinary point at random along the time series, one is likely to pick a point at which there is not a lot of unusual action (somewhere along the dashed lines in Figure 5-1). The likelihood of accurately predicting the next point is quite high, which is why trend-following is such a popular and successful analytical method. These points are common and expected, and the next moment is unlikely to contain an extreme event. The main activity in the time series is primarily focused at critical points (labeled a, b, and c on the plot). These points are short time frame, so the probability of being in that position is virtually zero. However, these critical points are the points that need to be understood. They can correspond to X-events, which are high impact and low probability. These critical points are the complement of the ordinary points of the time series and represent moments when the current trend is changing. If the curvature of the critical point is great, the X factor of the event is even greater.

Casti noted, however, that a time series curve to evaluate for a given trend is uncommon. What if a certain event has never happened before? In that case, there are no data, much less any sort of time series. How can the unknowns be measured and characterized? He explained that there are two pieces to assessing unknowns: (1) context, such as the landscape

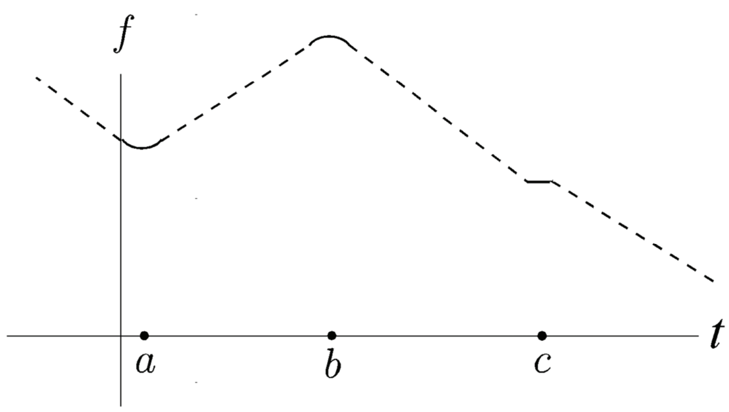

FIGURE 5-1 Time series of a trend.
NOTE: Critical points are labeled as a, b, and c.
SOURCE: Casti presentation, slide 3.

of possible events for the next moment; and (2) random triggers, the watershed event that selects the event at the next moment from the set of possibilities.

To predict an extreme event, it does not help to analyze random triggers, he said. They are unpredictable, so there is no pattern to discern or additional information to glean. Some examples of recent random triggers he cited included the collapse of Lehman Brothers, which precipitated the financial fallout, and the self-immolation of the Tunisian fruit seller that was the trigger for the Arab Spring. Casti asserted that, in contrast to random triggers, context is something that can be assessed. Two different drivers shape context: complexity mismatch and collective beliefs about the future. Casti cautioned that this is not a fully developed operational theory, and additional research is underway to better understand these drivers. For now, he said he can provide insights, not specific results.

Casti first addressed the idea of complexity mismatch. Tainter (1988) sought to look across history for common causes among civilizations that collapse and documented some common features, labeled "complexity overload." Casti explained that each civilization has problems that it must address. Typically, the civilization creates a new layer of structure to address a problem. The solution will long outlive the problem. As more problems are faced, an operational government becomes increasingly complicated and structured. At some point, all of the civilization's resources are consumed maintaining that structure, with nothing left to address the next problem. Casti identified the U.S. response to September 11, 2001, as an example. A new government structure (Department of Homeland Security) was put in place to address the new problem of terrorism. Casti defined complexity as the number of independent actions that a system can take at any time.

He then turned to a discussion of collective beliefs about the future, also known as human group psychology or social mood. How does a group think about its future? This metric is useful whether or not the beliefs correspond to the truth. Beliefs can strongly bias the character of the type of events a society can expect to see. Also important is the time frame under consideration—tomorrow, next week, next year, or future generations. Events have a natural unfolding time, and it is important to match the time frame of the collective beliefs to the time horizon of the event. For instance, the rise and fall of a civilization can take hundreds of years, so measuring day-to-day mood is not relevant. In contrast, popular culture changes rapidly, so it would be important to measure collective beliefs on a time frame of weeks if interested in popular culture. Casti emphasized beliefs, not feelings. Feelings can be ephemeral, but beliefs tend to be consistent. To be operationally useful, there needs to be a metric to assess collective beliefs. The metric should relate to actions that are the result of collective beliefs. One good way to characterize this is by looking at the financial markets, because they are a representation of decisions taken by people. Casti emphasized that this is a first step, not the last, in measuring collective beliefs. He observed that this metric has been the frequent subject of criticism, and he proactively addressed how the actions of a handful of traders could represent a whole population. He referred to his book (Casti, 2010) for more detail, but he postulated that traders do not act independently. They gather information and receive input from many different sources, as well as respond to the wishes of portfolio owners.

Casti applied the financial market metric to several examples. The first was U.S. presidential elections. Looking at the social mood (via financial indices) one week prior to presidential elections, there are 26 instances of clear trends. Of those 26 instances, 19 were positive and seven negative. In the case of the 19 positive trends, the incumbent or his party's candidate won the election in a landslide 13 times, and retained the office in all 19 cases. In the case of the seven negative trends, four incumbents or their party's candidate were ousted in a landslide, and all seven lost the election.

In a second example, Casti examined the relationship between the social mood metric and health epidemics. In this case, the effects are regional, so a global financial market indicator would not be sufficient. Instead, he looked at foreclosure rates 2 months before a large outbreak of the H1N1 virus in 2009. There was a strong correlation between foreclosure rates (Casti referred to this as the "fear index") and the incidence of H1N1 influenza. He did not attempt to explain this correlation, but he pointed out that the correlation indicates a possibility that people can be more susceptible to a health epidemic if they are in a negative place. Casti referred participants to the work of Alan Hall (Hall, 2009) for further studies of this effect.

According to Casti, X-events pose an opportunity as well as a challenge. For instance, those who survive an X-event are more resilient. X-events "clean out" social structures and processes that may have outlived their utility. While recovery can take a long while, the X-event can bring with it new opportunities. In the aftermath of the Fukushima nuclear incident, the Japanese are seriously questioning old structures, in place since World War II, that overemphasize government-industry relationships and are no longer viable. In an even more extreme X-event example, the asteroid that extinguished the dinosaurs provided opportunities for other organisms to evolve—leading to humans' presence on Earth today. In general, the system starts afresh after an X-event, new systems are put in place, and the process begins again. Casti stressed that this development cycle is neither linear nor circular, but spiral. A fresh start does not originate from the same place started from in the previous cycle. Instead, the new beginning is from a different (hopefully higher) level, progressing to new heights. Casti said X-events are necessary for rebirth and human progress.

DISCUSSION

In the discussion period, Casti was asked about the use of the stock market metric to gauge social mood. The questioner's concern was not that so few people were moving the market, but rather that the market matters for only a small segment of the population. Seventy percent of U.S. wealth is held by 10 percent of its citizens, while 50 percent of its citizens have no net assets. Perhaps the wealthiest Americans dominate the public discourse and therefore create the social mood for the nation, the participant suggested. However, in other nations it would be impossible to gauge public mood via the stock market. Casti agreed, and pointed out that he gave a talk about social mood in Havana, Cuba, which has no stock market. Also, a financial market index is a highly aggregated measure that does not allow the assessment of subsets of the population. In those cases, it may be important to use alternate measures of social mood. He expressed enthusiasm for social media and data mining. He also described other advantages to financial markets as a gauge of social mood: the data are clean, have a long history, and are publicly available.

A participant brought up the fact that in Casti's scenario, X-events are considered cleansing, removing institutions and procedures that have become obsolete. However, institutions are fairly adaptive, and a resilient institution may be more adept at adapting to a new world. Why should such institutions be removed? Casti clarified that he provided no arguments for which social structures would survive an X-event and which ones would be eliminated. It depends entirely on the nature of the event. He posited that to adapt in the aftermath of an X-event, an institution needs (1) to survive, (2) to absorb the event and carry on with its function, and (3) to show agility and take on new opportunities.

6

Resource Distribution and Global Inequality

The session on Resource Distribution and Global Inequality was chaired by steering committee member B.L. Turner II (Arizona State University), with presentations by Branko Milanović (World Bank), Parfait Eloundou-Enyegue (Cornell University), and Wolfgang Lutz (International Institute for Applied Systems Analysis). Their presentations and the ensuing discussion are summarized below.

GLOBAL INCOME INEQUALITY: HISTORICAL TRENDS AND POLICY IMPLICATIONS FOR THE FUTURE

Branko Milanović, Lead Economist, World Bank

Branko Milanović explained that he would talk about inequality, both global (among countries) and within single countries. To measure inequality, Milanović used data from the International Comparison Program, which is a large undertaking that assesses purchasing power in different nations.[1] While details of this project's results are subject to debate, he said, the project provides a comparison of prices across nations that can be used as a baseline metric. The International Comparison Program developed a price index normalized to the United States, in which a score

[1]For more information about the International Comparison Program, see http://go.worldbank.org/X3R0INNH80 [February 2014].

of 1 indicates purchasing power equivalent to that of the United States. China rated 0.4, meaning that goods and services in China cost 40 percent of what they cost in the United States. Norway rated 1.3, or 130 percent of the United States' costs. The International Comparison Project index can be used to normalize the per capita income of each nation.

Milanović defined three different concepts of inequality (Milanović, 2005):

- Concept 1: The mean per-capita income for each country is compared to the others. This disregards the overall population size of the nation and merely looks at the mean income value. Economists commonly use this metric to discuss income convergence.
- Concept 2: The mean per-capita income is used, but the statistics are weighted by each nation's population. In other words, every person is counted, but each is "assigned" the mean income for his or her nation.
- Concept 3: Comparisons are made using each person's individual income, without linkage to the national average. In this case, there is much more variation. Milanović stated that in this concept, it becomes clear that there is little overlap between the income distribution of a wealthy nation and that of a poor nation—poor people from a rich country are still relatively rich overall. For instance, the mean poverty line globally is $1.25 per day, but in the United States the mean poverty line is $14–15 per day; this amount is equal to the 75th percentile of world income distribution.

Milanović then presented data showing how these different inequality concept measurements have changed in time, shown in Figure 6-1, where the inequality measure is expressed as a Gini coefficient.[2] Under Concept 1, income has diverged, particularly in the period of globalization from 1980–2000. He explained that, in those two decades, Africa and Latin America experienced a net loss of growth. Most of the factors during globalization were working in favor of global inequality. Richer nations and China, however, fared very well. The data for Concept 2, Milanović explained, are driven by China, which brings the overall inequality measure down. China is contradictory, however; while its growth was the sole factor driving down global inequality, it was also experiencing an internal increase in inequality. In other words, China's increasing population and increasing average income contributed to lower global Gini coefficients under Concept 2. However, the Gini coefficient within China was

[2]The Gini coefficient is a statistical measure of inequality, represented as a measure between 0 (complete equality) and 1 (complete inequality).

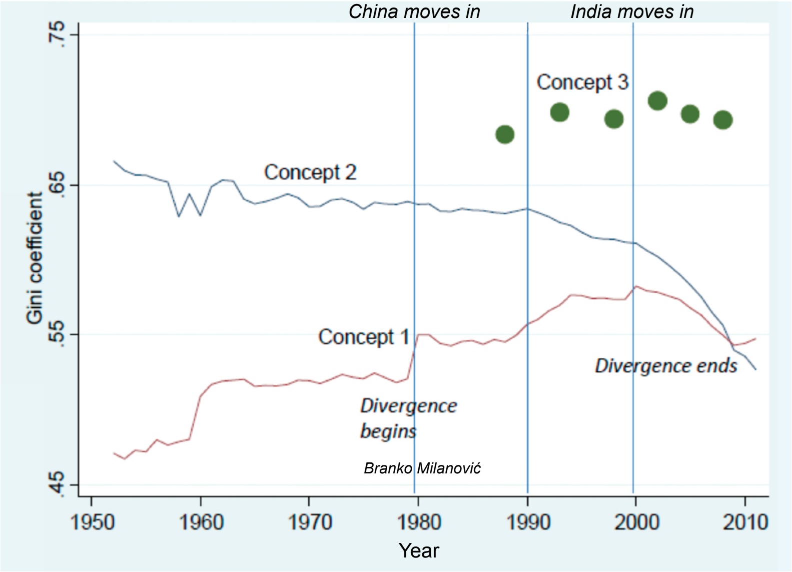

FIGURE 6-1 Inequality, measured by the Gini coefficient, as a function of time for three different inequality concepts.
NOTES: Concept 1 calculates the Gini coefficient using mean per-capita income for each nation, compared against the others. Concept 2 uses mean per-capita income, weighted by each nation's population. Concept 3 uses individual income data. Concept 3 is represented by a small set of discrete dots because survey results on individual income are not consistently available across time and nations. As poorer nations typically do not provide survey results as often as developed nations, the data for Concept 3 should be considered a lower bound estimate.
SOURCE: Milanović presentation, slide 3.

increasing for that same time period. In 2000, India also began a period of development, bringing the Concept 2 measure of inequality down even further. In contrast to the first two measures, the data for Concept 3 are fairly level; the increase in inequality among the other nations offsets the growth of China and India.

Milanović showed that the final Concept 3 "dot" in Figure 6-1 declines slightly, by about a total of one Gini point. While this is a small fraction of the total (1 point in 70), such a decline would be a historic and positive development. The Concept 3 measure of inequality rose from around 50 in the year 1820 to around 70 in 1960, where it has remained since. Reversing this curve would be a huge evolution in the international measures of inequality.

Milanović explained that the pattern of global inequality change differs from patterns of national inequality changes. In the past, the greatest inequality has been within nations (for example, a country with rich nobility and poor peasants), with the average ratio of inequality within a nation 4:1. However, inequality is now mostly disparate among nations. Today, income is largely determined by where an individual lives, in that 70 percent of income variability is based on global rather than national inequalities. This shift is largely the result of increasing population sizes in Southeast Asia, notably China and India. Milanović noted that one could look at inequality of carbon emissions as well: Because consumption patterns vary by income level, it should be possible to assess overall emission concentrations by measuring income levels in different areas.

A participant asked Milanović if the ideal situation would be one in which everyone in the world would have the same income, and therefore there would be no inequality. He replied the Gini coefficient is a measurement tool, and he attempted to present the measurements in a neutral way, without giving opinions. The ideal Gini coefficient is more a philosophical or political issue, not a demographic one, he explained.

POPULATION-INEQUALITY-SUSTAINABILITY: BEYOND IPAT

Parfait Eloundou-Enyegue, Professor,
Department of Development Psychology, Cornell University

Parfait Eloundou-Enyegue began his presentation by stating that the options for a 10-billion-person planet in the classic population-sustainability debate have usually been taken to one of two extremes: an apocalypse scenario (the Cassandra viewpoint) or a blissful scenario (the Pollyanna or Cornucopian viewpoint). He proposed searching for middle-ground options. He referred to one option suggested in a previous session, when it was stated the entire population of 10 billion could live in the state of Texas if humans lived more simply. In other words, the entire world population could survive but not thrive. Another scenario, which Eloundou-Enyegue pursued, was that consequences could be highly differentiated: apocalypse for some, bliss for others. He posited that in 2050, there may be significantly more competition and inequality. In that perspective, greater attention should be paid to inequality and to a framework that goes beyond the classic impact, population, affluence, and technology (IPAT) model.

Eloundou-Enyegue then discussed the limitations and restrictions of the commonly used IPAT model. (See the summary of Turner's presentation in Chapter 2 for an introduction to IPAT.) While IPAT is a useful tool, Eloundou-Enyegue argued that its utility is somewhat narrow, for the following reasons:

- IPAT restricts sustainability to its environmental dimension, and does not include other socioeconomic factors.
- IPAT is restricted to population growth, and does not consider demographic distinctions such as age, fertility, or family structure.
- IPAT focuses attention mostly to high fertility countries.
- IPAT's main rationale is Malthusian.

He proposed a new conceptual framework for thinking about sustainability, which he referred to as PIES (for Population-Inequality-Environmental and Economic Sustainability). He explained that PIES has three basic tenets:

1. There is more to population than size. In other words, factors such as the population's age distribution, differential fertility behavior, and family structure and formation are also important to model.
2. Sustainability goes beyond just environmental factors, and includes socioeconomic factors as well.
3. Global inequality is a mediator of population effects.

Eloundou-Enyegue pointed out that the PIES model contains nothing new, but is a different way to assemble the pieces. In the IPAT framework, he said, attention is focused primarily on the poor high-fertility nations, as they contribute the most to the population variable. He characterized this as a politically sensitive issue, as IPAT can "blame" the poorer nations for unsustainable practices. Under the PIES model, population concerns extend to all nations, although the issues facing each one are different. Central to the PIES model is the importance of population distribution, and connecting population inequality and sustainability. Eloundou-Enyegue represented problematic situations in population, consumption, or equality as a triangle; the large base of the triangle represents the population concentrated in adverse conditions.

Eloundou-Enyegue then turned to the challenge of measuring global inequality. It is difficult for people to recognize signs of inequality except in the simplest of circumstances. Often it can be difficult to distinguish inequality from other related concepts such as inequity, mobility, justice, difference, and stratification. It can also be challenging to identify the appropriate comparison group—whether to compare with one's neighbors, age group, compatriots, co-workers, or the world. Eloundou-Enyegue also explained there are many types of inequality, such as income vs. outcomes, differentials vs. inequality, inequality vs. inequity (endowments and rewards), inequality vs. mobility, local vs. global, actual vs. perceived, gross vs. net, and current vs. lifetime income inequality. He used actual vs. perceived inequality as an example by asking which would be better: a situation with a lot of inequality but no one was aware of it, or a situation with little inequality but it is felt more acutely. He suggested that while between-nation inequality tends to be larger in size, within-nation inequality is perceived more acutely by its citizens.

Eloundou-Enyegue identified two components when computing inequality: income (relative differences in income across groups being compared) and demographics (relative size of groups). Decomposing inequality into these two components can reveal what has driven historical trends.

Eloundou-Enyegue then briefly discussed trends and prospects in global inequality. He said that a major trend in global inequality is a "turning inward," or involution, which is a simultaneous decline in nation-to-nation inequality and increase in within-nation inequality. Given the greater salience of within-country inequality for most people, this pattern is likely to lead to a decrease in global well-being. Eloundou-Enyegue briefly touched on Kuznets's (1955) thesis, which stated that there is an inverted U-curve between per capita income and inequality. Kuznets's assumptions of inequality may no longer hold, Eloundou-Enyegue said, as there is now an increase observed in internal inequality across the world and a decrease in social mobility.

Eloundou-Enyegue then turned to the consequences of global inequality, asking if countries with greater inequality also have greater levels of consumption. He postulated that countries with more inequality tend toward poor stewardship and less interest in preserving the natural environment. However, they also tend to have less to consume. He also asked if countries with greater inequality have greater socioeconomic instability. Citing work done in 2011, Eloundou-Enyegue stated that health and social problems increase with increasing income inequality (Ortiz and Cummins, 2011).

In the final section of his talk, Eloundou-Enyegue discussed the demographic causes of inequality. In examining current population trends in global inequality, he looked at a number of possible factors. Between countries, he examined relative population growth, age structure, and migration and remittances. Age structure proved to be the largest contributor to inequality. Within countries in high-fertility settings, he examined differential fertility, fosterage, and teen pregnancy. Among those variables, differential fertility was the greatest contributing factor to inequality; there were significant differences between birth rates in the upper quintile and lowest quintile. In low-fertility settings, he examined increased homogamy and family formation. There, marriage rates and premarital fertility rates were the largest contributing factors.

Eloundou-Enyegue pointed out that in the classic IPAT decomposition, GNP per capita and the relative size of a country's population are the variables considered. However, overall population is not a significant variable, representing only about 1.5 percent of the contribution to global trends in between-country inequality between 1980 and 2010. This is not a surprising result, he commented, as the relative size of any given country does not tend to change much over time. Eloundou-Enyegue said in an expanded decomposition of the trends in global between-country inequality (one that includes variables such the adult per capita income, age structure, and country size), international differences in age structure turn out to be crucial. Economic trends and performance still account for most of the inequality, but a population's age structure plays a larger role than generally acknowledged. The IPAT model and Malthusian principles emphasize population size and growth, but he argued that demographic distribution matters more.

Eloundou-Enyegue said inequality trends are likely to continue, and social capital, family trends, and the life chances of children born to diverse circumstances are profoundly different. Also, increasing differences in premarital fertility, as well as an increasing tendency to marry as one's educational level increases, will also lead to greater inequality.

Eloundou-Enyegue concluded by noting that previous conversations about population and sustainability, framed by the IPAT model, reduce the population variable too much by exclusively focusing on size or growth. The PIES model is a broader framework that allows for an expanded analysis. Returning to his introductory point about the two extremes for the 10-billion-person scenario, he said that the likely scenario is that the future will be a cornucopia for a few and a disaster for many. It is a matter of policy to determine what happens, he suggested.

INTERGENERATIONAL TRADE-OFFS, DEMOGRAPHIC METABOLISM, AND THE LONG-TERM BENEFITS OF EQUITABLE EMPOWERMENT IN THE NEAR TERM

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

Wolfgang Lutz began his presentation by commenting that intergenerational justice is a hard concept to operationalize. A focus on intergenerational trade-offs rather than on justice could be easier, but it is still difficult because the preferences of unborn generations remain unknown. It is more pragmatic to focus on trade-offs between different age cohorts already alive. In all these cases, conventional economics is not helpful. Instead, Lutz said that there should be a metric for well-being that is consistent for people who have lived at different points in history—a figure of merit that is equally valued across time. This figure of merit should incorporate aggregate indicators of well-being, which for sustainable development would not decline over time or for any subpopulation. The figure of merit should also include the depletion of natural stock and how that depletion feeds back to the future well-being of humankind. A simple metric to use is that of survival and avoiding premature death—as he pointed out, all people agree that staying alive (in good health) is a good thing. Another option for a figure of merit is the Human Development Index,[3] which also includes education and material standard of living and thus broadens the choices people have beyond simply survival (United Nations, 2013).

Lutz then introduced the concept of demographic metabolism, which models how societies change through intergenerational replacement. It can be used to model the future composition of a population according to relevant characteristics that persist over life (such as higher level of education, certain opinions, and identity). These cohort effects are in addition to age effects (changes that everyone experiences as a function of age) that can also be modeled. Demographic metabolism, therefore, can be seen as a predictive theory of socioeconomic change. It was originally introduced as a concept by Ryder (1965) but not operationalized until more recently. Demographic metabolism provides a useful analytical handle to understand intergenerational trade-offs by focusing on stable characteristics, and it can be used to forecast information about populations into the future. Lutz illustrated demographic metabolism with the example of the changing educational attainment distribution in South Korea. In South Korea in 1985, a significant part of the population was uneducated, but these people tended to be in the older age categories. In addition, within the older population, many more women than men were uneducated. Because of South Korea's increase in its education policies in the 1950s, the 1985 demographic data show that few people (men or women) under the age of 35 remained uneducated. Lutz presented South Korea's demographic and education data from 1985 through 2010, which clearly demonstrated demographic metabolism: As time progressed, the uneducated older people were replaced with the more educated next generation. In addition, as educational levels increased, fertility decreased, and fewer

[3]The Human Development Index is a single composite metric that combines indicators of life expectancy, educational attainment, and income to measure development (United Nations Development Reports, see http://hdr.undp.org/en/statistics/hdi [February 2014]).

people were born into successive generations. Using this information, one can project future populations and their education levels.

Lutz said that at the global level, the most profound differential across societies is the average level of a mother's education; an increase in education contributes more than income or any other variable to the decline of both fertility and infant mortality. He cited a *Science* article (Lutz and Samir, 2011) that discusses maternal education and population, and cited evidence with respect to the causality between increased maternal education and slower population growth. He stressed that education is not merely a proxy for socioeconomic status; there is strong evidence that it has direct functional causality. There is also evidence to support a linkage between maternal education and poverty reduction in Latin American countries. Figure 6-2 shows the population fraction living in poverty in Latin America as a function of the proportion of women with secondary education or greater.

Lutz then explained the scenarios used for the Intergovernmental Panel on Climate Change (IPCC) analysis since 2000.The IPCC Special

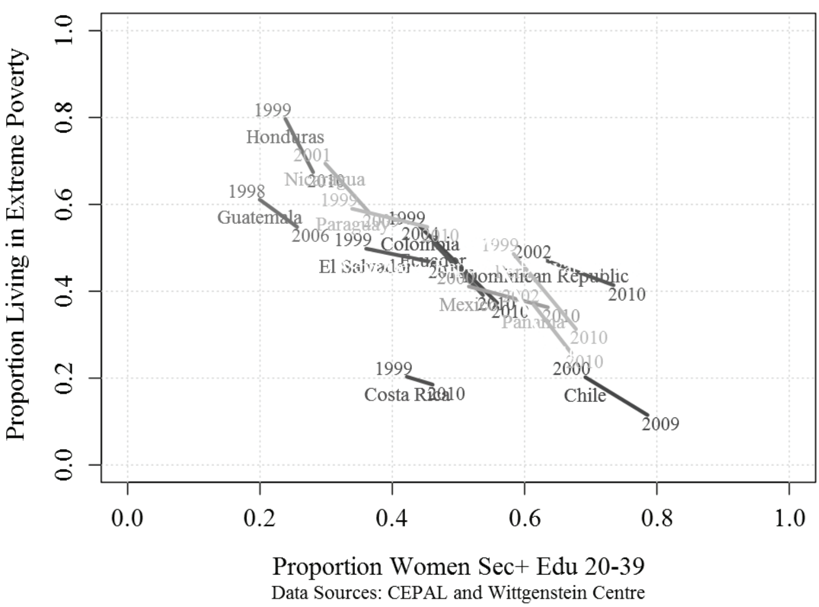

FIGURE 6-2 The population fraction living in poverty in Latin America as a function of the proportion of women with secondary education or greater.
NOTE: Each nation is plotted with a different color, showing results across time in the 1998–2010 time frame.
SOURCE: Lutz presentation, slide 22.

Report on Emissions Scenarios (SRES) only included total population size and GDP. In 2013, new shared socioeconomic pathways (SSPs) scenarios were developed. They offer much more social detail and include age, gender, and education in addition to urbanization and GDP. The SSP scenarios are based on the understanding that education is the third most important source of observable population heterogeneity, following age and gender.

Lutz then described population and its interactions with climate change. The human population affects climate change via consumption (energy usage and land use changes) as well as via innovation and technology (solutions for greenhouse gas emissions). He pointed out that much less is known about the effects of climate change on future human well-being, and the most relevant and critical question is to understand how dangerous climate change will be for humankind. While the IPCC reports give detailed information about likely future climate conditions with uncertainty margins, much less is known about the future adaptive capacity of societies to cope with these changes. There is also a differential effect on people and their health and mortality rates, depending upon their demographic characteristics. According to Lutz, a frequent mistake is to match future climate conditions to today's society and health capabilities; in reality, one must project both into the future.

Lutz then looked at the five SSP scenarios, including population and age- and education- pyramid information for each scenario. (The five SSPs are defined and described in the presentation by James A. Edmonds; see Chapter 4.) Under SSP2 (known as the "business-as-usual" or "middle-of-the-road" scenario), population peaks at 9.4 billion around the year 2070, with an expansion of the higher educated population and a shrinking of the uneducated population. Lutz referred to a *Science* article (Lutz et al., 2008), in which, based on age specific education data, he and his colleagues showed that the distribution of education within a society is a key driver for economic growth. Furthermore, a more educated population is linked to decreased disaster mortality and increases the population's adaptive capacity to respond to climate change.

Lutz closed by reiterating the importance of understanding how dangerous climate change is to human well-being. Without an analytic answer to that question, he said it is hard to respond appropriately to the challenges posed by climate change.

DISCUSSION

During the discussion period, a participant asked if inequality is bad for health—or, alternatively, if there is an absolute poverty level that is bad for health. The participant pointed out that focusing on absolute poverty levels focuses on the lowest populations. She pointed out that the past few talks have seemingly focused instead on relative outcomes (such as the Gini coefficient) and not absolute levels. Lutz responded by saying that instead of looking for a desired level of inequality, one should focus on desired outcomes across an array of issues (such as education, land use, and income). Inequality can then be assessed in the context of those outcomes, to avoid setting any intrinsic desirable level. Eloundou-Enyegue pointed out that, in a previous discussion, some inequality was suggested as fundamentally good to spur innovation and effort, although others might argue that inequality is on principle a negative characteristic. He broke the idea up into three tiers of thinking. In the first tier, one thinks about the consequences of inequality on humanitarian grounds and concern for the poor. In the next tier, one thinks about matters of economic efficiency. In the third tier, one focuses on status and stress—even the very rich cannot shield themselves from social unrest associated with uncertainty and inequality. Thus, he said, inequality is a concern for everyone at every tier of thinking. Milanović said that inequality does have a precise definition, such as the Gini coefficient. He pointed out that Wilkinson and Pickett (2009) found a strong correlation between increasing inequality and other negative outcomes, such as increased health and mortality rates. The danger with the Gini coefficient approach, he suggested, is that it focuses entirely within national borders, and in so doing equates a rich American with a rich African and a poor American with a poor African, when in reality those populations are not at all the same.

A participant asked the speakers to draw links between the current and future intergenerational inequality, in terms of human capital, natural capital, and other capabilities. Lutz said the first step is to find one broad metric by which to assess whether intergenerational inequality is improving. He said currently the best metric is survival (life expectancy at birth), as it is universally accepted, but a more meaningful and direct metric may exist. Eloundou-Enyegue suggested a look at current patterns. Unequal societies today are likely to bifurcate further—some in the population will have the incentive to reduce fertility rates, while others will invest in larger families. The inequality of the two groups will continue to drift even further apart. The risk is that this pattern will continue indefinitely. Milanović said that migration is a tool that has the potential to significantly reduce inequality. Currently, about 3 percent of the population migrates, but 8 percent of the population would like to do so; thus, he said, there is a pent-up demand for migration.

A participant asked about the probability of escaping the lowest quintile of income—in other words, the likelihood of rising out of poverty. The participant stated that the current data in the United States vary by city; in cities such as New York and Boston, one has a 12 percent chance of leaving poverty. In Atlanta, the chance drops to 4 percent. The participant asked if absolute inequality is the only metric or if another metric can measure social mobility. Milanović responded that data on intergenerational mobility show a correlation between current inequality and lack of mobility. This is particularly true in the United States, where there is high inequality and low intergenerational mobility. Milanović said the correlation between parent and child income is quite high, around 0.5. In European countries, the number is closer to 0.3. He stated that the lack of social mobility in the United States conflicts with Americans' self-perception; they believe their children have the opportunity to move up quickly in the world (known as the "Great Gatsby curve"). Eloundou-Enyegue said that mobility in the United States has been structural in nature—that new "slots" in the middle class have opened up in addition to merely replacing someone in the middle class. If these opportunities vanish, so does mobility. Lutz pointed out that by far the most important path to upward social mobility is education, and this is true in every country in the world. The Nordic countries have high-quality public education and a correspondingly high level of social mobility. In countries where the best education is private, mobility is significantly lower. Eloundou-Enyegue countered that only so much inequality can be addressed by education alone, however, and there needs to be concerted cultivation—a deliberate attempt to invest in children beyond the classroom. Milanović noted, for example, that the average family income for a student attending Harvard University is in the second highest percentile of average American income—yet another indicator of lack of mobility.

7

Interaction Between Earth and Societal Systems

The final session of the workshop before a plenary discussion was chaired by steering committee member Terry Chapin (University of Alaska), with presentations by Lisa Berkman (Harvard University) and Brian O'Neill (National Center for Atmospheric Research).

THE DISTRIBUTION OF POPULATION HEALTH AND CONSUMPTION RISK IN LOW-, MIDDLE-, AND HIGH-INCOME COUNTRIES: THE ROSE PARADIGM REVISITED

Lisa Berkman, Director,
Harvard Center for Population and Development Studies,
Harvard University

Lisa Berkman explained she would focus on public health issues, and include the perspectives of demographers, epidemiologists, and economists to discuss four statements:

1. A framework is needed for determinants of population health—the Rose paradigm.
2. Demographic distribution of populations matters more than average populations when considering the global future of population health.
3. Social and economic determinants are important in shaping patterns of population health. Heterogeneity and inequality are both

important, for health as well as consumption (as discussed in previous talks).
4. A governance structure is needed to promote sustainability.

Berkman argued that when considering the drivers for climate change and world health, responsibility rests with rich nations. While population is an important issue, consumption is equally important, and consumption is clearly the purview of the wealthier nations.

Berkman then described Geoffrey Rose's contributions to population health research (see Box 7-1). She explained that under the Rose paradigm, everyone in a population changes in the same way, so in response to a stimulus, the whole population would be pushed in one direction. However, this tends not to be true; instead, the distribution can change its shape and size, which Rose did not consider and is outside his paradigm. Berkman used the example of body mass index (BMI) for women in developing nations (Razak et al., 2013). In Bangladesh and Bolivia, the number of women with low BMI (in other words, malnourished women) did not change appreciably over time. However, the number of women with high BMI increased. Berkman referred to this as a "double burden"—now these countries are experiencing difficulty with both underweight and over-

BOX 7-1
Understanding the Rose Paradigm

In his 1985 work *Sick Individuals and Sick Populations*, Geoffrey Rose studied blood pressure in two populations, a group of Kenyan nomads and a group of London civil servants. He found that the distribution curve was the same in both populations, but the average systolic value was about 10 points higher for the London population. The presumption is that over time and with such drivers as economic development, the Kenyan curve will creep to a higher and higher systolic average until it overlaps with the London population. Rose postulated that, if a mean moves in a certain direction, the deviating tail of the distribution will correspondingly move in that same direction. Rose stated, "Distributions of health-related characteristics move up and down as a whole: the frequency of 'cases' can be understood only in the context of the population's characteristics…The population thus carries a collective responsibility for its own health and well-being, including that of its deviants" (Rose and Day, 1990, p. 1031). The paradigm infers that intervention strategies, such as sanitation, fluoridation, or seat belts, should push the whole population across its demographic distribution to be healthier in an equal way.

SOURCE: Data from Rose (1985) and Rose and Day (1990).

weight populations. Berkman pointed out that the ideal scenario would be one in which those with low BMI would gain weight and those with high BMI would lose weight. Even the ideal scenario is an asymmetric one, inconsistent with a Rose shift. Berkman said that this demonstrates how a single variable's mean or average does not represent what is happening in a country. Looking only at average BMI in Bangladesh, for instance, would show an average increase, with no sensitivity to the fact that there is still an undernourished population. A more sensitive measure would provide information about both the center of the population and its extremes.

Berkman then examined social disparities within countries. She showed data that indicate that overall mortality rates have been dropping over time. Cancer rates in the United States from 1950–1990, however, show the drop is not consistent across socioeconomic status. Populations with the highest socioeconomic status show a drop in cancer-related mortality over time, but the lowest quintile shows an overall increase in mortality in the same time period. The reason, Berkman said, is simple: smoking. A reduction in smoking caused cancer rates to plummet in certain income classes. She referred to this as "exporting failure": those who are the best off learn that a behavior is bad and they stop the behavior, but less well-off populations take up that behavior. Exporting failure takes place across income classes within a nation, and across nations—from the wealthiest nations to the poorer nations. Negative behaviors that have been exported include smoking, dietary behaviors that lead to obesity, and high rates of energy consumption. As a result, she said, inequality is widening across the world.

Berkman closed with a discussion of governance requirements and the concept of legitimate coercion developed by Mansbridge (2013). She acknowledged that this area is not her own field of expertise, but said that it is an important topic to discuss. She pointed out that the government coerces its populations all the time. While illegitimate coercion can be recognized, what does legitimate coercion look like, she asked. How can large, highly interdependent structures produce sufficient legitimate coercion to solve collective action problems? She said that legitimate coercion can be normative (i.e., people believe it is right) or empirical (i.e., people see evidence that it is right). She said that climate change is an example where legitimate coercion may be critical. Berkman suggested that experts in collective action problems be brought into the discussion to see how the idea of governance structures could be addressed.

As a final thought, Berkman posited that health is socially patterned, and that social disparities exist in health. While these disparities are ubiquitous, they are also variable and have numerous possible health ramifications. The challenge, she said, is to find social and economic policies that influence large-scale health risks so that population health might be improved, disparities reduced, and sustainable societies and global environments created.

DEMOGRAPHY AND CLIMATE CHANGE: CURRENT UNDERSTANDING, FUTURE DIRECTIONS

Brian O'Neill, Scientist III,
National Center for Atmospheric Research (NCAR)

Brian O'Neill prefaced his presentation with a discussion of recent events in Boulder, Colorado, the location of NCAR. The area recently flooded; initial estimates say it was a 1-in-1,000-year rain and a 1-in-500-year flood—in other words, a rare and unexpected event. There were eight flood-related deaths in the area, along with an estimated $1 billion in damages. O'Neill said the region has begun a discussion of how to measure the impact of such an event on society. The losses of life and property were very important in the local community. However, overall life expectancy rates did not change in the area as a result of eight deaths. O'Neill said he raised this issue to show that, in a broader discussion of measuring the impact of climate change, using life expectancy as a primary metric is setting too high a bar. Something short of a catastrophic scenario is still part of the collective concern. The Colorado flooding also provided an example of differential vulnerability. In many cases, different neighborhoods received the same level of hazard but the results were markedly different: A mobile home community would be destroyed, while a high-income housing development would only experience wet basements. O'Neill pointed out that, when assessing the scope of the impact of climate change, it is important to account for the condition of different populations, in addition to simply the level of physical hazard.

O'Neill then described work on the relationship between demography and climate change, structured around the determinants of risk, which results from the interaction of a physical hazard (storm, flood, heat wave, etc.) and the exposure to and vulnerability of a population or ecosystems. Figure 7-1 shows a schematic of how aggregate risk is determined for natural disasters, and risks for climate change can be conceptualized in a similar manner.

O'Neill then summarized the Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) model. This model looks at historical data to assess the importance of demographic, economic, and technological factors on the emissions that cause climate change. It essentially converts the IPAT model (see summary of Turner's talk, Chapter 2) into a statistical model, where P, A, and T are not assumed to be linearly

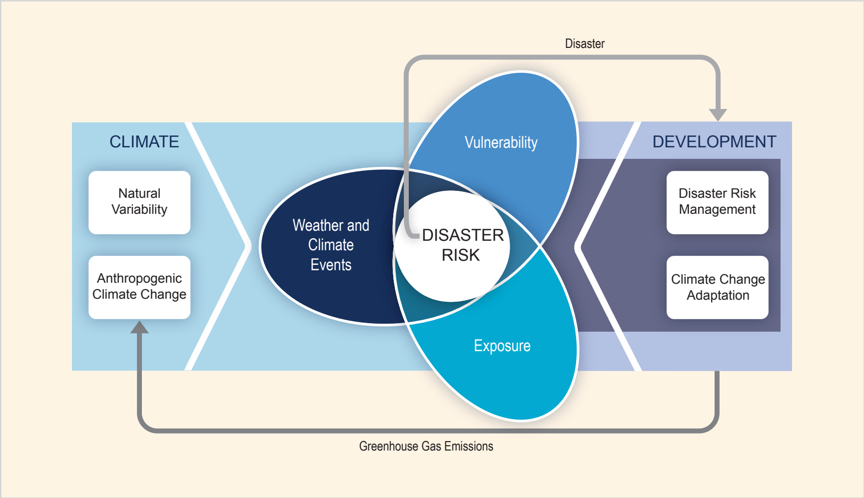

FIGURE 7-1 Schematically key concepts involved in disaster risk management and climate change adaptation, and the interaction of these with sustainable development.
SOURCE: O'Neill presentation, slide 2. Available: http://ipcc-wg2.gov/SREX/report/report-graphics/ch1-figures/ [February 2014].

independent variables. When estimated using national-level historical data, the STIRPAT model has shown that, on average, population is proportional to emissions, although this relationship varies across different sub-groups (for example, when population is grouped by income). Other demographic variables (such as age and urbanization) can also be statistically significant. Another approach to studying these relationships uses structural models that include causal relationships. For example, aging and urbanization in such models can lead to different levels of labor productivity and consumption behavior, which then lead to different levels of economic growth and production structure, which in turn influence emissions. Education can also influence emissions through its links to fertility (see Lutz's discussion of maternal education, Chapter 6) as well as to its links to consumption, labor productivity, and innovation capacity. However, O'Neill said he finds the innovation variable to be rather complex, and he did not include it in his analysis, although other models do consider innovation capacity and technological change.

O'Neill then discussed the integrated Population-Economy-Technology-Science (iPETS) model, a global economic model that allows for heterogeneity within regions (similar to models discussed by Edmonds). Within regions, iPETS simulates household decisions about consumption, industry decisions about production, overall land use, and market equilibrium—all factors that affect carbon emissions. The model is then given three country-specific population scenarios determined by the United Nations' high-, medium-, and low-population projections. The results show large population effects in carbon emissions (O'Neill et al., 2010). O'Neill stated that to limit emissions to a 2-degree Celsius shift, current emissions would need to be cut 80 percent by 2050, a reduction that is not plausible through demographic changes alone.

O'Neill also examined how education affects the Human Development Index (a metric also discussed by Lutz, above). He found a fairly substantial increase in the Human Development Index with increased education level.

O'Neill then showed data related to the spatial population distribution in the United States. Projections of the U.S. population distribution in the year 2100 show a more concentrated picture of population than at present, with more people living along the coasts. For instance, it is projected that Florida will double its coastal population by 2100 even though coastal populations are more vulnerable to climate change effects. (O'Neill noted that this was the NCAR projection; an International Institute for Applied Systems Analysis [IIASA] model showed little change, while an Environmental Protection Agency [EPA] model showed a nearly three-fold increase in coastal population.) O'Neill later clarified that these numbers did not include any projected changes to the location of the coastline itself due to rising sea levels. He said that the United States coastline is unlikely to change much by 2100, except under a high sea-level rise scenario. He noted that high sea-level rise is very likely to happen at some point and substantially affect the Florida coast, but the timing of that rise is very uncertain.

Turning to the data related to human exposure to heat, O'Neill noted the study looked at the number of days per person spent above 35 degrees Celsius. Increases in this heat exposure variable can be the result either of increased temperature or increased population in hot areas. Heat exposure days for the United States as a whole increased anywhere from 50–100 percent, depending upon the population projection used, with many regional effects. California, for instance, will experience many more heat exposure days in 2050, mostly attributable to the expected increase in population by that time.

O'Neill closed his presentation by summarizing his main point: The net effect of population growth is an increase in energy use and emissions. He argued that demographic characteristics such as urbanization and aging do matter, but their impact varies in different parts of the world. He said that education has a strong impact on well-being (i.e., the Human Development Index), although the impact on emissions is not terribly significant. He briefly mentioned that the spatial distribution of population can strongly affect a population's exposure to climate-related hazards, and development pathways have a strong influence on climate change risks. He noted he included some demographic interactions in his models, but other potentially important ones may still need to be included, such as the importance of women in the workforce, the details of urbanization, and lengthened time to retirement. It is important to include spatial variation in population densities as well as demographic characteristics (such as age, income, and education) that vary spatially, in seeking to explain population correlates of climate change and vulnerability. Finally, he suggested, it would be important to identify the most important determinants of vulnerability, because currently the relative importance of a population's characteristics (such as income, education, spatial distribution, levels of inequality, and more) in responding to specific hazards is still unknown.

DISCUSSION

A participant postulated that the danger that climate change poses to human well-being is not well understood by the public. Public statements made by some people that climate change will cause millions of deaths are contradicted by other people who say climate change will cause no deaths. It becomes difficult for the public to understand the magnitude of this problem. O'Neill pointed out that the importance of climate change should not be calibrated from public statements of just anyone. He acknowledged that the science of climate change has not been communicated effectively enough, although he said the IPCC data contain the most reasonable assessment of current status and future projections. He pointed out that the risk of climate change is highest for unique and threatened systems such as fragile ecosystems and species, some Arctic cultures, and small island states. These are likely to be severely impacted even by a 2-degree increase in temperature. However, there are not likely to be large-scale health consequences or disasters in a 2-degree change, except in a truly extreme scenario.

A participant then asked about the patterns of changing BMI, asking why some of the developing world is following the U.S. pattern, while other countries are not. Berkman responded that many countries (notably India) have neglected those with the lowest socioeconomic status in favor of supporting the rising middle class. This is a country-level policy issue, and she suggested national policy is likely the reason for different patterns.

Another participant asked for clarification on urbanization and its relationship to emissions. O'Neill explained that urbanization leads to an increase in labor productivity. While consumption patterns change and geographic location changes, the urbanization impact on emissions is dominated by labor productivity increases.

The difference between the tail and the bottom of a population distribution was questioned. Berkman suggested a concentration on high-risk populations (the bottom one-third of the socioeconomic status) rather than thinking about how to reduce inequality. She said it is likely more advantageous to change the shape of the distribution rather than move the distribution as a whole.

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Appendix A

Workshop Agenda

Monday, September 30, 2013

8:30 a.m. Welcome
BECS Board Director

8:35 **Introduction to the Workshop**
William Rouse (Session Chair)

8:45 Earth as a System
William Rouse

9:30 Understanding population in human-environment relationships: Science shaped by world-views or evidence?
B.L. Turner II

10:15 Discussion

11:00 **Challenges to the Earth System: Character and Magnitude of the Challenges in 2050**
W.G. Ernst (Session Chair)

11:05 Demographic trends and their consequences
John Bongaarts

11:35 Demographic and economic drivers of consumption and environmental change abstract
Andrew Jorgenson and Juliet Schor

12:05 p.m. Urbanization in the 21st century: Challenges and opportunities for environmental sustainability
Peter Marcotullio and Karen Seto

12:35 Discussion

2:00 **Challenges to the Earth System: Consequences to the Earth System**
Henry Harpending (Session Chair)

2:05 Biodiversity and ecosystem services in a world of 10 billion
Steve Polasky

2:35 Future demand and supply pressures on water: Implications for agriculture and other sectors
Siwa Msangi

3:05 Energy, land, and water on a 10 billion person planet: An integrated perspective
James A. (Jae) Edmonds

3:35 Discussion

5:00 **Special Presentation**
X-Events and human progress (or, why the trend is not your friend)
John Casti

Tuesday, October 1, 2013

8:30 a.m. **Equitable Resource Distribution**
B.L. Turner II (Session Chair)

8:35 Global income inequality: Historical trends and policy implications for the future
Branko Milanović

9:05	Population, internal inequality and conspicuous consumption in Africa: Trends and implications for sustainability Parfait Eloundou-Enyegue
9:35	Intergenerational tradeoffs, demographic metabolism, and the long term benefits of equitable empowerment in the near term Wolfgang Lutz
10:35	Discussion
11:00	**Interaction Between Earth and Societal Systems** Terry Chapin (Session Chair)
11:05	The distribution of population health and consumption risk in low, middle and high income countries: The Rose paradigm revisited Lisa Berkman
11:35	Demography and climate change: Current understanding, future directions Brian O'Neill
12:05 p.m.	Discussion
1:45	Plenary discussion
3:15	Workshop adjourns

Appendix B

Workshop Participants

Lisa Berkman, Harvard University
Peter Blair, National Research Council
John Bongaarts, Population Council
John Casti, X-Center and CCSE
F. Stuart Chapin, University of Alaska, Fairbanks
Tom Clarke, Cabell Brand Center & Kissito, Inc.
James E. Edmonds, Joint Global Change Research Institute
Parfait Eloundou-Enyegue, Cornell University
W.G. Ernst, Stanford University
Mary-Elizabeth Gifford, Wellness Warrior
Megan Haidet, Seeds of Success
Robert Hauser, National Research Council
Richard Johnson, Global Helix LLC
Andrew Jorgenson, University of Utah
Eugenia Kalnay, University of Maryland
Mary Ann Kasper, National Research Council
Bill Kelly, American Society for Engineering Education
Kevin Kinsella, National Research Council
Meredith Lane, National Research Council
Ellyn Lester, New School of Architecture and Design
William Lutz, Oxford Institute of Population Ageing / IIASA
Peter Marcotullio, Hunter College, City University of New York
Rose Marie Martinez, Institute of Medicine
Sowtrik Mazumder, Praxair India Private Limited

Branko Milanović, World Bank
Fernando Miralles-Wilhelm, University of Maryland
Safa Motesharrei, University of Maryland
Siwa Msangi, International Food Policy Research Institute
Mary Ellen O'Connell, National Research Council
Brian O'Neill, University Corporation for Atmospheric Research
Maria Oria, Institute of Medicine
Stephen Polasky, University of Minnesota
Proctor Reid, National Academy of Engineering
William Rouse, Stevens Institute of Technology
B. L. Turner II, Arizona State University
Elda Varela, Southeast Climate Science Center
Hassan Virji, START: System for Analysis, Research, and Training
Wenying Wu, AATA International Inc.
You Wu, Earth System Science & Interdisciplinary Center
Victor Yakovenko, University of Maryland

NOTE: The federal government entered a shutdown on October 1, which prevented 22 federal employees who had planned to attend from participating in the workshop.

Appendix C

Acronyms

BMI	body mass index
EPA	U.S. Environmental Protection Agency
FAO	Food and Agriculture Organization of the United Nations
GCAM	Global Change Assessment Model
GDP	gross domestic product
HANPP	Human Appropriation of Net Primary Productivity
IDA	International Development Association
IIASA	International Institute for Applied Systems Analysis
IPAT	impact, population, affluence, and technology model
IPCC	Intergovernmental Panel on Climate Change
iPETS	integrated Population-Economy-Technology-Science Model
NCAR	National Center for Atmospheric Research
NRC	National Research Council
PIES	Population-Inequality-Environmental and Economic Sustainability Model

RCP	representative concentration pathway
SRES	Special Report Emissions Scenarios
SSP	shared socioeconomic pathway
STIRPAT	Stochastic Impacts by Regression on Population, Affluence, and Technology Model

Appendix D

Biographical Sketches of Workshop Presenters

Lisa Berkman is Thomas D. Cabot professor of public policy and of epidemiology and director of the Harvard Center for Population and Development Studies. Prior to becoming director, she was chair of the Department of Society, Human Development and Health at the Harvard School of Public Health from 1995–2008. She is also the former head of the Division of Chronic Disease Epidemiology at Yale University. She is a member of the Conseil Scientifique de l'Institut de Recherche en Sante Publique (IReSP) in France and of the Institute of Medicine. She has a Ph.D. in epidemiology from the University of California, Berkeley.

John Bongaarts is a Population Council vice president and distinguished scholar, where he has worked since 1973. He serves as chairman of the National Research Council Panel on Population Projections. He is a member of the Royal Dutch Academy of Sciences and the U.S. National Academy of Sciences and a fellow of the American Association for the Advancement of Science. He has a Ph.D. in physiology and biomedical engineering from the University of Illinois.

John L. Casti is a research scholar at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria, where he heads an initiative for the study of Extreme Events in Human Society. He has worked at the RAND Corporation in Santa Monica, CA, and served on the faculties of the University of Arizona, New York University, and Princeton University. In 2000, he formed two companies devoted to the employment of tools and concepts from modern system theory for the solution of problems in business and finance. He received his Ph.D. in mathematics at the University of Southern California in 1970.

James E. (Jae) Edmonds is a chief scientist and Battelle Laboratory Fellow at the Pacific Northwest National Laboratory's Joint Global Change Research Institute and adjunct professor of public policy at the University of Maryland, College Park. He is the principal investigator for the Global Energy Technology Strategy Program to Address Climate Change. He has served in the capacity of lead author on every major Intergovernmental Panel on Climate Change (IPCC) assessment to date and presently serves on the IPCC Steering Committee on New Integrated Scenarios. He received his Ph.D. in economics from Duke University.

Parfait Eloundou-Enyegue is an associate professor in the Department of Development Sociology in the College of Agriculture and Life Sciences at Cornell University. His research areas include the sociology of education, social change, and the demography of inequality, with a major focus on refining existing frameworks for estimation of the effects of demographic change on the formation of human capital. He is a member of the International Advisory Board for the World Family Map Project, a member of the board of trustees of the U.S. Population Reference Bureau, and a panel chair for the International Union for the Scientific Study of Population. His Ph.D. is from Pennsylvania State University.

Andrew Jorgenson serves as the director of graduate studies of the Sociology Department at the University of Utah. He is also a member of the American Sociological Association's Task Force on Sociology and Global Climate Change and affiliated with the Scholars Strategy Network. His Ph.D. is from the University of California, Riverside.

Wolfgang Lutz is leader of the World Population Program of the International Institute for Applied Systems Analysis, director of the Vienna Institute of Demography of the Austrian Academy of Sciences, professor of applied statistics at the WU-Vienna, and professorial research fellow at the Oxford Institute of Ageing. He is coprincipal investigator of the Asian MetaCentre for Population and Sustainable Development and is a member of the National Academy of Sciences Committee on Population. He holds a Ph.D. in demography from the University of Pennsylvania and a second doctorate (Habilitation) in statistics from the University of Vienna.

Peter Marcotullio is associate professor in the Department of Geography, Hunter College, City University of New York (CUNY). He is also codirector of the Environmental Studies Program at Hunter College and the codeputy director of the CUNY Institute for Sustainable Cities. From 2001–2005, he participated in the Millennium Ecosystem Assessment as the co-coordinating lead author of the urban systems chapter. He is program associate with the International Human Dimensions Program's Urbanization and Global Environmental Change project and council member of the International Council on Ecopolis Development. He holds a Ph.D. in urban planning from Columbia University.

Branko Milanović is a lead economist in the World Bank's research department. Previously, he was a World Bank country economist for Poland and a research fellow at the Institute of Economic Sciences in Belgrade. Since 1996, he has also served as a visiting professor at the Johns Hopkins University's School for Advanced International Studies. He was a senior associate on a 2-year assignment with the Carnegie Endowment for International Peace's Global Policy Program, and he remained an adjunct scholar with the Endowment until early 2010. He received his Ph.D. in economics from Belgrade University.

Siwa Msangi is senior research fellow within the Environment and Production Technology Division and leads the International Food Policy Research Institute (IFPRI) research theme on Global Food and Natural Resources. He manages a research portfolio that includes the economic and environmental dimensions of sustainable intensification of agriculture, aquaculture and livestock, biofuels and the bioeconomy, climate change impacts on agriculture, and climate adaptation, as well as resource management of surface and groundwater. His Ph.D. is from the University of California, Davis.

Brian O'Neill leads the Integrated Assessment Modeling group within the Climate Change Research section at the National Center for Atmospheric Research. He worked previously at the Environmental Defense Fund and on the faculty of the Watson Institute for International Studies at Brown University. In addition, he founded and led from 2005–2009 the Population and Climate Change Program of the International Institute for Applied Systems Analysis. His Ph.D. is from New York University in earth systems science.

Stephen Polasky holds the Fesler-Lampert chair in ecological/environmental economics at the University of Minnesota. 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). 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 of the American Association for the Advancement of Science in 2007. He received a Ph.D. in economics from the University of Michigan.

William B. Rouse is a researcher, educator, author, and entrepreneur. His current positions include Alexander Crombie Humphreys chair in economics of engineering in the School of Systems and Enterprises at Stevens Institute of Technology, professor emeritus in the School of Industrial and Systems Engineering at Georgia Institute of Technology, and principal of Rouse Associates, LLC. His earlier positions include executive director of the Tennenbaum Institute and chair of the School of Industrial and Systems Engineering at Georgia Tech, CEO of two software companies, and earlier faculty positions at Georgia Tech, University of Illinois, Delft University of Technology, and Tufts University. He is a member of the U.S. National Academy of Sciences and the U.S. National Academy of Engineering. He received his Ph.D. from the Massachusetts Institute of Technology.

Juliet Schor is professor of sociology at Boston College. Before joining Boston College, she taught at Harvard University for 17 years, in the Department of Economics and the Committee on Degrees in Women's Studies. Schor is a cofounder of the Center for a New American Dream, a national sustainability organization; of the South End Press; and of the Center for Popular Economics. She received her Ph.D. in economics from the University of Massachusetts.

Karen Seto is co-chair of the Urbanization and Global Environmental Change Project of the International Human Dimensions Programme on Global Environmental Change, and a coordinating lead author for Working Group III of the Intergovernmental Panel on Climate Change Fifth Assessment Report. She also serves on several National Research Council committees, as well as the U.S. Carbon Cycle Science Steering Group. From 2002-2008, she was the Global Thematic Leader for Ecosystem Management Tools for the Commission on Ecosystem Management of the International Union for Conservation of Nature. Her Ph.D. in geography was earned at Boston University.

Billie Lee Turner II is the Gilbert F. White professor of environment and society in the School of Geographical Sciences and Urban Planning at Arizona State University and a research professor in the Graduate School of Geography at Clark University. He is engaged in the study of human-environment relationships through an examination of the use of land and resources by the ancient Maya civilization in the Yucatan peninsular region; the intensification of land use among contemporary smallholders in the tropics; and land use and land-cover change as part of global environmental change. He is a member of the U.S. National Academy of Sciences. He earned his Ph.D. in geography from the University of Wisconsin–Madison.