Role of economics in analyzing the environment and sustainable development

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The environmental sciences have documented large and worrisome changes in earth systems, from climate change and loss of biodiversity, to changes in hydrological and nutrient cycles and depletion of natural resources (1–12). These global environmental changes have potentially large negative consequences for future human well-being, and raise questions about whether global civilization is on a sustainable path or is "consuming too much" by depleting vital natural capital (13). The increased scale of economic activity and the consequent increasing impacts on a finite Earth arises from both major demographic changes—including population growth, shifts in age structure, urbanization, and spatial redistributions through migration (14–18)—and rising per capita income and shifts in consumption patterns, such as increases in meat consumption with rising income (19, 20).

At the same time, many people are consuming too little. In 2015, ~10% of the world's population (736 million) lived in extreme poverty with incomes of less than $1.90 per day (21). In 2017, 821 million people were malnourished, an increase in the number reported malnourished compared with 2016 (22). There is an urgent need for further economic development to lift people out of poverty. In addition, rising inequality resulting in increasing polarization of society is itself a threat to achieving sustainable development. Eliminating poverty (goal 1) and hunger (goal 2), achieving gender equality (goal 6), and reducing inequality (goal 10) feature prominently in the United Nation's Sustainable Development Goals (23). A recent special issue in PNAS on natural capital framed the challenge of sustainable development as one of developing "economic, social, and governance systems capable of ending poverty and achieving sustainable levels of population and consumption while securing the life-support systems underpinning current and future human well-being" (24).

The discipline of economics arguably should play a central role in meeting the sustainable development challenge. The core question at the heart of sustainable development is how to allocate the finite resources of the planet to meet "the needs of the present, without compromising the ability of future generations to meet their own needs" (25). A central focus of economics is how to allocate scarce resources to meet desired goals; indeed, a standard definition of economics is the study of allocation under scarcity. More specifically, economics studies the production, distribution, and consumption of goods and services, which are both a key driver of development (increasing standards of living through providing food, housing, and other basic human requirements) and a main cause of current changes in earth systems. Economics, combined with earth system sciences, is crucial for understanding both positive and negative impacts of alternatives and the trade-offs involved. Economics, combined with other social and behavioral sciences, is crucial for understanding how it might be possible to shift human behavior toward achieving sustainable development. Economics has well-developed fields in development economics, ecological economics, environmental economics, and natural resource economics, with large bodies of research relevant to the sustainable development challenge. The application of economic principles and empirical findings should be a central component in the quest to meet the aspirations of humanity for a good life given the finite resources of the earth.

Indeed, an extensive body of work by economists provides key insights into aspects of sustainable development. At its best, this work integrates work by

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other natural and social sciences into a policy-relevant framework and demonstrates the rich potential for collaborations among economists, natural scientists, and other social scientists on sustainable development challenges. For example, economists have developed integrated economic and climate models to address important climate change policy questions, such as how much and how fast greenhouse gas emissions should be reduced (26–31). In 2018, William Nordhaus shared the Nobel Prize in economics, in large part for his seminal work on such models. These models have sparked large debates within economics over fundamental issues such as the proper discount rate (32–35), and with the natural sciences over the likely scale of damages from climate change (36, 37). Another Nobel Prize winner in economics, Elinor Ostrom, used economic models to highlight the importance of governance and institutions for sustainable use of common property resources (38–40). Another important area of work by economists directly relevant to sustainable development defines and measures inclusive wealth (13, 41–49). Ken Arrow, yet another Nobel Prize winner in economics, was a leader in this field. It is also notable that the intellectual roots of inclusive wealth trace to work in the 1970s of two Nobel Prize winners in economics, William Nordhaus and James Tobin (50). Inclusive wealth is a measure of the aggregate wealth of society, including the value of natural capital along with the values of human capital, manufactured capital, and social capital. Inclusive wealth is a sufficient statistic for showing whether or not global society is on a sustainable trajectory. For the past two decades, the Beijer Institute of Ecological Economics, part of the Royal Swedish Academy of Sciences, has held annual meetings bringing together leading economists and ecologists to discuss issues at the intersection of ecology and economics, which have resulted in a number of high-impact papers (51). The idea for a forum to highlight work in economics on environment and sustainable development originated at one of these meetings.

Despite these examples and many others, the center of gravity in the analysis of sustainable development remains in the natural sciences, and the center of gravity in economics remains far removed from the challenge of sustainable development. The natural sciences that form the core of earth systems science, including ecology, geology, climatology, hydrology, and oceanography, are a logical place to start to build understanding of the current state and the evolution of earth systems. Natural scientists have taken the lead in prominent analyses of pathways to achieve sustainable development. For example, Pacala and Socolow (52) outline feasible methods using existing technology to reduce greenhouse gas emissions to secure a livable climate. Foley et al. (53) analyze how to meet growing food demand without expanding the footprint of agriculture. Costello et al. (54) suggest how extensive fishery reform could result in improved productivity and ecosystem health. Tallis et al. (55) analyze how to improve material standard of living for a growing population in ways that simultaneously sustain biodiversity, reduce greenhouse gas emissions, and reduce water use and air pollution. These works show that it is feasible to achieve multiple sustainable development goals with existing technology. The harder challenge is combining what is feasible in a biophysical sense with the difficult economic, political, and social hurdles that prevent society from getting to sustainable outcomes (55). In other words, natural science understanding is necessary but not sufficient to achieve sustainable development.

While natural science understanding is insufficient on its own to achieve sustainable development, the same is true of economics. Economists alone do not have the knowledge base supplied by the natural sciences necessary to understand the complex ecological systems within which the economic system operates and on which economic activity causes impacts. Progress in sustainable development requires collaboration between social scientists, including economists and natural scientists. Of course, achieving sustainable development requires institutions and political alignment that go well beyond assembling the science knowledge arising from integrated scientific knowledge.

Numerous examples show the incomplete nature of collaboration between economists and other disciplines engaged in the analysis of sustainable development. To take one recent example, there were no economists involved in a special section on "Ecosystem Earth" published in *Science* in April 2017 that contained discussions of population, consumption, agricultural production, land use, human behavior, collective action, and policy (56). The lack of involvement by economists in ongoing discussions of sustainable development leads to gaps in understanding production and consumption decisions, the resulting market outcomes that drive global environmental change, and how to regulate or reduce negative environmental impacts from economic activities.

The incomplete engagement of economists mirrors the structure of the economics discipline. The fields of ecological, environmental, and resource economics are not core fields within economics. There are few ecological, environmental, or resource economics publications in flagship journals within economics. For example, in 2018 only two papers published in the *American Economic Review* listed classification codes for renewable resources and conservation, nonrenewable resources and conservation, energy economics, or environmental economics (57, 58). Only a small minority of the top economics departments have fields in ecological, environmental, or resource economics. In contrast, virtually every top economics program offers fields in labor economics, industrial organization, and international trade. Ecological, environmental, and resource economics programs often are in schools of the environment or natural resources, schools of public policy, or in departments of agricultural economics. In addition, economics is notable among academic disciplines for its relative isolation: "Though all disciplines are in some way insular. . .this trait peculiarly characterizes economics" (59). Compared with other social scientists, economists have far lower citation rates for work in other disciplines. Jacobs (60) found that the percentage of within-field citations in economics was 81%, versus 59% for political science, 53% for anthropology, and 52% for sociology. In addition, the core of the economics discipline is relatively isolated from the natural sciences that have played a large role in sustainability science to date, ecology, geology, climatology, hydrology, and marine biology. Network maps of disciplines using citations patterns often show economics and fields, such as ecology and geosciences, at opposite ends of the spectrum (figure 3 in ref. 61).

Given the large role of economic activity in causing rapid change in earth systems, and the scale of the sustainable development challenge, there is an urgent need for more rapid integration of economics into the core of sustainable development, and for more rapid integration of sustainable development into the core of economics.

Sackler Colloquium on "Economics, Environment, and Sustainable Development"

This special issue contains a collection of articles presented at the Sackler Colloquium on "Economics, Environment, and Sustainable Development" held at the Beckman Center in Irvine, California in January 2018. The colloquium focused on 21st century challenges requiring advances in fundamental economics at the nexus of global environmental change and sustainable development. The main purpose of the colloquium was to highlight work by talented economists working in ecological, environmental, or resource economics on sustainable development challenges. Part of the motivation for the colloquium, and the publication of this collection of articles, is to convince economists that sustainable development challenges are vitally important to global society and pose intellectual challenges that are the equal of any subject currently analyzed by economists.

The symposium had four major themes: (*i*) ecosystem services and natural capital; (*ii*) behavioral economics, policy, and institutional design for sustainable development; (*iii*) economic development and sustainability; and (*iv*) issues in empirical economics relevant for sustainable development. Papers in this special issue address at least one, and in many cases several of these themes.

Ecosystem Services and Natural Capital. Ecosystem services are the contributions that nature makes to human well-being. Ecosystem services include regulating services (e.g., filtering pollution, coastal protection, pest regulation, pollination), material provisioning services (e.g., food, energy, materials), and nonmaterial services (e.g., aesthetics, experience, learning, physical and mental health, recreation). Various types of natural capital—often in conjunction with other forms of capital—and human labor provide ecosystem services. Destroying or degrading natural capital can result in reduced flow of ecosystem services, with consequent negative impacts on human well-being.

Research by economists, in conjunction with ecologists and other natural scientists, is essential for going beyond merely listing the types of ecosystem services and natural capital, to understanding the value of the flow of services or the stock in capital in terms of their contribution to human well-being. Integrated economic–ecological modeling can generate understanding of the trade-offs resulting from actions that alter ecosystems, and show how changes in ecosystems result in changes in the value of the flow of ecosystem services and the stock of natural capital. Examples of integrated work examining the value of ecosystem services and trade-offs exists at the national level (e.g., refs. 62 and 63) and local to regional levels (e.g., refs. 64 and 65), but much work remains to be done. Some of the pressing issues and questions that would benefit from greater involvement of economists are discussed below.

Measuring the value of ecosystem services. What are the best ways to apply market and nonmarket valuation methods to translate biophysical indicators into a common monetary metric measuring the welfare contribution of ecosystem services? One promising avenue to valuation links environment to health (66, 67). Difficult issues include integrating natural science and economic models to understand how changes in ecosystems lead to changes in the flows of ecosystem services (68, 69) and how to measure the value of nonmaterial ecosystem services, such as aesthetics, experience, learning, and mental health (70). Even where benefits measures exist, such as for improving water quality, it is not clear that all relevant benefits are accurately measured (71). Furthermore, it is often important to understand who benefits from ecosystem services and the distribution of benefits and costs of potential management and policy options.

Measuring the value of natural capital. Valuing natural capital involves making predictions about the future flows and values of ecosystem services (69). As baseball great Yogi Berra once said, "It's tough to make predictions, especially about the future." Recent efforts to estimate the social cost of carbon aptly illustrate the difficulties of valuing natural capital and ecosystem services. Estimating the social cost of carbon involves predicting future impacts, requiring integrated natural science and economic modeling, and understanding potentially catastrophic events (72). Constructing an estimate of the social cost of carbon also involves valuing nonmarket benefits, and classic economic problems, such as choosing an appropriate discount rate and degree of risk aversion (e.g., refs. 73 and 74). Economic analysis can increase knowledge of how various forms of capital, including natural capital along with human and manufactured capital, combine to produce goods and services of value to people (13, 44). To what degree can other types of capital substitute for natural capital, and what kinds of natural capital are irreplaceable?

Incorporating dynamics and uncertainty. Making predictions about earth systems is more difficult with the potential for tipping points involving large and sudden shifts (75). How can economic models incorporate notions of tipping points and the value of resilience and what data are needed to support empirical applications of such models (72, 76)? An additional issue arises with the combination of uncertainty and potential irreversible outcomes (e.g., species extinction) that gives rise to option value (77, 78). Issues are made more complex by the fact that most environmental–economic problems are characterized by ambiguity rather than risk, meaning that the familiar expected utility paradigm may not be applicable.

Behavioral Economics, Policy, and Institutional Design for Sustainable Development. Achieving sustainable development will require changes in human behavior and actions in relationship to the environment. Many important environmental and resources issues have elements of the "tragedy of the commons" where individuals following their own self-interest results in highly inefficient outcomes because individuals ignore external costs (or benefits) of their actions on others. Both standard and behavioral economics have much to offer in understanding what motivates individual and group behavior, how to structure incentives to shift behavior in desirable directions, and how to design policies and institutions to achieve desirable societal outcomes (79–81).

Some of the pressing issues and questions that would benefit from greater involvement of economists are discussed below.

Behavioral economics and individual choices involving environmental outcomes. What does behavioral economics teach us about trying to change behavior to overcome the tragedy of the commons, provide public goods, or internalize externalities? Are appeals to being good environmental stewards, information about performance relative to peers (e.g., energy or resource use relative to similar households), financial incentives, laws, and regulations more effective in promoting more proenvironmental behavior (82)? Do financial incentives crowd out nonfinancial motivations for protecting the environment or strengthen intrinsic motivation (82, 83)?

Social interactions and group behavior involving environmental outcomes. Humans are a social species. Economics has long studied individual behavior in isolation but there is ample evidence from social science that social interactions influence individual choices. How group interaction affects choices and environmental outcome, including cooperation to overcome the "tragedy of the commons," is a rich area of investigation (82, 84, 85).

Risk, uncertainty, and long-term consequences. How do people process risk, uncertainty, and ambiguity and what lessons does this hold for environmental issues that are inherently complex, with outcomes that are difficult to assign probabilities (76)? Are people myopic, and even if they are, can they be motivated to undertake current sacrifices to provide future generations with benefits?

Design of environmental policy and institutions. Environmental issues span the gamut from quite local (e.g., communal use of a fishery, forest, or grazing lands) to global (e.g., climate change and ozone depletion) and involve complex feedbacks between social and ecological systems (86). Well-designed institutions can create incentives that drive performance toward desirable outcomes, or if ill designed can lead to poor outcomes (87). How can we design effective international environmental agreements for global environmental issues in a world of nation states? How can we effectively provide public goods and internalize externalities where governments are absent, weak, corrupt, or inefficient? When do payments for ecosystem services (88) or contributions to environmental groups (89) deliver desirable outcomes? What does the evidence from behavioral economics teach us about proper design of environmental policy and institutional design?

Economic Development and Sustainability. Sustainable development is not just about sustainability in the sense of how to maintain the environment. Sustainable development is about how to simultaneously alleviate poverty/improve material standards of living and maintain or enhance vital natural capital necessary for future well-being. Much of the work in environmental sciences focuses on environmental sustainability while much of development economics focuses on alleviating poverty. Making progress on sustainable development requires integration of research in development and environment.

Some of the pressing issues and questions that would benefit from greater involvement of economists are discussed below.

Integrating development and environment. What is the relationship between poverty alleviation and the environment? Are there win–win outcomes that reduce poverty and improve environmental quality (e.g., ref. 54) or are there inevitable trade-offs? Are payments for ecosystem services a promising approach for promoting environmental outcomes in developing countries (88)? Is the main effect of economic development to impose more stress on the environment through increased resource use and pollution from a greater scale of production and consumption, or are leap-frogging options available that will result in cobenefits vs. trade-offs? Will increased stress lead to crossing tipping points and catastrophic future outcomes, and how should society manage in the face of such prospects (72, 76)? Alternatively, does greater technological improvement and investment in pollution control, along with lower population growth that occurs at higher income levels outweigh the scale effect? What is the key role of protected areas in safeguarding biodiversity and potential adaptation to climate change vs. conversion of habitats to direct human uses? What different financing models might be developed to facilitate transitioning from unsustainable uses of natural resources to sustainable uses of those resources (e.g., fisheries), where the biggest financial impediment is making the transition, not sustaining the reformed fisheries?

Measures of sustainable development. Economists have developed measures of inclusive wealth that attempt to measure the value of all assets, including natural capital, human capital, and manufactured capital (13, 41–49). A difficult problem with empirical measures of inclusive wealth is correctly valuing natural capital for which there is no market value (see the above challenge on valuing ecosystem services and natural capital). At present, attempts of measure inclusive wealth include only a fraction of natural capital, typically only including natural capital values associated with natural resource commodities and carbon. Can we estimate comprehensive measures of inclusive wealth that include even difficult-to-value forms of natural capital?

Equity issues. Aggregate measures like inclusive wealth often hide distributional issues of who benefits and who does not from additional economic growth. Are there ways to represent distributional issues in a fair manner in aggregate economic measures like inclusive wealth or gross domestic product? Alternatively, is it better to disaggregate benefits and costs by group, and focus special attention on the poorest groups in society? If the world benefits from protecting habitat types in developing countries (e.g., tropical rain forests), what approaches would enable developing countries to protect these global public goods?

The role of innovation. Since the start of the Industrial Revolution, innovation and technology have fueled economic growth and rising material standards of living. However, because there is no price for most ecosystem services and natural capital, innovation incentives skew against maintaining or enhancing natural capital and the ecosystem services they provide. To promote proenvironment innovation, is it necessary to price ecosystem services and natural capital or, alternatively, is it better to provide direct incentives for innovation to enhance natural capital and ecosystem services?

Issues in Empirical Analysis. The past two decades have seen a major shift in empirical methods used by economists, with increased emphasis on research design using random assignment and quasi-experiments to better capture causal relationships (90). Although the "credibility revolution" was somewhat slower to take hold in environmental and resource economics than in some other fields, such as labor economics, recent years have seen an increased application of randomized control trials and quasi-experiments, particularly in applications involving individual or household decisions around use of land use, water, resources, and energy. In addition, the increasing availability of large, spatially detailed datasets along with increased computational power has opened the door to many new opportunities for rigorous investigation (91). Machine learning and other computationally rich approaches hold significant potential.

Some of the potential areas for innovation at would benefit from greater involvement of economists are discussed below.

Application of randomized control trials and quasi-experiments. Economists use randomized control trials and quasi-experiments to analyze individual or household decisions (92). A challenge is using such approaches to study larger-scale issues in sustainable development at regional, national, or international scales (86). There is a need for wider application of rigorous empirical methods for large-scale sustainable development issues.

Reduced form data intensive analyses. Use of large datasets with observations that vary across space and time offers an alternative approach to providing credible evidence on the impact of environmental policies when randomized control trials are either impossible or prohibitively expensive. The increase in geographically delineated data through time makes this approach applicable to a wider range of applications (66, 67, 93–95).

Integrated assessment models. The use of integrated assessment models has become well accepted in the context of greenhouse gas emissions and, increasingly, air-quality fate and transport (96), but needs exist for extensive application of these methods in other areas including water quality, water quantity, habitat, and so forth (97). Incorporation of both the drivers of change that can be impacted by policy so that costs of policy change can be included (63, 98), as well as downstream impacts, are also needed.

Scenarios and future trends. Global assessments of environmental status and trends conducted by such entities as the Intergovernmental Panel on Climate Change, the Millennium Ecosystem Assessment, and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services make use of scenarios to describe future trajectories. These scenarios are often based on expert opinion and do not have estimates about the likelihood that such a trajectory will occur. Can economists apply econometric tools and integrate economic data and principles with natural science to provide a more rigorous grounding on which to base future projections?

Summary

The challenge of achieving sustainable development is large and pressing. Major on-going changes in earth systems could cause potentially large negative consequences for human well-being. How to reduce poverty and address rising inequality in the face of these environmental changes raise important social and economic aspects of sustainable development in addition to the environmental dimensions. Strong arguments exist for devoting greater efforts to increase our understanding of the environmental, social, and economic dimensions of sustainable development, which will require greater integration of economics, social sciences more generally, and the natural sciences. Here, we focused on economics, but similar issues arise in other social and behavioral science disciplines. There is an urgent need for more rapid integration of social and behavioral disciplines into the core of sustainable development, and for more rapid integration of sustainable development into the core of these disciplines.

The papers in this special issue collectively represent a cross-section of work illustrating progress by economists on important issues in environment and sustainable development. These papers tackle many of the themes and challenges discussed in sustainable development and provide positive examples of the type of work needed to address sustainable development challenges. By providing a spotlight on the research frontiers, at least as they appear currently in economics, we hope to change the ecology of the economics profession in ways that stimulate further research and the involvement of economists in integrated research relevant to environmental and sustainable development challenges.

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