The Economics of Sustainable Development

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The desire for economic growth, coupled with growing concern about the environmental impact of development, has led to the concept of "sustainable development." This term may seem paradoxical because "development" implies change, while "sustainability" implies permanence. However, the term is actually consistent with economic thinking; namely, it implies the selection of polices that maximize objectives subject to constraints.

Much has been written on the concept of sustainable development and its many implications, including work by Batty (2001), Lele (1991), and Redclift (2005). For example, Batty (2001) suggests that sustainable development and the movements associated with it present a challenge and an opportunity to agricultural and resource economists, and along this line, several economists (Pezzy 1992; Solow 1974; and Stavins 1990) have developed economic models that incorporate sustainability. This paper will present a research agenda and conceptual foundation that are consistent with the notion of sustainable development, namely the challenge of achieving economic growth given ecological constraints, and it will introduce some of the policy paradigms it implies. It will also argue that economic research on sustainable development requires the incorporation of biophysical relationships into economic models as well as multidisciplinary interaction, and that the pursuit of sustainable development will lead to the expansion of a bioeconomy that will be part of a larger transition from nonrenewable to renewable resource dependence. The first section will present models of sustainable economic development processes as an economic optimization problem. The second section will discuss some of the technological factors that affect sustainable development. Next will be a discussion on how renewable resource and sustainable development are interconnected, with an emphasis on the special role of the bioeconomy. This section will be followed with a discussion on some of the policy challenges of sustainable development. Finally, the paper will address some of the implications for applied economics.

Modeling Sustainable Development: The Objective Function

A formal definition of the notion of sustainable development was introduced in "Our Common Future" (also known as the Brundtland Commission [1987]): "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Economists have subsequently modeled this using an economic growth model with intergenerational equity constraints (Pezzy 1992; Solow 1974; and Stavins 1990). However, most of the literature on sustainability, which arose from concern about limits to growth, intergenerational equity, and uncertainty, led to the introduction of policy prescriptions that require detailed analysis at both the macro- and micro-levels. This section will discuss how sustainability considerations can be addressed when modeling the objective functions of economic optimization problems, and later how they can be incorporated in modeling production functions and stocks in the economy.

A standard approach to modeling sustainable development at the macro-level is to expand previous models of economic growth to include intergenerational equity

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constraints. In particular, the model determines levels of production, consumption, and investment patterns that maximize the net present value of discounted per capita utility subject to the standard dynamics of capital goods, with an additional constraint which assumes that consumption does not decline across generations. Once optimal choices are determined, different assumptions about the behavior of producers and consumers are used, implementing governmental policies that include restrictions on production or consumption, either directly or through financial incentives.

An alternative method to addressing sustainability is to incorporate the theory of justice approach presented by Rawls (1999), and to pursue policies that maximize the lowest utility available to any generation. The maxi-min framework developed by Solow (1974) is a good starting point for this approach, as it accommodates the challenge of managing renewable and nonrenewable resources.

The maxi-min approach is novel, but thus far has limited political appeal and its application is difficult. One reason for this is because of uncertainty regarding the future, which reflects both the lack of knowledge and randomness. Since uncertainty is a major problem, one approach to dealing with it is to expand the standard model and maximize the net present value of expected utility subject to the equation of motion of capital stocks, and to constrain expected utility so that it is nondecreasing over time. However, findings by behavioral economists such as Tversky and Kahneman (1981) suggest an asymmetry of attitude towards wins and losses, as well as the existence of loss aversion. One practical solution is to incorporate probabilistic constraints on outcomes in a way that expands traditional safety rules (Lichtenberg and Zilberman 1988). For example, the safety fixed approach suggests that in each period, the net present value of discounted average utility is maximized subject to the constraint that expected utility would not decline over time; the approach also suggests that the probability of average utility in every period is below an undesirable level is constrained to below 1% or 5%. Probabilistic constraints can be linked to the notion of resilience emphasized by natural scientists such as Holling (1973) and Chavas (1993). Resilience is the capacity of an ecosystem to respond to changes that may lead to the extinction of a species. Thus, resilience implies restrictions on key stocks that represent natural capital, but since these stocks are directly related to human well-being, there is a direct link between constraints on these stocks and utility.

Technology

The pursuit of sustainable development has a larger impact on the modeling of production relationships and capital goods in objective functions. Modeling production relationships should account for some basic notions that are available from the sciences and actual practices. In particular, several concepts have become very useful in modeling production systems, especially in agriculture and natural resources.

1. The importance of discrete technology choice: Classical literature on production assumes that well-behaved production functions and input choices are choices regarding levels of continuous variables (e.g., how much fertilizer should be used). However, much of the debate associated with sustainable development revolves around the adoption of various categories of technologies that represent a discrete choice. These categories include green revolution technologies, pesticides, solar energy, biotechnology and biofuel, etc. Thus, modeling sustainable development from the start will include inputs that mix discrete and continuous choices, especially when it comes to micro-level decisions. Undergraduate students are taught about production functions and substitutions between capital and labor, but not about discrete technologies and discrete choices, which is left for graduate school.
2. Input use efficiency: Much of an applied input is not actually utilized in the production process. Input use efficiency is the fraction of input used in production process. Input use efficiency depends on the technology used and the biophysical conditions in place (Caswell and Zilberman 1985). For example, in the case of irrigation, water use efficiency depends on the technology employed (drip vs. farrow vs. sprinkler) and on the water holding capacity of the soil (it is higher on heavy soils than on

sandy soils). Energy use efficiency varies among various types of engines, vehicles, and environments. Application efficiency of chemical pesticides varies depending on the application method (aerial vs. manual) and environmental conditions, for example, windy environments reduce efficiency (Khanna and Zilberman 1997). This distinction is useful in assessing the likely impact of new technologies, where they are most likely to be adopted, and how they will affect production and input use when unutilized inputs (residues) are a source of environmental damage (e.g., runoff of unutilized fertilizers may contaminate bodies of water).

3. Damage control inputs: Significant fractions of output produced by agricultural and other systems are lost because of pest or disease damage. Damage control inputs include chemical pesticides, genetically modified varieties [GM], biological control, etc. Thus, actual output is (1 – [% of damage/100]) multiplied by potential output (maximum produced without the damage, which depends on initial conditions; Lichtenberg and Zilberman 1986). This notion is useful in assessing optimal pest control application and analyzing where and when technologies like GM varieties will be introduced under various conditions.
4. Complementarity among inputs and technological packages: Production consists of several processes, and each may be affected by a specific technology or input. For example, agricultural production output depends on nutrient provision, irrigation, and pest damage control. Thus, for a price-taking farmer, adopting a technology that reduces pest damage will increase the value of enhanced fertilization and irrigation. One may expect that productivity-enhancing technologies will be introduced in packages of complementarity elements, as was the case with the Green Revolution, where improved varieties were introduced together with fertilizers and sometimes irrigation, leading to major increases in yields (Feder, Just, and Zilberman 1985; Zilberman, Zhao, and Heiman 2012).

These basic notions help provide context for analyzing production processes and identifying where, when, and how new technologies will be introduced. But sustainable development requires considering pollution and input risk, and these two other notions are very important for analyzing production systems.

5. Pollution functions: Every production system has byproducts, and frequently these byproducts are a source of externalities. For example, burning wood in stoves generates in-house air pollution that may endanger the inhabitants (Smith, Mehta, and Maeusezahl-Feuz 2004). Sometimes the residue of applied inputs is an externality, as is the case with fertilizer and irrigation (Khanna and Zilberman 1997). Pollution is affected by production, which can represent both discrete technology choice and level of intensity of certain inputs, environmental conditions (the aerial application of pesticides may generate more significant externalities when it is windy than when it is not), as well as the level of pollution abatement inputs.
6. Risk generating functions: Frequently, the main concern about the environmental side effects of production are the risks that they generate, namely high impact, mostly low probability events that may include poisoning by toxic chemical residue, and accidents from industrial plants (Bhopal in India, etc.), among others. One way to address this issue is to use stochastic pollution functions. However, public health professionals, especially toxicologists, have developed a body of literature that provides a foundation for the regulation of chemicals, and its basic concepts are incorporated in the design of infrastructure projects such as bridges, dams, etc. The basic dependent variable is the probability of a bad outcome, and the risk generating function relates this probability to behavioral and policy choices, as well as various states of nature, which are random variables. The risk generating functions have random elements because of heterogeneity among locations and agents, random states of nature, and uncertainty. Lichtenberg and Zilberman (1988) developed a framework to incorporate a risk generating function in economic decision-making with several applications (Lichtenberg 2010). Modeling risk and the reliability of effort in controlling

it is an important part of the effort to incorporate precautionary concerns in policy design.

7. Spatial and dynamic considerations: Much of traditional production theory assumes homogeneous agents, which is useful in developing complex models of strategic behavior using game theory. However, incorporating environmental considerations in economic decision-making requires the recognition that heterogeneity matters, both in terms of individual agents and especially across nations. A chemical spill may have totally different implications if it occurs near a city rather than in the middle of an unpopulated area. Also, there are significant efficiency losses, as well as pollution generation due to conveyance and transport. For example, in traditional water systems, only 25% of the extracted water is often actually used by crops; the other 75% represents conveyance and irrigation efficiency loss (Chakravorty, Hochman, and Zilberman 1995). Thus, policy design has to adjust to variations over space.
   Similarly, the same level of pollution may have different impacts over time. For example, water quality depends on the concentration of toxic chemicals present, and may reach certain thresholds of danger to humans. Thus, when environmental side effects depend on stock variables, changes over time matter, and these types of considerations must be accounted for. There is a growing body of literature on optimal resource management over space and time (see Smith, Sanchirico, and Wilen 2009; Xabadia, Goetz, and Zilberman 2006) that provides a foundation for modeling such systems.
8. Increasing returns to scale: Much of the neo-classical literature assumes constant or decreasing returns to scale, but in many situations, especially when it comes to information technology and knowledge, economies of scale matter and many of the results and predictions of neo-classical literature and solutions do not apply. Lack of space prevents me from expanding on this topic. However, the work of both Krugman (1980) and Arthur (1989) provide an important framework on how scale considerations affect economic organizations and production systems. A big challenge is to further incorporate economics of scale considerations in developing solutions to environmental problems.
9. Generating innovation: The notion of induced innovation (Binswanger 1974) suggests that new technologies are outputs of the production process. Evenson and Kislev (1976), for example, developed a production function of the productivity of innovation, where the properties of new technologies are improved as more inputs are allocated to experimentation. There is also a growing body of literature on the innovation process. Innovation starts as an idea introduced by scientists or professionals, and to be utilized the innovation has to be upscaled, marketed, and adopted (Zilberman, Zhao, and Heiman 2012).
10. Putty-clay technologies: Johansson's theory of putty-clay production distinguishes between the short-run and long-run as well as micro and macro production functions (Johansson 2005). It argues that existing capital goods are not malleable and that once capital goods exist, a production unit operates under a short-term production function with limited substitution between capital and other inputs. In the long-run, investors have much more flexibility, and therefore there is a difference in the decision making process over a choice of design of a technology and the use of inputs. At the macro level, aggregation can result in both short-run and long-run production functions and can be used for different types of predictions.

Johansson's theory of production distinguishes between two types of inputs—discrete (technologies) and continuous (which are the levels of input use). Modeling of technologies should incorporate both of its elements. Understanding the timing of investment in new technologies is of major importance.

This represents a partial list of technological issues that should be incorporated into modeling sustainable development, but there are many other considerations not included here, such as household models of production, product quality considerations, etc. Understanding the innovation process and managing it is the key to developing technological solutions that can help meet the challenge of sustainable development.

Population, Capital, and Resources

Neo-classical growth theory (Solow 1956) considers two inputs—capital and labor—and labor was assumed to be a function of population size. There was minimal formal modeling of population growth, and much of the economic analysis assumed constant returns to scale and investigated the dynamics of output and capital per capita. However, population size matters in sustainability considerations given constraints on resource availability. Concerns about the Earth's carrying capacity led Ehrlich (1968) and Daly (1992) to view population control as a major imperative of environmental policy. However, given the substitution between capital and different forms of labor, and given that different technologies can vary in their input use efficiency, it is quite likely that more people can be sustained under a given set of resources if consumption levels are reduced, or if resource use efficiency is increased. Thus, even among countries with similar standards of living, there are large differences in energy and resource use dependent on population density (Nakicenovic, Grübler, and McDonald 1998). Due to a lack of space, population policies will not be addressed here. Instead, emphasis will be placed on developing sustainable policies that recognize differences between various forms of capital, and that emphasize the transition away from nonrenewable resources.

The neo-classical theory of economic growth originally emphasized physical capital. More advanced models incorporated putty-clay considerations and heterogeneity of capital goods based on vintages (Solow 1974). Probably the most important contribution of an agricultural economist to modern economics came from Theodore Schultz (1961), who emphasized other forms of capital, primarily human capital. While traditional capital theory emphasized processes of investment leading to the accumulation of physical capital, Schultz emphasized the importance of learning and the generation of knowledge. Furthermore, human capital has been essential in the adoption of innovations, which can have both positive and negative effects on the environment. For example, advanced knowledge can lead to reductions in the cost of fishing, as well as the depletion of fish populations. However, the development of policies may be able to mitigate negative side effects.

More recently, economists have adopted the notion of social capital, which is loosely defined as a set of relationships between individuals and institutions that enhances effectiveness of actions within society (reduced transaction costs, increased individual security, etc.[1]). Ecologists and environmental economists emphasize the notion of natural capital, which is a set of natural assets that can provide amenities. The services of natural capital are ecological or environmental services that may be under-provided, as many forms of natural capital can have the properties of public goods. The goal of much of the environmental economics literature is to develop mechanisms for provisions of ecosystem services (Bulte et al. 2008).

An important sub-category of natural capital is natural resources, which is divided into renewables (water, fish, etc.) and nonrenewables (minerals, oil, etc.). Hotelling (1931) introduced an economic theory of nonrenewable resources, which predicted that given initial stocks, the optimal exploitation of these resources would decline over time at a rate depending on the rate of interest. Thus, when an economy is dependent on nonrenewable resources utilized with other inputs, it is very difficult to sustain a given level of average economic welfare because nonrenewable resources with a given stock can only be mined, not grown, meaning that consumption levels must decline over time, converging to zero over the long-run. However, it is useful to recognize that in reality, managing resources does not fit the Hotelling model, as noted by Adelman (1990). An operationally important measure of renewable resource stocks is *known reserves*. Some of the mined resources can be re-captured through recycling. Thus, for many resources that are considered nonrenewable, the equation of motion that matters depicts changes in known reserves over time, which is equal to new discoveries plus recycled amounts, minus consumption. This suggests that in the long-run, once all the reserves are known, if a certain percentage of a stock can

[1] You can incorporate this into a damage function.

be recycled, one can sustain consumption that is equal to the recycled amount.

When it comes to petroleum-based products, there are still sufficient reserves of oil and other sources of petro-carbons that non renewability will mostly be a long run problem. One resource that is subject to a more immediate concern is the capacity of the atmosphere to absorb carbon while maintaining livable conditions for humans. Thus, for practical purposes, utilizing the atmospheric carbon capacity is a nonrenewable resource for which the Hotelling model applies. The concern with climate change and the limited capacity of the atmosphere to absorb carbon emphasizes the need to rely more on renewable resources that provide energy and other goods, but also contribute significantly fewer greenhouse gas emissions. The equation of motion of renewable resources is equal to growth minus consumption, and a steady state is achieved when consumption is equal to growth.

Humans can affect the growth of some renewable resources, primarily agricultural crops. While early human societies of hunter-gatherers were mostly harvesters of available renewable resources, the development of agriculture resulted in a system where humans were involved in the production of natural resources, including breeding, raising, and harvesting crops. Scientific knowledge in genetics, and more recently in biotechnology, has led to improved productivity in breeding many of the crops used today (Diamond and Ordunio 1997). Indeed, crops and livestock raised today have been bred for productivity rather than for survival in nature, and have been modified through breeding over time to have different capacities than their ancestors. For example, the Holstein cow is very good at producing milk, but is not likely to survive for long in the wilderness. The use of nutrients, pest control, and irrigation allow for the production of more output from a given genetic variety, and technological advancements are improving the ease of harvesting. Generally, the transition from hunting to farming can be explained by economic rationale. Farming became a cost-effective way to increase food productivity per acre, and is now evolving to aquaculture, which is used to grow fish and may provide a sustainable solution to depleting fisheries and other elements of what is known as the bioeconomy, which allows for the production of fuel and chemicals from renewable resources.

Renewable Resources and Sustainable Development

Concerns about nonrenewable resources, whether it be fossil fuels, minerals, or the capacity of the atmosphere to absorb carbon, suggests the need to gradually move towards a renewable economy. Such an economy would aim to prevent reliance on nonrenewable resources and maintain use at or below a sustainable level through recycling and continued consumption of renewable resources below their rate of growth.

Some of the key elements of the renewable economy are:

1. Conservation: Overuse of renewable resources may lead to their depletion, which would negate the objectives of sustainable development. Many natural resource uses are wasteful, as seen in the case of by-catch fish or low rates of utilization of harvested wood, and can be reduced through conservation. Conservation may consist of reducing the level of consumption of final goods, meeting human needs by consuming goods that are less resource-intensive (e.g., consume less meats and more vegetables and fruits), and increasing the input use efficiency of natural resource-consuming activities (e.g., fuel efficient engines and electronic equipment). Increased knowledge has led to the development of much more energy efficient technologies. One obvious example is the miniaturization of computers and other electronic equipment (Schaller 1997), which has also led to a reduction in materials used to construct these items. But as increased input use efficiency leads to reduced prices, the overall consumption of the final products tends to increase. Add to that the increases in global incomes, and even with drastic increases in input use efficiency, resource consumption may not decline. While automobile fuel efficiency is likely to continue to decline, the number of cars on the road will increase as vehicle ownership becomes more widespread in developing countries,

which limits the capacity of conservation to reduce use of nonrenewables like fossil fuels. Incentives, regulation, and research can induce conservation, but this may be insufficient to reduce nonrenewable resource consumption to sustainable levels.
2. Recycling: As was argued earlier, recycling can substantially reduce the extraction of some nonrenewable resources such as minerals. However, it has limited capacity to reduce the use of consumable resources like fuels.
3. Use of renewable fuels, such as solar and wind: The replacement of energy derived from fossil fuels is the major challenge in the transition to a renewable economy. While these renewable sources of energy may become more important in the long run (Chakravorty, Roumasset, and Tse 1997), their storage and transmission presents major challenges that will reduce their competitiveness compared to liquid fuels for years to come.

These three elements of the renewable economy are not likely to fully address the challenges of climate change and other human needs that require the transition to a renewable economy (Long et al. 2011). Another element of the renewable economy is the new bioeconomy, defined as the part of the economy that utilizes new biological knowledge for commercial and industrial purposes in order to improve human welfare (Enriquez-Cabot 1998). The bioeconomy is a key element of the renewable economy, and will be essential for future sustainable development. It will challenge traditional agricultural practices, and its evolution depends on effective policy-making and management. Some of its major challenges will be addressed below.

The Bioeconomy

Traditional societies relied on agriculture and on harvesting living organisms for many of their activities. However, fossil fuels and other petroleum-based chemicals have become major elements of the modern era. The renewable economy—and the bioeconomy in particular—aims to reduce dependence on fossil fuel-based products and substitute them with renewables. Zilberman et al. (2013) suggest that it is useful to distinguish between the traditional bioeconomy and the new bioeconomy. The traditional bioeconomy was a natural resource-based industry that relied on fermentation to produce a wide range of products, while the new bioeconomy relies on advanced biology, particularly the discovery of DNA and other molecular techniques, and introduces a new range and quality of natural resource products.

The traditional bioeconomy used fermentation to produce alcoholic products, cheeses, and a variety of pickled foods (e.g., sauerkraut and kimchi), and has many lessons for the new bioeconomy. Pickling has been used as a major means of preserving food and overcoming seasonality constraints, but can be mismanaged and cause negative health effects. Concerns about risk have led to the regulation of products from the traditional bioeconomy, particularly alcohol. Attempts to ban alcohol (e.g., prohibition in the United States in the early 1900s) have proven ineffective, and regulatory regimes recognize the need to balance benefit and risk. As will argue later, excessive regulation may hamper growth and reduce the social benefits of the new bioeconomy.

The major applications of the new bioeconomy considered here include genetic modification, biofuels, and green chemistry. Genetic modification has had a large range of applications in medicine and is a foundation of the fast-growing medical biotechnology industry (Lebkowski et al. 2001). Agricultural biotechnology has also grown rapidly. However, the use of genetically modified crops (GMOs) is a subject of restrictive regulation, and their utilization has been limited to four major crops (corn, soybeans, cotton, and rapeseed). Furthermore, the United States, Brazil, and Argentina are the major users of GM technology in these four crops, and China and India have adopted GM cotton. In spite of its limited use, GM technology already provides major benefits by increasing the estimated supply of corn and soybeans by 13% and 20%, respectively, and reducing their estimated prices by 20% and 30%, respectively (Barrows, Sexton, and Zilberman 2013). The adoption of GM varieties in Europe and Africa, and the expansion of its use to major food crops like wheat and rice, is likely to significantly reduce the food price inflation seen in recent years (Sexton and Zilberman 2011). Some of the key elements of the new bioeconomy are listed below, and include genetic modification, and biofuels and developments in green chemistry.

1. Genetic modification: Genetic modification of crops is a major contributor to sustainable development. Existing GM varieties significantly reduce crop damage (Qaim and Zilberman 2003), greenhouse gas emissions, and the footprint of agriculture (Barrows, Sexton, and Zilberman 2013). Today GMOs are in their infancy, but they provide new and more precise means to improve crops and adapt to changing conditions. New innovations instituted at various stages of developments are likely to increase the input use efficiency of water and fertilizers in crop production and of grains as sources of animal feed. The development and adoption of these innovations has stalled because of regulations (Bennett et al. 2013). Nonetheless, GMOs improve the speed of development or modification of crop varieties and thus can provide a means of adapting to climate change (Zilberman, Zhao, and Heiman 2012).
2. Biofuels: For millennia, wood, dung, and oils supplied energy for cooking, heating, and other functions. Here we refer to the agricultural (broadly defined) production of feedstocks and their industrial processing for modern applications. Examples include the production of ethanol, biodiesel, and wood chips to replace fossil fuels. The production of biofuels for transport fuel was motivated by the high price of oil and other fuels, balance of trade considerations, and concerns about climate change (Rajagopal and Zilberman 2007). However, direct and indirect effects on food prices (Zilberman et al. 2013) and the environment (greenhouse gas emissions and deforestation (Khanna and Crago 2012) raised questions about biofuels. Yet liquid fuels have relative advantages in major applications and are most likely to be produced sustainably through biofuels. Learning by doing in sugarcane and corn biofuels production has improved their environmental and economic performance (Khanna and Crago 2012). Research on second and third generation biofuels is promising, and several will be produced on nonagricultural lands in the foreseeable future (Youngs and Somerville 2012). The evolution of biofuels is dependent on policy, and the emergence of clean and efficient biofuels is more likely to be followed by continued investment in research and appropriate pricing of carbon (Chen and Khanna 2013).
   The future of biofuels is also affected by the future of GMOs. Policy changes that will enable the introduction and large-scale adoption of GMO rice and wheat varieties, which will increase rice and wheat yields by more than 10%, and the adoption of GM traits in Africa and Europe may reduce food commodity prices and free up lands that will allow the adoption of sugarcane for biofuel in India and other developing countries. Greater acceptance of transgenic technology is likely to increase its utilization in biofuel feedstock production and improve the productivity of sugarcane, grasses, and trees considered for the production of second-generation biofuels. The design of biofuel policy and the interaction of biofuels and biotechnology policies are subjects for future research.
3. Green chemistry (broadly defined): Green chemistry represents a transition from petroleum-based chemicals to biomass-based chemicals (Clark, Luque, and Matharu 2012). Green chemistry emphasizes a reduction in the toxicity of outputs, recycling, energy efficiency, and production of decomposable products with minimal waste. Its principles of operation are consistent with some of the concepts associated with sustainable development elucidated above. The reliance on biomass suggests that the transition to green chemistry will lead to a more spatially distributed network of bio-refineries instead of the highly centralized refinery systems in place today, suggesting that the transition to green chemistry will be an engine for regional development. Increased reliance on plant and animal feedstocks will enhance investment in bio-prospecting in order to discover new feedstocks and valuable chemicals. Research to develop advanced biotechnology methods and products will be crucial to the development of the bioeconomy. For example, one of the impediments to using many crops as feedstocks is their high lignin content,

and the development of varieties with lower lignin content will reduce the cost and increase the range of products that can serve as feedstock for fuel and other applications.

Policy Challenges

The pursuit of sustainable development, which implies maintaining or improving individual economic welfare while not compromising the welfare of future generations, may take several forms. These include population control (not considered in detail here), reduced consumption and pollutions levels, and the reduction and in some cases elimination of dependence on nonrenewable resources. This pursuit includes major technological and institutional challenges, which have to be addressed by policy. The technological challenges may include reengineering production and consumption systems to increase input use efficiency, developing and introducing affordable renewable fuels, and establishing a new bioeconomy that will produce much of the food, fuel, and chemicals consumed in an environmentally-friendly manner.

The challenge that the new bioeconomy poses for agriculture is immense. For example, agriculture has to produce a significant amount of feedstock for biofuels and other chemicals, while at the same time producing food for humans and livestock. Since food prices are currently higher than ever, even if increased input use efficiency of food products is taken into account, sustainable development may require a substantial increase in the productivity of agricultural resources.

The policies that will induce a transition to a sustainable economy consist of several elements:

1. Investment in R&D and the development of human capital: Recent experience with information technology and medical biotechnology suggests that the educational-industrial complex, especially in the United States, has been very effective in developing new technology paradigms. The educational-industrial complex is based on the allocation of public support for research at universities and institutes which, through processes of technology transfer (Graff et al. 2002), either sell rights to the private sector to develop new innovations, or contribute to the establishment of startups. Public sector investment may be required for the development of technologies that are underdeveloped by the private sector (ones serving orphan crops and poor populations), and creative policy may be needed to control and avoid the tragedy of the anti-commons (Bennett et al. 2013). Alston, Beddow, and Pardee (2009) have documented the decline in support for agricultural research, and Margolis and Kammen (1999) have acknowledged the low levels of support for renewable energy systems. These patterns have to be changed to facilitate the transition to a sustainable economy.
2. Financial incentives and other policies to induce the adoption of technologies and practices consistent with sustainable development: As Huang et al. (2012) have shown, the adoption of alternative energy and the use of fossil fuel is affected by policy design. For example, carbon pricing is likely to be very effective in inducing conservation, improving energy use efficiency, and introducing efficient forms of alternative energy. Initial support of new technologies that allow learning by doing can be justified, but must be done carefully, and must recognize the potential for abuse.
3. Regulation and education. Nuclear power, biotechnology, and other innovations emphasize the importance of regulation in affecting the future of a new technology. The major challenge of policy processes is to develop science-based regulation that balances benefit and cost and that will allow sound experimentation with new technologies that maximize net social benefit in the long run. To make informed regulatory decisions, policy-makers and the public need to be well informed and educated about the implications of alternative policy regulations.

Implications for Applied Economics

The pursuit of sustainable development will depend on the formation of science-based policies, and applied economics is uniquely suited to contribute to this effort. To understand the alternative impacts of various policy trajectories, and to improve policy design, economists and researchers need to integrate quantitative understanding of the workings of natural resource and economic systems. These are the hallmarks of agricultural and natural resource economics research. I view economics as an integrated discipline that provides the tools to make and judge social choices. Our effectiveness in the future will depend on our capacity to improve our understanding of human behavior and political economy with the ability to use scientific knowledge in decision-making. Agricultural and resource economists have a strong empirical and quantitative base and are very effective in incorporating econometrics and statistical analysis with normative tools (programming, CGE, etc.) as well as methods from other disciplines. These are good foundational elements for sustainable development research.

The notion of sustainable development considers society and the universe as an integrated system, and concerns about sustainability, environmental, and natural resource issues will force our research to go beyond sectoral limitations. Indeed, the borders between research on agricultural, energy, and resource issues are fading. There is much overlap between sectors and policymaking, and with globalization there is greater interdependence among countries. The new transformation from agricultural to applied economics is welcome progress that will allow us to build a stronger team of researchers to address these challenges of sustainable development.

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