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Economics of Sustainable Development and the Bioeconomy

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Abstract *Sustainable development can be attained by policies that are derived by analyses that integrate biophysical considerations into economic models. We show that policies and incentives that correct market failure can attain sustainable development through enhancing conservation, recycling, the use of renewable resources, and development of the bioeconomy, which relies on biological processes and feedstock to produce renewable products. The design of sustainable development policies and analysis of the bioeconomy pose new challenges to applied economists, who are uniquely qualified to integrate economic analysis with biophysical considerations.*

Key words: Sustainable development, bioeconomy, dynamics, heterogeneity, adoption, renewable resources.

JEL codes: Q16, Q18, Q20, Q55.

Economic analysis and decision tools are especially apt for researchers pursuing sustainable development goals, namely, economic growth subject to environmental and sociological constraints. The bioeconomy utilizes new knowledge of life sciences to produce a wide range of products from the living organisms and the waste they generate, and is a major component of sustainable development. In pursuing these objectives and developing a strong bioeconomy, agricultural and resource economics research is essential to the development of policies that will guide the evolution of the bioeconomy.

The first section of the paper identifies major features of sustainable development's economic perspectives, and presents tools to analyze and quantify the bioeconomy. The second section introduces economic research on measuring the bioeconomy and designing policies to steward it towards sustainable development objectives. The final section outlines the research agenda for agricultural and resource economics aimed at pursuing sustainable development and establishing a strong bioeconomy sector as part of it.

Economics of Sustainable Development

Policy making in the twentieth century strove to enhance economic growth and improve the living conditions of humanity. Yet at the same time, Rachel Carson's *Silent Spring* (1962) and the Club of Rome in 1968, among others, contributed to the growing realization that we live in a world with resource scarcity and other environmental challenges. This led to the establishment of environmental regulation agencies in the United States and elsewhere in the 1970s (e.g., the Clean Air Act of 1970). Furthermore, the United Nation's Brundtland Commission committee in 1987 defined the following notion of sustainable development: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Further analysis of this term and its implications, as well as the recognition of the economics of biological systems, suggested that sustainable development should also consider equity, irreversibility, as well as uncertainty, risk, and the processes of learning associated technological change and environmental vulnerability. Batie (1989) suggests that sustainable development challenges agricultural and resource economists to expand policy analysis and the evaluation of market activities to consider sustainability implications of policy choices and to create initiatives that will result in sustainable outcomes.

By recognizing the factors affecting sustainable development, much of the research on sustainable development expanded dynamic growth models (Stavins 1990; Pezzy 1992). Solow (1974) suggested that sustainable development policies should be derived from the maximization of expected net present value of utility per capita, thus assuring that utility levels of the poorest individuals does not decline over time. Neumayer (2000) develops a methodology for measuring changes in the stock of natural resources, and shows that these changes matter for the measuring of sustainable development. Incorrectly accounting for the opportunity costs of using natural resources results in significant biases in the estimation of economic growth. The introduction of theories of endogenous growth (Romer 1994) suggested that significant investments in research and development should be key components of sustainability strategies.

The literature on sustainable development has evolved to recognize heterogeneity within the economy and across various forms of capital and natural resources (Arrow et al 2004). In particular, the literature distinguished between human capital, physical capital, and natural capital. Arrow et al. (2004) model the design of sustainable development policies as maximization of the net expected discounted utility of consumption per capita, subject to three constraints: (*a*) technological capacity; (*b*) the dynamics of the various types of capital; and (*c*) that consumption must not decline over time. In particular, this approach calculates for each period the amount of all types of capital and physical labor utilized, output produced, resources extracted, and pollution generated subject to equations of motion of capital stocks and population growth, as well as the constraint that utility of consumption per capita does not decline over time. A major implication of this approach is to recognize that under plausible conditions sustainable development occurs when the *productive base* of the economy, which is defined as the sum of all forms of capital in the economy, adjusted for population growth and technological change, is not declining over time. In particular, this implication suggested a new notion of genuine capital, which is the value of all sources of capital, and that sustainable development occurs when (*a*) the rate of growth of genuine capital, minus (*b*) the rate of population growth, minus (*c*) the contribution of economic growth (measured by total factor productivity) to the growth in genuine capital are non–negative.

The notion of genuine capital has practical implications and provides a basis for assessing the overall productivity and sustainability of an economy. For example, countries may have rising consumption per capita, but if it is only based on the export of non-renewable resources it would not be considered sustainable. Using this approach, Arrow et al. (2004) measured the performance of various countries and found that during the last three decades of the twentieth century, genuine investment was positive in most regions but negative in sub-Saharan Africa and the Middle East. A further finding by these authors was that the growth rate of genuine capital per capita was negative for most of the developing world, except China, due to China's lower population growth. The reason is the high rate of population growth in most developing countries, which is faster than the rate of growth in genuine capital. A third finding by Arrow et al. (2004) is that measures of economic growth based on genuine capital are smaller than traditional measures of growth (e.g., Gross National Product). Between 1970 and 2000, genuine capital was significant in China, modest in most developed countries, close to zero in India and Bangladesh, and negative in the Middle East and sub–Saharan Africa.

The Arrow et al. (2004) analysis suggests that economic performance adjusted for sustainability considerations can be enhanced by introducing pricing—or policies that embody them—for externalities and public goods. Furthermore, the literature recognizes that to understand sustainable development, it is important to understand how resource dynamics interact with macroeconomic considerations. For example, van der Ploeg (2011) discusses whether, from a national perspective, discovering new natural resources is a curse or blessing. He gives the example of the Dutch Disease, where the major discovery of natural gas in the 1960s in The Netherlands led to an export boom in primary commodities, but had a negative effect on economic growth by reducing the competitiveness of other sectors as real exchange rates increased. This suggests the need for strong institutions able to manage the windfall profits from a natural resource boom.

While macro–level analysis of sustainable development has provided a more refined vantage point on national accounting and provides quantitative justification for environmental policies, a more detailed micro–level approach is needed to develop more refined sustainable development strategies. Micro–economic approaches to sustainability have to recognize heterogeneity across locations and between individuals (instead of using aggregate measures) both in terms of economic and biophysical factors. Barbier (2016) emphasizes the distinction between weak sustainability, which was analyzed by the macro models presented by Arrow et al. (2004), and strong sustainability, which recognizes the uniqueness and substitution constraints of different forms of capital, especially natural capital. For example, strong sustainability suggests that the pursuit of economic growth is constrained by protections of biodiversity and preservation of special locations and ecosystems that may go beyond the obvious locations (e.g., Yosemite, the Amazon).

While weak sustainability pursues economic growth subject to aggregate constraints, implementation of strong sustainability requires identifying specific environmental constraints that must be met when pursuing economic development. This may open a Pandora's box where different groups may come with proposals for the preservation of environmental and social amenities. For example, the Endangered Species Act (ESA) is one approach to identify such criteria as it implies that threatened and endangered species should be protected through different mechanisms. Brown and Shogren (1998) suggest that assessing the impact of the ESA under different assumptions is a research priority. This requires both assessing its implementation and impact on property rights, as well as the cost of alternative specifications of the act.

Local agencies as well as civil groups have established other criteria for preservation and protection. Such agencies establish groups to implement protection measures and certification and to assure that the utilization of resources adheres to sustainability criteria. Dragunsanu et al. (2014) review the literature on Fair Trade and identify how challenging it is for certification aimed at sustainability objectives to result in outcomes that are either efficient or improve income distribution. Zilberman (2014) suggests there is a difference between the popular notion of sustainability that develops policies that aim to meet specific conservation objectives and may be socially costly, and the notion of sustainable development that aims to improve welfare subject to environmental and social constraints. Wesseler (2015) stresses the importance of explicitly considering irreversibility effects in the assessment of sustainability to avoid overinvestment and excessive depletion of natural resources.

How does the discipline measure these various effects and develop policies that usher more sustainable processes? Economics and especially applied economic disciplines that deal with agricultural and resource economics are uniquely suited to analyze sustainable development policies. These sub-disciplines are able to incorporate knowledge from various sciences into economic decision-making rules, and to develop policy solutions that include the pricing and allocation of market and non-market goods. Empirical economic analysis can utilize data on observed behavior to identify the behavioral factors that affect choices, including the adoption of technologies, response to environmental regulation, etc. Applied economic models can also obtain optimal pricing and resource allocations by maximizing social welfare (e.g., net present value of the sum of economic surpluses) subject to markets as well as behavioral and environmental constraints. The combination of econometric estimation based on past performance with simulations, predictions, and optimizations based on these estimates provides applied economic analysis with powerful tools to develop and analyze sustainable development strategies at different levels of aggregation.

Applied agricultural and resource economists develop conceptual frameworks that integrate biophysical concepts to economic decision-making applicable to developing sustainability strategies. These models have been effective in estimating the productivity of crops, pollution-generation functions, the adoption of Green Revolution and irrigation technologies, the design of payment for ecosystem services strategies, and establishing strategies to restore fisheries and to trade water rights, among others (Kling et al. 2010; Lichtenberg et al. 2010). These models can also lead to policy design. For example, in the context of climate change, they can guide designs of strategies for adaptation, which may include, among others, investment in research that leads to innovations, and incentives and regulations that may lead to the adoption of these innovations.

Applied economic models are works in progress and can be expanded and refined as new data sources, computational capacity, and scientific knowledge are advanced. Zilberman (2013) argues that the analysis of sustainable development policies needs to be dynamic and distinguish between non-renewable resources (e.g., minerals). Non-renewable resources vary in their degree of scarcity and as long as discovery is greater than use, they are treated practically like renewables. One of the important non-renewable resources is the capacity of the environment to absorb pollutants, and thus management of greenhouse gases (GHG) as well as water quality are important elements of sustainable development. Renewable resources may be divided to non-living (e.g., water, sunlight, waste) and living (e.g., plants). Initially, humans harvested living resources through fishing, hunting, and other means. But with the introduction of agriculture, humans moved to a system of husbandry whereby breeding, feeding, and harvesting were all managed by humans. Agricultural sciences, to a large extent, were used to modernize husbandry strategies. The transition from hunting to farming started thousands of years ago, and as agricultural productivity increased, it enabled more people to be fed, and perhaps preserved wildlife. A similar transition in fishing only started within the past 50 years, which has marked the transition from reliance on fishing to aquaculture. While this transition may increase the consumption of fish, the utilization of various sciences may also enable it to save some wild fisheries.

The tools developed by applied economists are crucial in developing policies to bring forward major strategies to obtain sustainable development (Khanna, Swinton, and Messer 2018). These strategies include the following: (*a*) conservation, either through incentives and other policies that reduce the use of inputs that are scarce or polluting, or lead to the adoption of technologies that increase input use efficiency; (*b*) recycling, when non-renewable resources are reused or refashioned and may allow overcoming their scarcity; (*c*) use of non-living, renewable fuel sources like solar and wind energy; and (*d*) the bioeconomy.

The Economics of the Bioeconomy

The development of the bioeconomy has become a major policy focus within and among countries, each developing their own national strategy. For example, the U.S. definition encompasses health, agriculture, bioenergy, and food within the bioeconomy, while the European Union's (EU) definition encompasses food, agriculture, forestry, and marine resources. There is a shift in the EU from researching the content of biological resources to the optimization of industrialized processes. For example, German conglomerate ThyssenKrupp and biotechnology R&D organization Cluster Industrielle Biotechnologie e.V. are developing processes to repurpose carbon, as well as other chemicals. The objectives for developing the bioeconomy vary across nations, and they include economic growth, energy independence, rural development, and sustainable development (Wesseler and von Braun 2017).

Two major sets of elements contribute to the growth of the bioeconomy: (*a*) new developments in molecular and cell biology, which began with the discovery of DNA and has continued to expand as our ability to document the genome, understand the functions of genomics, and manipulate organisms through transgenic transformation and gene editing, as well as bioinformatics; (*b*) the desire to shift from reliance on petroleum in terms of energy production and chemicals and other materials to reliance on renewable green resources. The transition to switch away from petroleum-based products is based on concerns of climate change, scarcity considerations, and new discoveries in biology, both in terms of molecular methods and organismal knowledge that expands the range of feedstock available for new products, including waste inputs.

Lessons of the Traditional Bioeconomy

The traditional bioeconomy is one of the oldest industries that utilizes fermentation to produce products such as bread, wine, cheese, kimchi, and beer. This industry has been crucial throughout history because it allows for the storage and preservation of food to allow seasonal and transportation constraints to be overcome. Fermented products like beer and wine had significant medicinal benefits in addition to their nutritional value and palatability. As we will see, the new bioeconomy may face similar challenges of the traditional bioeconomy; but while the traditional bioeconomy was built gradually by traditional means and trial and error and only recently has been modernized, the new bioeconomy is science-based and part of the industrial-educational complex where publically-supported university research provides some of the basic ideas that trigger economic growth and industrial development (Zilberman et al. 2013).

There are several lessons from traditional bioeconomy that apply to the modern bioeconomy. First is a reliance on multi-stage production systems where farming activities, broadly defined (e.g., grapes in a vineyard, wheat in a field), produce the feedstocks that are then processed by a biorefinery, again broadly defined, to produce end products like wine and bread. The commercialization of such activities requires a design of supply chains that includes feedstock production, processing, and then distribution and marketing of the product. These supply chains may also have different forms; they may be vertically-integrated, rely on contracts between refineries and feedstock producers, and many other arrangements. The design of supply chains is an important economic decision-making problem. Du et al. (2016) and Zilberman,Lu, and Reardon (2017) argue that we are more likely to see vertically-integrated systems when the innovator has efficient credit, is concerned with maintaining control of the technology, and is uncertain of subcontractors to operate. On the other hand, contracting to farmers is more likely when innovators are resource-constrained or have relative advantages in refining and marketing.

A second lesson from traditional bioeconomy is the importance of obtaining maximum value from feedstocks during the refining process, which suggests that the refining process continues to improve. For example, milk processing will result in multiple products—whey, cheese, butter, etc.—and this suggests that new knowledge is useful in expanding the utilization of feedstocks and thus reducing unutilized residue. Similarly, biomass can be converted into a number of products and be reused in a cascading way where first the highest value-added products are produced and reused until they are finally converted into energy, thus supporting the development of a circular economy (Keegan et al 2013).

A third lesson regards the tradeoffs between the benefits and risks associated with the final product that may have significant policy implications. For example, alcohol has served as nourishment and medicine for millennia but at the same time overconsumption has negative health and social side effects. There have been attempts to ban the product, for example during Prohibition in the United States, which have proven too extreme. Therefore, policy makers have gradually developed a regulatory framework that includes restrictions on use and sale, as well as penalties and education.

Major Components of the Modern Bioeconomy

A key component of the modern bioeconomy is the use of biotechnologies that include transgenics and gene editing. While transgenics have been adopted widely in medicine, their use in agriculture has been limited; scientists have discovered many traits, but only a few have been commercialized (Bennett et al. 2013). In particular, Bacillus thuringiensis (Bt), a bacterium varieties and herbicide–resistant varieties have been adopted for corn and soybean mostly in the United States, Brazil, and Argentina, and transgenic cotton has also been adopted in India and China. Significant evidence exists that adopting these varieties increases yield, reduces pesticide use, increases supply of major grains while reducing their price, and thus benefits the poor and increases welfare (Barrows, Sexton, and Zilberman 2014; Klümper and Qaim 2014).

Without the adoption of transgenics technologies, GHG would have been much greater (Barrows, Sexton, and Zilberman 2014; Taheripour, Mahaffey, and Tyner 2015). Furthermore, while the major academies of sciences have stated that transgenic crops do not pose any new risks, they have been practically banned in Europe (Smart et al. 2015) and exhibit low adoption rates in Africa, where they could provide much benefit (Wesseler et al. forthcoming). Adoption of these technologies, for example in wheat and rice, and the introduction of traits that enrich nutrient content of foods, could have increased economic welfare and human health (Zilberman, Kaplan, and Wesseler 2016). Some of the restrictions on transgenics reflect political economic considerations (Graff et al. 2015; Herring and Paarlberg 2016), and they may reflect consumer attitudes toward biotechnology (McCluskey, Kalaitzandonakes, and Swinnen 2016). Both the political economy and perception are the result of multiple factors, including the way the technology was introduced, its timing, framing, and the concentration of ownership of intellectual property by, specifically, Monsanto.

Understanding this issue is important as we broaden the scope of crop biotechnology through the introduction of gene editing. Gene editing technologies can further expand agricultural productivity and reduce its environmental impact, but its potential depends on the regulatory framework (Huang et al. 2016). Furthermore, the ownership of intellectual property to the gene editing technology CRISPR is not fully settled and the way that the technology is introduced will affect its acceptance and utilization (Egelie et al. 2016). Therefore, understanding the impacts of regulation on the introduction and use of new technologies and intellectual property management are important areas for further research.

Plants form complex relationships with bacterial communities, namely, the microbiome. This is another area of much promise that was neglected in the last several decades. Host plants interact with the microbiome to enhance nutrient uptake, protect against pathogens and abiotic stress, as well as modulate their metabolic capacities (Mitter et al. 2013). Characterizing and then manipulating a plant's microbiome can enhance crop production while minimizing the need for pesticides and fertilizer, thus improving the sustainability of feedstock production for fuel and feed.

The concern about GHGs, high oil prices, and national energy independence in the first decade of the new millennium have led to the emergence of policies to develop biofuels in the United States, Europe, and other countries. Since 2000, we have seen the emergence of significant ethanol production, and to a lesser extent biodiesel production. Much of the production of ethanol is from first-generation feedstocks, which includes corn and sugarcane. But we have also seen the emergence of second-generation biofuels including cellulosic feedstocks (Yao et al. 2017).

Biofuel industries have been subject to support and subsidization (de Gorter, Drabik, and Just et al. 2015). In particular, the introduction of biofuels contributed to price increases in agricultural commodities, especially during 2008-2010, that seem to have had negative economic impact (Hochman et al. 2014) . Furthermore, while biofuel support was justified partially by their contribution to reduce greenhouse gas emissions, there was strong concern about their negative impact on emissions mostly through their impact on land use change. There has been a large body of literature on the impacts of biofuel, but over time, it has been realized that productivity of biofuel production has been increased significantly through learning-by-doing and their land use effects were much smaller than initially estimated (Khanna and Crago 2012; Babcock 2015). Furthermore, reassessment of the distributional effect of biofuels through increased food prices suggests that its impact on the poor might have been positive since many of the poor are farmers (Huang et al. 2012). Quantitative estimation of the impact of the growth of biofuels on human welfare and income distribution, as well as land use and the environment, is thus affected by both model and empirical specifications (Zhang et al. 2013; Steinbuks and Hertel 2016; Hochman and Zilberman 2016).

A key element of the modern bioeconomy is the production of various products and chemicals from renewable feedstocks that replace similar products produced from non-renewable sources. The growth of the bioeconomy is the result both of supply factors (i.e., improved technology) and growing consumer demand for bio-based products as well as policies. This has led to a re-growth of the wood-based construction material industry, development of greening systems to cope with air pollution (Wesseler and von Braun 2017), and increased use of waste products in construction and packaging. As shown from the traditional bioeconomy, utilization of bio-based products is an essential component of achieving not only environmental indicators but also being cost-competitive with existing industries (e.g., sugarcane and bagasse). To this end, numerous bio-based products are already commercialized or being brought to the market, where chemical molecules are gradually being changed to bio-based molecules with projected or known uses. Furthermore, bio-based products comprised 9% of the global chemical sales market in 2012 (de Jong et al. 2012), and it is predicted to grow to 22% by 2025 (Biddy, Scarlata, and Kinchin 2015). Research in green chemistry is aiming to produce major building block chemicals (e.g., methanol, glycine, carbon dioxide, lactic acid, acetone) from renewable sources. Indeed, transgenics have enabled the development of new enzymes that increase the effectiveness of bioreactors and enable the production of new bioproducts.

There are also strong bioeconomy geographic clusters including the San Francisco Bay Area, Boston/Cambridge, and the triangle of Brussels, Ghent, and Leuven, as well as clusters in Japan, France, and Romania. These clusters, whose emergence was assisted by favorable market conditions and local policies, allow for economies of scale and complementarity between various enterprises in research, finance, and production, and lead to the introduction and production of new bioproducts (Wesseler and von Braun 2017). The value added of the new bioproducts sector, excluding food, feed, and energy, is estimated to be around 2% of GDP in the United States, and 7% in Germany and the Netherlands (Wesseler and von Braun 2017).

Another important expected contribution of the new bioeconomy is that it will generate economic growth in rural areas. The conversion of biomass into base chemicals can be done in biorefineries that are much smaller in scale than those used for converting fossil feedstocks (Clomburg, Crumbley, and Gonzalez 2017). This allows the establishment of many small biorefineries close to the biomass producing areas, while those converting fossil feedstocks are mainly allocated along coastal areas and are large in size. In the United States, this has in particular benefitted rural areas in the Midwest, where the majority of biofuel refineries have been established. Expectations are that the number of biorefineries in rural areas worldwide will grow and they will not only be limited to the generation of bioenergy but contribute to the production of bio-based products (Virgin and Morris 2017).

The recent experience with the new bioeconomy (transgenics, biofuels, bio-based products) presents several important lessons for its development in the future. First is the importance of the educational-industrial complex, where universities supported by public sector funding for research develop and patent new innovations that are then further developed and commercialized by the private sector. This de facto public-private partnership has given the United States a relative advantage in the development of the modern biotechnology sector, as well as the information technology sector (Zilberman et al. 2013). Thus, while the details of the research establishment can and should be modified, continuing public support of research is very important for the future of biotechnology. Second, it is clear that only a small percentage of new biotechnology innovations and ideas are being commercialized and utilized. Transgenics and biofuels, as well as bioinformatics, have not achieved their full potential, and many good ideas that could improve human welfare and environmental health are currently untapped. Some of the limited success in utilizing these technologies are due to legal and regulatory constraints, intellectual property rights, as well as economic and behavioral factors. Understanding how basic technologies can be better developed and utilized is another important challenge for future research. Finally, the bioeconomy will expand the range of crops produced by agriculture and how waste becomes an input in a different process, and may have significant impacts on the food sector, and land use and the environment. Understanding the impacts that new segments of the bioeconomy have on the broader economy, and especially the food sector and environment, are crucial for developing regulatory systems that will, in turn, govern the evolution of the bioeconomy (Smart, Blum, and Wesseler 2017). This suggests another area for research.

Lessons for Economic Research and Education

Sustainable development and the related notion of sustainability are becoming increasingly important policy objectives for governments at different levels, as well as in the private sector. Our analysis suggests that there is a growing need to strengthen the conceptual understanding of different notions of sustainability and their implications. In particular, there is a need to design effective policies that aim to achieve sustainability objectives, and more importantly, to analyze the implications of proposed policies.

One of the major strengths of economics, due to its rigorous foundation in methods, is in its capacity to evaluate proposals and sort out inferior ones (Pardey and Smith 2004). Such analysis can be performed both at the conceptual level and at the empirical level – and empirical studies should evaluate performance of mechanisms aimed to achieve sustainability objectives both *ex ante* (by simulation) and *ex post.* Such a research agenda may have a large range of applications and may lead to better targeting of conservation and protection efforts, more efficient policies to attain them, improved assessment of certification programs, and design of overall integrated policy strategies at all levels to improve economic performance and environmental quality.

Development of the bioeconomy is a major implication of sustainable development for the agricultural and natural resources sectors, and as we saw, suggests a plethora of new research avenues to be effective. Growth of the bioeconomy requires significant investment in research and infrastructure, as well as policies for efficient and equitable transfer of technologies from public to private sector, and support fledging new industries in an efficient manner. Recent research on biofuels suggests that many of the biofuels policies have had major flaws, resulting in costly resource allocation; at the same time, the state of art of assessing them is imperfect and needs to be improved (Khanna and Zilberman 2017). Based on the recent past, we may expect the emergence of multiple suggestions for policy and institutional designs for alternative mechanisms and policies to expand the bioeconomy, and research to develop the tools to assess the economic and environmental impact of such policies will be a major priority.

Recent research on biotechnology and biofuels identifies several specific areas of priority research. First is improved decision-making and the targeting of public research funds. Second is a better understanding of alternative schemes of technology transfer between the public and private sectors, along with the development of mechanisms that will allow access and implementation of major innovations aimed at disadvantaged groups and minor crops. These may require guidelines for the distribution of property rights for innovation as well as compensation schemes. The public sector is needed when technological development may not be profitable for the industry but may improve overall social welfare. For example, the private sector may implement new biotechnology innovations for corn and soybean based on their own profit motive, but government intervention may be needed to bring to bear innovations that do not create sufficient profit, but nonetheless have consumer benefits or benefit society as a whole, for example, biofortification, vaccines, or malaria control.

The third area of research regards the design of effective regulations of new technologies in a way that will enhance efficiency, meet environmental objectives, and also address issues of acceptance and perception, which requires thorough knowledge. This research may require both conceptual understanding as well as an empirical component that would assess the impact of regulations as well as perception in practice.

Fourth, there is a need to understand the economics and performance of the supply chains that emerge to implement new technologies, how they are affected by various policies, and their competitiveness and trade policies. As Du et al. (2016) argue, supply chains may be introduced to enhance the profit of innovators and may lead to non-competitive (e.g., oligopolistic and oligopsonistic) outcomes. Balancing competitiveness with innovation will become an increasing policy challenge and require better understanding of economics.

Fifth, sustainable development policies that aim to address issues such as climate change and new bioeconomy industries should be developed within a global economic system. Thus, understanding the global economic impact of alternative policies and the emergence of different markets affected by these policies require global analysis that takes into account international trade arrangements and regulations. For example, some of the biofuel policies in the United States and Brazil were motivated by international trade considerations. The study of biofuels cannot ignore the behavior of OPEC and the peculiarities of the international fuel market (Hochman, Rajagopal and Zilberman 2010). Sustainable development policies must take into account the Paris Agreement and European and American carbon markets.

Sixth, it is important to understand consumers' attitudes towards sustainability and the bioeconomy, as well as towards new technologies. Many of these issues are addressed by Lusk and Bieberstein 2014, but the history of agricultural biotechnology suggests that consumer acceptance has been crucial and affects the trajectory of these new technologies.

Seventh, it is important to understand the political economy of policies that aim at both sustainability and the bioeconomy. The world is not ruled by economists, and resources are allocated by a dual system of politics and markets (Stiglitz, Braverman, and Hoff 1993). Understanding how policy is determined by political choices affected by economic considerations is important for prediction and impact assessments, as well as policy design. Better understanding of consumer perception and acceptance of the bioeconomy will enhance the ability to study the political economy. As the bioeconomy is more firmly established and new initiatives are proposed, it is no longer sufficient to understand only what is economically possible, but also what is politically feasible.

Eighth, the emergence of the bioeconomy blurs the distinction between agricultural, environmental, and energy policies. While these distinct policies represent a historical precedence, their separation may be costly. Research identifying possibilities and assessing the cost of implementing these policies at different levels of government will become a major priority.

A ninth major research challenge is to identify the environmental and economic impact of different sectors of the bioeconomy and policies aimed at establishing and augmenting them. This type of research will be essential for all the research objectives mentioned above, and may entail research both at the market level and at economy-wide levels (partial versus general equilibrium), as well as research on environmental impacts and life-cycle analysis (Rajagopal and MacLean 2017).

Concluding Remarks

One of the unique features of agricultural and resource economics is its need to incorporate both biophysical considerations and the different stages of product life in impact assessment. As we mentioned earlier, conducting sustainability analysis requires understanding production, pollution, and risk functions in assessing the impacts of policies on consumer and producer behavior. Estimating pollution functions, or damage functions in the case of climate change, requires new tools and data that are not part of traditional economic analysis. Furthermore, assessing the impact that biofuel policies or other components of the bioeconomy have on climate change requires life-cycle analysis because these products are produced at multiple stages. Thus, economic research in these areas leads to the development of new analytical tools that expand and enrich the purview of economics.

This type of analysis requires multidisciplinary cooperation between natural scientists, engineers, and social scientists and requires investment in infrastructure and data that are not covered by the mainstream economic research effort. Furthermore, research in biofuels suggests that the existing tools of life-cycle analysis that were developed by engineers are not appropriate for the purpose of economic analysis and therefore need to be modified and adapted to such analysis (Rajagopal, Vanderghem, and MacLean 2017). Similarly, the result of epidemiological and toxicological models used to assess the impact of pesticides need to be modified and adjusted to be used effectively in economic analysis (Cropper, Hammitt, and Robinson 2011). The expansion of economic research to cover environmental issues requires both new data and new methodologies. The availability of spatial data on agricultural production practices as well as output and greenhouse gases would allow better estimations of production and pollution functions. But because of their variability over space and time, one needs to develop methods to assess aggregate relationships that will allow the computation of aggregate outcomes (prices, quantities, etc.), as well as the development of mechanisms to translate the implications of these policies to different locations. This requires combinations of econometrics and general economic analyses that may be performed by multiple interacting models, and these integrated models will be a challenge for future research (Khanna and Zilberman 2012). The unique dimensions of research into sustainability and bioeconomy in terms of data, modeling, and the need for interdisciplinary collaboration requires unique and dedicated research funding and support, and amplifies the justification for distinct disciplines of agricultural and resource economics.

To be effective, the new research on sustainability and bioeconomy requires effective communication and dissemination strategies. This research has implications to farmers, landowners, and consumers, as well as policymakers around the world. Moreover, the implications are relevant from local water districts up to international organizations. They require multiple channels of communication with new content and new direction to existing extension and natural resource services that will need to utilize new technologies and recognize the changing structure of agriculture to communicate the data. The need to incorporate new knowledge and considerations will challenge farmers, but new information technologies can enhance their capacity to take advantage of new opportunities. Extension may need to develop more interactive services to address the needs of farmers, work more closely with intermediaries like consultants, and further train service providers in order to make effective use of new capabilities. Similarly, researchers will need to communicate the results at different levels. Agricultural and resource economists will need to communicate and interact with natural scientists, and publish in multidisciplinary outlets more frequently. Agricultural economists cannot afford to be in a silo, and journals like *Science* and *Nature* should be considered as part of their desired outlets of communication as much as the *American Economic Review, American Journal of Agricultural Economics, and Applied Economic Perspectives and Policy*. At the same time, there is a growing value of non-technical communication to non-academic professionals as well as the public. We are facing an era of fast changes in agricultural and natural resource management, and we need to provide the public with the means and information needed to understand these changes and adjust.

Finally, considerations of sustainable development and the growing importance of the bioeconomy require modifications to education and training. Undergraduates and graduates in agricultural economics need to be more aware of basic models and tools. They need to have the capacity to use and interpret data and simulations, as well as interpret results from other disciplines for their work. Similarly, there is a growing need to increase economic literacy in other disciplines. Biologists that develop new biotechnologies need to understand returns on investments, supply chains, and intellectual property rights in order to be effective in their future activities. Thus, the infusion of economic information to other disciplines and the expansion of science within the economic curriculum is essential. Furthermore, there may be a need to expand the range of topics covered by traditional agriculture schools with the growth of the bioeconomy. Moreover, with increasing life expectancy and the high rate of change in knowledge, it is essential to develop mechanisms that allow for life-long learning for professionals and the public about agricultural and environmental issues, especially in the context of sustainable development and the bioeconomy. This may require universities to expand their course offerings for continued education and provide a new area of collaboration between university and extension.

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