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# Technology and the future bioeconomy

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**Abstract**

New discoveries in life sciences and the challenge of climate change are leading to the emergence of the bioeconomy where basic methods of advanced biology are applied to produce a wide array of products while also improving environmental quality. The emergence of the bioeconomy is a continuing evolutionary process of transition from systems of mining nonrenewable resources to farming renewable ones. This transition benefits from the modern tools of molecular biology that have expanded the human capacity to breed new organisms and utilize them to increase productivity in agriculture and fisheries as well as produce a wide array of products that were extracted in the past. This transition is leading to the integration of the agricultural sector with the energy and mineral sectors. The introduction of biotechnology has already improved the productivity of medicine as well as agriculture but, in the case of agriculture, has encountered resistance and regulatory constraints. The evolution of the bioeconomy requires continuous public investment in research and innovation as well as the establishment of a regulatory framework and financial incentives and institutions that would lead to continuous private sector investment in the development and commercialization of new products. One of the biggest challenges is the development of a regulatory framework that would control possible human and environmental externalities from new biotechnology products and, at the same time, not stifle innovation.

*JEL classifications*: Q1, Q2, Q3, Q4, Q5

*Keywords*: Bioeconomy; Renewable resources; Nonrenewable resources; Biotechnology; Biofuel; Discounting; Sustainability

## 1. Introduction

Concern about climate change, population growth, pollution, and the rising prices of essential inputs, such as fuels, has led to increased emphasis on the development of technologies that are perceived to be renewable and sustainable. The 20th century discovery of deoxyribonucleic acid (DNA) and our increased understanding of life sciences have led to research aiming to expand the use of modern biology-based technologies that utilize organic matter for the production of outputs that are for both human consumption and industrial use. The "bioeconomy" is defined as the part of the economy that utilizes new biological knowledge for commercial and industrial purposes and for improving human welfare (Enriquez-Cabot, 1998).

This article aims to understand the basic forces that will shape the emergence of the bioeconomy, the challenges that it presents, and its implications for the macroeconomy. First, we review the economics of natural resources to understand where the bioeconomy fits within a larger economy. Then, we model it and identify some of the challenges and trade-offs facing the emerging bioeconomy. Finally, we will use this information to make policy recommendations and review its implications for agriculture.

## 2. The bioeconomy in the context of resource economics

The resource economics literature distinguishes between different types of resources. The first distinction is between renewable and nonrenewable resources. Nonrenewable resources, such as minerals and oil, have finite stocks even though their availability may increase with discoveries in the short run. The seminal work of Hotelling spawned a large body of literature to analyze the economics of these resources (Fisher, 1981). Conversely, renewable resources can be produced at a certain level infinitely and the literature (Conrad and Clark, 1987) identifies conditions for the optimal use of renewable resources. Renewable resources can be divided into physical (water renewed by rainfall, wind, sunlight) and living (forests, fish, and other

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wildlife) systems. Note that most renewable and nonrenewable resources are exhaustible if the rate of extraction is faster than the rate of regeneration. The main distinction is that, at a certain level of utilization, renewable resources can potentially be sustained forever.

Living systems can be divided into systems that are harvested and systems that are farmed. In the case of major agricultural commodities, such as grain and livestock, humans transitioned from harvesting to farming thousands of years ago when agriculture emerged. A more recent and similar transition is seen in the shift from fishing to fish farming (Berck and Perloff, 1985) and, currently, biofuels serve as an example of a shift from a harvesting system to farming. There are many other examples of biological processes being harnessed to produce fine chemicals, representing another transition from nonrenewable to renewable resource use. Thus, a key element of the bioeconomy is the facilitation of this transition. The productivity of renewable resources is dependent on climatic and biophysical conditions. Thus, as the bioeconomy emerges, it has to adapt to climate change.

The bioeconomy will replace products that are derived from nonrenewable resources, such as fossil fuels, with products derived from renewable resources, such as biofuel, and allow for the transition from products derived from harvesting to products that are farmed. The bioeconomy will also expand the range of products that are farmed to include fine chemicals, such as beta-carotene. Therefore, the modern bioeconomy farms growing these new products will not be idyllic, like that of "Old McDonald," but, rather, high-tech facilities. Another major aspect of the bioeconomy will be the expansion of the human role in the breeding process. Using advances in biotechnology and synthetic biology, humans will modify and design new organisms for harvesting valuable products.

## 3. Utilizing renewable *vs.* nonrenewable resources

The transition from mining nonrenewable resources to harvesting renewable resources in order to produce an input can drastically change the economics of businesses that produce a product, such as energy. An oil company has high search costs and high initial investment but, once a well is discovered, it will have relatively low variable costs. These variable costs may increase over time as the stock decreases and is eventually depleted.

However, if fuel is produced with a renewable system, such as biofuel, then there is an even larger initial investment, which goes toward expenses, such as purchasing land and building a refinery to convert the feedstock into fuel. However, due to the renewable nature of the system, the output remains constant or may even increase over time. In addition, variable costs may decline over time because of technological changes.

The profile of expected earning for a given investment is shown in Fig. 1. The transition from a nonrenewable to a renewable resource becomes more profitable as the search cost

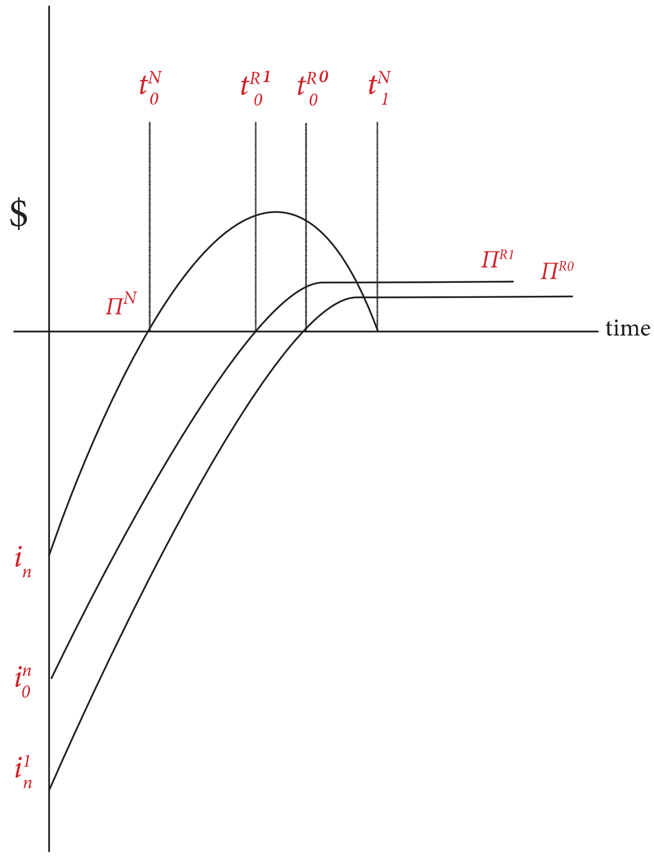


Fig. 1. Profitability per unit of time under both systems.

for the new wells of nonrenewable resources increases and the cost of conversion from renewable resources to a final product declines with research and development.

Both systems require an initial period of investment followed by the period of production. The (expected) net profit per unit of time under the nonrenewable system is $\prod^N$. Note that, for an early period, where $0 \leq t < t_0^N$, $\prod^N$ is negative and, when $t_0^N \leq t < t_1^N$, $\prod^N$ is positive. After $t_1^N$, it is no longer profitable to mine the resource.[1] Let us consider a traditional renewable-resource system where profit per unit of time is $\prod^{R0}$. Let us assume that the renewable technology requires a larger investment but, once in operation, it continues to deliver profits. Thus, firms invest in the renewable system during the initial period, $0 \leq t < t_0^{R0}$ but, after $t_0^{R0}$, they continue to operate the system indefinitely. There is obviously a difference in the time profile of renewable versus nonrenewable resources, and long life expectancy of nonrenewable resources may make investments in them attractive, especially during periods of low interest rates. If social discount rates are smaller than private interest rates, there will be underinvestment in renewable resources without intervention. Furthermore, if the nonrenewable resource generates more pollution than the renewable resource, then taxation of

[1] It may be profitable to mine the resource during periods of high resource prices until the resource is exhausted.

environmental externalities may make investment in renewable resources more attractive.

There is nothing morally wrong with the use of nonrenewable resources as long as the net social benefits considered (including externalities) justify it. We expect in most cases to observe an "internal solution" where both nonrenewable and renewable resources are utilized. Consider the case where a product can be obtained by renewable and nonrenewable production. The nonrenewable quantity produced at period $t$ is $X_t^N$, and the renewable quantity is $X_t^R$. Let $MSC_N(X_t^N)$ and $MSC_R(X_t^R)$ denote the marginal social cost for nonrenewable and renewable quantities, respectively. Each of these marginal social costs is the sum of the marginal production of each quantity ($MC_i(X_t^i)$ for $i = R, N$) plus the user costs ($MFC_i(X_t^i)$ for $i = R, N$)—user cost is the marginal discounted future cost of extracting or harvesting in period $t$—plus the marginal externality costs of quantity extracted or harvested in period $t$ denoted as ($MEC_i(X_t^i)$ for $i = R, N$). Thus,

$$MSC_i\left(X_t^i\right) = MC_i\left(X_t^i\right) + MFC_i\left(X_t^i\right) + MEC_i\left(X_t^i\right) \text{ for } i = R, N.$$

Along the optimal path, the quantities of the renewable and nonrenewable resources produced are determined so that their marginal social costs are equal and both are equal to demand for the two products denoted by $D(X_t^T)$, where total output is $X_t^T = X_t^N + X_t^R$. Thus, along the optimal path,

$$MSC_N\left(X_t^N\right) = MSC_R\left(X_t^R\right) = D\left(X_t^N + X_t^R\right).$$

The optimal outcome is depicted in Fig. 2, where total quantity, $X_t^T$, is determined where demand and the aggregate social marginal costs intersect (point A) and set a price, $P_t$. The optimal quantity of renewable resources harvested and nonrenewable resources mined are depicted at points B and C in Fig. 2. Because of the decomposition of the marginal social costs, the externalities associated with the renewable and nonrenewable resources will affect the optimal level of products yielded from the two resources.

Recycling can be interpreted as another form of renewable resource use. The stock of used products (used cars, recycled paper products, etc.) is processed to produce outputs that would otherwise be produced from inputs that are mined or harvested. Optimal recycling levels are found when the marginal social cost of recycling reaches the marginal social cost of supply by mining or harvesting. As the stock of extractable resources declines over time and the stock of used products increases over time, the importance of recycling increases.

## 4. Harvesting *vs.* farming

The transition from hunter-gatherer societies to farming systems is considered a major step in human evolution. There are trade-offs when determining whether to obtain a product through harvesting a renewable resource or by farming. According to Carlson and Zilberman (1993), the production of a crop or livestock is a multistage process, which includes breeding, feeding, and harvesting. A major difference in the hunting activities of each system is the effort that is exerted by humans in each stage of the production process. The fisherman or hunter only invests effort in the harvesting stage while farmers invest in all stages. They plant the crop (breeding), fertilize it, and harvest it. The contribution of humans to these three stages varies across location and situations. Human contribution to breeding has increased over time due to a more thorough understanding of genetics as well as continued development of techniques of selective breeding and modern biotechnology. There is a trade-off in allocating efforts to the different stages of production between the farming and harvesting systems. Farming systems invest resources in breeding and feeding in order to reduce the efforts of harvesting. The domestic cow is bred to gain weight and be immobile so that it is easy to harvest. Farming systems have evolved and intensified over time, relying increasingly on exported inputs (water, fertilizers) and advancements in knowledge to increase yields that support growing populations.

The fundamental works on the economics of fisheries and forestry suggest that, in natural renewable systems, harvesting costs decline as the size of the population increases (Clark, 1990). As the size of the human population increases the demand for harvested goods, the amount harvested increases, which, in turn, leads to reductions in the size of wildlife populations. Analytical models and empirical examples (Conrad and Clark, 1987) emphasize the ecological pressure that may arise from population growth and the collapse that uncontrolled growth in harvesting may usher. Thus, increased population increases the relative value of farming versus harvesting systems. There is a large and distinguished literature on the evolution of farming systems (Boserup, 1965). Binswanger and McIntire (1987) emphasize the role that population growth plays in moving from systems of slash and burn to more intensive farming systems.

Humans started as hunter-gatherers and then gradually transitioned to farming, including the production of agricultural crops and animal husbandry. Even presently, people meet their demands for meat through both farming and hunting. Optimal allocation of resources between hunting and farming occurs when the marginal net cost of breeding + feeding + harvesting in farming systems is equal to the marginal net cost of hunting. Thus, improved breeding technologies and improved efficiency of feeding will reduce the marginal cost of farming and increase the share of crops and meats that are provided by farming rather than harvesting. One of the main byproducts of the improved productivity of farming systems is the reduced reliance on hunting, actually leading to the expansion of wildlife populations. Similarly, increased productivity of farming through breeding has led to intensification and reduced land use in agricultural production while increasing wildland.

While the farming of crops and meats has been established for thousands of years, aquaculture is relatively new. But increased knowledge and improved techniques in fish husbandry has increased the share of fish and seafood produced by farms.

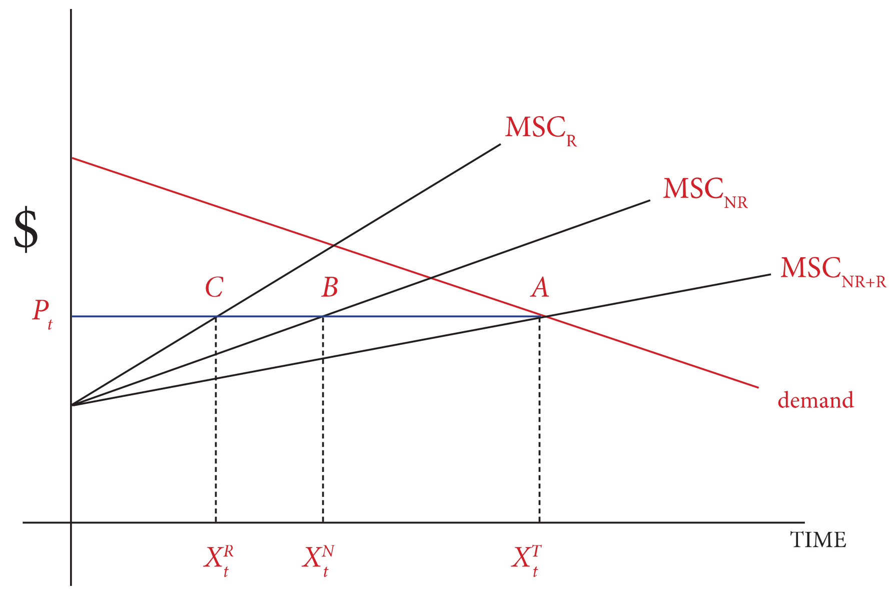


Fig. 2. Optimal allocation between renewable and nonrenewable resources.

In almost all cases, domesticated varieties of crops and animals are different than the wild varieties. For example, domesticated corn is much larger and more productive than the wild varieties from which it originated. Breeding efforts and improvements in breeding over time have increased the cost-effectiveness of these techniques and have led to reductions in environmental footprints.[2] The transition to farm systems leads to a substitution from land and labor used in harvesting and hunting systems to energy and human capital that are needed in farming systems. This substitution is sometimes associated with a reduction in the environmental footprint of agriculture as less land is required to produce the same quantity. One of the important byproducts of the introduction of aquaculture is the reduced pressure on natural fish populations. Advancements in biology are also likely to introduce farmable products, such as agar (an alga that has industrial applications and has been depleted) as well as algae that can be used for producing food additives, such as beta-carotene, and other fine chemicals. Biofuels represent another set of products that are being farmed and are an important part of the bioeconomy. There has been growing concern about the impacts of biofuels on the price of food as the growing demand for food and biofuel have been the major contributors to rising prices of agricultural commodities (Zilberman et al., 2011). The future of biofuels will depend on improvements in agricultural and, in particular, biofuel technologies.

## 5. The role of technology

The key factors in the transition from hunting to farming are knowledge and the development of new technologies, which may include improved feeding systems, such as fertilizers, crop protection that reduces pest damage, and breeding of varieties that are more productive and less susceptible to disease. Alston et al. (1995) documents the high rate of return on research and suggests that improvement of human capital and human skills combined with appropriate investments were major contributors to the intensification and improvement of farming systems. While the discovery of the basic principles of genetic and selective breeding associated with farming have had an immense impact and have been major contributors to the Green Revolution, the introduction of new biotechnologies that are based on a better understanding of the principles of molecular and cell biology are also major contributors to further increases in agricultural productivity and, in particular, increases in yield per acre and reductions in the use of pesticides (Qaim and Zilberman, 2003). Sexton and Zilberman (2011) argue that adoption of genetically modified (GM) varieties in corn and soybeans has contributed to significant increases in production, enabling societies to meet the drastic increase in demand for food associated with increased incomes in Asia. Furthermore, increases in the adoption of GM technology in Europe and Africa and the introduction of GM wheat and rice, which have not been used before, may further reduce the environmental footprint of agriculture and increase the amount of land available for biofuels.

There are many manifestations of research on improved productivity through feeding. The three most prominent examples include the development of fertilizers, irrigation, and the development of advanced animal diets. Research has not only improved input technology but has also helped in continuing the development of how inputs are applied in order to enhance input-use efficiency. Caswell et al. (1990) argued that output is a function of effective inputs consumed by the crop where

[2] Aquacultural practices are still in their infancy and have much room to improve in terms of efficiency and, especially, environmental impacts.

effective input is the product of actual input and input-use efficiency. Technologies that improve input-use efficiency (e.g., drip irrigation in the case of water and precision farming in the case of fertilizer) tend to increase production and reduce input use and pollution. If the process of feeding is interpreted as supporting the growth of the crop,[3] then a key element of this process is protection against disease and pests. Lichtenberg and Zilberman (1984) introduced the notion that actual output is measured by *potential output* * (1 – *damage*), and pesticides are damage-control agents that help increase yield. GM organisms (GMOs) are an example of a breeding technology that actually serves to reduce pest damage thus falling in line with our expanded definition of this feeding process. One of the major contributions of research and innovation has been seen in the reduction of the harvesting costs in farming. As mentioned earlier, the transition from hunting to farming may have occurred as a result of the high cost of harvesting in hunting systems compared with that of the combined cost of breeding, feeding, and harvesting in farming systems. One way in which farming systems reduce the cost of harvesting, especially in the case of wildlife, is through the use of fences. Selective breeding as well as genetic engineering result in varieties that increase output within a unit of space thus reducing harvesting costs. Furthermore, the development of monoculture is, to a large extent, motivated by a desire to reduce harvesting and crop-maintenance costs. As technology improves and precision farming and nanotechnology continue to allow more specialized treatment of crops, one may expect the introduction of diversified farming systems that produce more outputs with lower operational costs.

The bioeconomy consists of industries that rely on biological processes to produce major products. Fermentation was a base for the traditional bioeconomy and resulted in a myriad of products, including wine, beer, cheese, and a variety of pickled foods. Fermentation played a crucial role throughout the world because it allowed food to be stored during the off-season when fresh food was not available and, thus, enabled humans to expand the range of ecosystems in which they could live (Zilberman and Kim, 2011). Furthermore, alcoholic products were very valuable medicinally as well as nutritionally. Artisans developed these first-generation products derived from fermentation, and producers of these products had trade secrets giving them monopolistic power. Altogether, the fermentation-based industrial bioeconomy consists of thousands of products differentiated by quality, purity, and location.

The artisan-based fermentation industries emphasized the time-tested, best-management practices. However, over time, the role of science in traditional industries, such as wine and beer, became more prominent, leading to drastic changes in industry practices and helping its expansion. The wine industry is one obvious example, and development in oenology has been instrumental in the New World industry and has even led to changes in practices in the Old World. While the traditional fermentation-based bioeconomy originated from the developments of artisans, over time, it became a vehicle for the application and development of science. In no place was this more apparent than in France, where one of the greatest medical scientists of all time, Louis Pasteur, was a scholar of wine and fermentation. Thus, fermentation industries benefited from modern science and contributed to it as well.

Modern biotechnology was triggered by the discovery of DNA in the 1950s and is associated with ongoing scientific discoveries that have been made since. Applications for modern biotechnology are perhaps the most significant products of the new educational industrial complex that emerged in the United States and other Western countries in the second half of the 20th century (Graff et al., 2002). To a large extent, universities supported by the public sector funds (National Institutes of Health, National Science Foundation, etc.) have been producing major innovations in life sciences that are patented. The rights to apply many of these patents have been transferred to the private sector via organizations, such as the Office of Technology Transfer. Private companies invest in further research and development activities that result in commercial products and, in turn, pay universities royalties arising from the sales of these products. The introduction of the Bayh-Dole Act of 1980, which gave universities the right to patents supported by federal agencies and enabled them to sell these rights to private companies, accelerated technology transfer from the public to the private sector. Graff et al. (2002) suggest that, since some of the major corporations were reluctant to invest in universities' patents, offices of technology transfer were helping university faculty to collaborate with venture capitalists and establish start-up companies that aim to commercialize modern biotechnology applications. Some of the biggest names in biotechnology, such as Genetech and Amgen, are examples of this. Frequently, these types of start-ups are taken over by major established companies. Monsanto, for example, incorporated Calgene and several other ag-biotech start-ups.

Further, evolution of the education–industrial complex has occurred recently as major companies have begun to recognize the creative engine embodied by universities in the generation of new biotechnologies. An example of this involves companies in the energy sector who have established major alliances with universities to develop new types of biofuels, e.g., the U.C. Berkeley Energy Biosciences Institute, the research alliance between Stanford and Exxon Mobile, and the partnership between U.C. Davis and Chevron among others. There are several major biotechnology industrial hubs being developed around universities, including one in the Bay area, one in Boston, and another in San Diego, and similar activities are emerging in England, Israel, and Singapore. So the model of university research in the life sciences that triggers new innovations developed by industry is a major contributor to the development of the bioeconomy.

However, one of the drawbacks of this model is that there is a gap between optimal research from the private sector versus

[3] One may consider the notion of "sustaining" to incorporate both feeding and protection. However, we use the narrow, yet more concrete, term "feeding."

the social perspective. Private companies are less likely to develop technologies that meet the needs of specialty crops[4] and the poor, each of which are socially desirable. Development of technologies that meet the needs of the poor and specialty crops requires resources from public sectors, both nationally and globally, as well as nongovernmental organizations, such as the Gates Foundation. When the private sector in developing countries aims to develop technologies that serve the needs of the poor, they may need access to intellectual property controlled by major corporations. Since much of the innovation that is used for modern biotechnology was originated by the public sector (Graff et al., 2003), there were suggestions regarding the establishment of institutions, such as a clearinghouse for intellectual property, that would give rights to technology developers to use public sector intellectual property rights (IPRs) for the purposes of specialty crops and the poor (Graff and Zilberman, 2001).[5] Indeed, several organizations, including the Public Intellectual Property Resource for Agriculture (PIPRA) and the Africa Technology Foundation, have been established to facilitate the development and commercialization of innovations to meet the needs of the poor in developing countries. Thus, the development of the bioeconomy in developing countries may require more direct involvement from the public sector farther up in the product supply chain in order to compensate for the limited ability of consumers to pay for new biologically based products. Economic growth would reduce the need for public sector involvement in technology development, yet we expect the link between university research and private sector innovation to be crucial in the development of the bioeconomy.

## 6. Indirect effect of the transition to the bioeconomy

On the surface, a transition from obtaining a product by harvesting renewable resources rather than mining nonrenewable ones is an improvement. It is perceived to be more "sustainable." The progression from hunting to harvesting and finally to farming appears beneficial from an environmental standpoint. But the reality is more complex. Increased intensification of agricultural production requires the use of inputs, such as fertilizer that may be nonrenewable (phosphorus). Intensification may also entail the diversion of water, which may have negative ecological implications and result in pollution and soil erosion. The assessment of the "sustainability" as well as other environmental effects of these bioeconomy practices must take into account the myriad of activities associated with renewable systems.

This set of issues has been emphasized in the assessment of the transition from fossil fuel to biofuel. While the actual consumption of biofuel utilizes energy generated through the process of photosynthesis, the farming of the biofuel feedstock and the conversion of the feedstock to fuel require extra energy and generate greenhouse gas (GHG) emissions. Life cycle studies that evaluate the overall quantity of GHG emissions associated with the production of biofuels have identified instances where the transition from fossil fuel to biofuels may increase overall GHG emission (Rajagopal and Zilberman, 2008).

The literature on the GHG effect of biofuels has utilized life cycle analysis and found that not all biofuels are alike. While both Brazilian sugarcane ethanol and corn ethanol lead to reductions in GHG emissions relative to the fossil fuels that they replace, biodiesel produced from soybeans may result in a GHG deficit relative to diesel (Laborde, 2011). There is growing evidence that processes of learning by doing have reduced GHG emissions in the production of biofuel in both the United States and Brazil. Thus, one of the challenges of the new biofuel sector and the bioeconomy is to reduce the environmental footprint of biofuels.

The transition to farming as well as the increase in intensification has to be viewed through the perspective of its overall impact on the environment, which may require life cycle analysis. Such assessments may reveal that certain renewable production processes are inefficient and costly in terms of overall market and nonmarket inputs.

When economic efficiency is the paramount criteria for assessing resource allocation, products produced by renewable systems may not be optimal if costs of production, correctly evaluated to take into account externalities and other social costs, are greater than that of nonrenewable systems. This may be one reason why the transition to the bioeconomy will be gradual. Frequently, products (e.g., fuels) are obtained more cheaply by mining nonrenewable resources than by growing them in a renewable fashion even if the social costs are taken into account. The introduction of policies that lead a producer to assess the social cost of their activities combined with technological change may accelerate the transition from nonrenewable to renewable production. Still, this transition will take time.

Even after the transition from nonrenewable to farming systems, some nonrenewable inputs may be used. Ideally, renewable systems would only rely on renewable inputs but this is not always socially optimal because some nonrenewable inputs are abundant and have low social costs. The transition to systems that rely solely on renewable inputs requires innovations that will lead to better management systems in terms of the precise use of inputs, recycling, crop rotation, nutrient cycling, etc. It may require new products as well as different seed varieties, e.g., crop varieties that are able to fix nitrogen. However, development of such technologies and their adoption will require policies that provide support for research and development as

[4] The U.S. Food, Conservation, and Energy Act of 2008 has defined specialty crops as "fruits and vegetables, tree nuts, dried fruits, horticulture, and nursery crops (including floriculture)" (Agriculture Marketing Service, U.S. Department of Agriculture, 2012.)

[5] In many cases, rights to intellectual property are limited to certain regions and in other cases patents are not registered in many developing countries. Furthermore, corporations may be willing to provide the rights to use their technology for crops that target the poor in developing countries. Thus, PIPRA and similar organizations assist technology developers in developing countries in navigating the IPR legal thicket.

well as pricing that will make adoption worthwhile and their introduction will take time.

Another important dimension of the transition to the bioeconomy is the expansion of farming activities to include the production of fuels, fine chemicals, and other products. This may increase both the environmental footprint of agriculture as well as the area consumed by human systems and may, in turn, lead to the destruction of areas of wilderness. Expansion of farming systems led to deforestation in Europe, North America, and Asia, and the expansion of biofuel and aquaculture systems is likely to result in the conversion of land used for environmental services, such as forests, to land used for agricultural activities. The expansion of farming activities competing with food production may lead to increases in the price of food, raising food security issues. One of the challenges of expanding the range of products produced by agriculture is increasing the productivity of agricultural production to make food affordable globally while also expanding the range of products produced by farms. The environmental impact of the expansion of farming depends on the extent to which agricultural land will be expanded and which land will be converted to farming. Much of this expansion depends on the productivity of these farming activities. For example, production of a given volume of sugarcane ethanol will require less than half the amount of land if biotechnology can double the yield of sugarcane or increase the amount of fuel produced per unit of feedstock. Thus, the expansion of land use for products that are farmed makes more sense from an environmental perspective if the efficiency of the farming and processing is greater and if these processes are less polluting. The development of crop systems that are highly productive and generate minimal side effects is the reason that biotechnology that relies on modern biology for improved crop breeding is likely to be a crucial element of the bioeconomy. However, it should be augmented with the use of advanced methods of ecological and precision farming.

While the expansion of farmed land and the amount of water available will be part of the expansion of the bioeconomy, introduction of land- and resource-development policies that steer development away from land and other resources, which embody high ecological and social value in nonagricultural use, and move it toward those supporting land and resource conversion to farming will improve social welfare. The improvement of monitoring and natural resource assessment technologies provide a scientific base to such policies. However, the challenge is the political will necessary to introduce and enforce them.

## 7. Regulation and acceptance

While, in principle, society, and, in particular, the environmental community, is supportive of the transition to the bioeconomy and renewable systems, there is resistance to the establishment of specific initiatives. This is not a new phenomenon. Technologies (including the plow, tractor, and cotton gin), selectively bred crops (including the potato and tomato), and the germ theory of disease and pasteurization are just a few among many innovations that have encountered resistance (Olmstead, 2012). Thus, new biotechnologies, such as GMOs, are in good company. The environmental movement has a tradition of emphasizing protection and defense and is thus concerned about new innovations that, on the surface, may have the potential to cause harm. However, the tendency to preserve and sustain the status quo is not compatible with processes, such as climate change, and impacts associated with increased income and population growth. Furthermore, political–economic arguments suggest that the introduction of new technologies may be opposed by groups that are likely to suffer economic losses associated with the adoption of these technologies (Rausser et al., 2011). Thus, pesticide manufacturers are likely to support actions that slow the introduction of GMOs and some farmers may not welcome them due to their potential to lower commodity prices (Graff and Zilberman, 2001). Consumers that may benefit from low prices may not be aware of such benefits and could be susceptible to fear and persuasion from environmental groups that support restrictive regulation. While regulation is important both for the protection of society as well as for the development of goodwill toward the technology, excessive regulation may be harmful to technological innovation, especially given the importance of private sector investment in the development of new biotechnologies.

While GM varieties have been adopted extensively in the production of corn and soybeans primarily in the United States and Latin America and in the production of cotton in many countries, GM technology has not been introduced in wheat and rice and has been practically banned in Europe and much of Africa. Furthermore, the regulation of GM is expensive and some argue excessive (National Research Council, 2010). One of the main side effects of excessive regulation is that the ability to introduce new GM varieties is limited to a few major companies that have the resources to invest in the regulatory process, stifling new innovation (Just et al., 2006). Potrykus (2010) argues that the introduction of Golden Rice has been delayed by several years due to redundant regulation, and Graff et al. (2009) suggest that the ban of GM in Europe has led to the contraction of biotechnology innovation and has gone on to stifle further innovations. Thus, one of the major challenges in developing the bioeconomy is the establishment of an efficient regulatory system that will incorporate environmental constraints while enabling socially desirable innovative activities.

## 8. Conclusion

New discoveries in life sciences and the need to reduce externalities, such as GHG emissions, from production systems are leading to the emergence of the bioeconomy where basic methods of advanced biology are applied to produce a wide array of products while also improving environmental quality. The emergence of the bioeconomy is a continuing evolutionary process of transition from systems of mining nonrenewable resource to farming renewable ones. Furthermore, modern tools of molecular biology have expanded the human capacity to breed new organisms and utilize them to increase productivity in agriculture and fisheries as well as produce a wide array of products that were mined originally. This transition to the bioeconomy is expanding the range of products produced by agriculture beyond food and fiber and is leading to the integration of the agricultural sector with the energy and mineral sectors among others. The enhancement of the productivity of agricultural systems, taking into account new emerging technologies, including biotechnology, precision farming, and ecoagriculture, will be required in order to meet growing demand from agricultural systems without drastically increasing their environmental footprint. However, the evolution of the bioeconomy requires continuous public investment in research and innovation as well as the establishment of a regulatory framework and financial arrangements that would lead to continuous private sector investment in the development and commercialization of new products. One of the biggest challenges is the development of a regulatory framework that would control possible human and environmental externalities from new biotechnology products and, at the same time, not stifle innovation.

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