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Technology and the Future Bioeconomy

David Zilberman, UC Berkeley zilber11@berkeley.edu

Eunice Kim, UC Berkeley eunicemikim@berkeley.edu

Sam Kirshner, UC Berkeley skirshner@berkeley.edu

Scott Kaplan, UC Berkeley scottkaplan@berkeley.edu

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Technology and the Future Bioeconomy

David Zilberman, Eunice Kim, Sam Kirshner and Scott Kaplan¹

Abstract

New discoveries in the 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 non-renewable resource to farming renewable ones. This transition benefits from modern tools of molecular biology that have expanded human capacity to breed new organisms and utilize them in order to increase productivity in agricultural production 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 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 lead to continuous private sector investment in development and commercialization of new products. One of the big challenges is the development of a regulatory framework that will control possible human and environmental externalities from new biotechnology products, and at the same time not stifle innovation.

Introduction

Concern about climate change, population growth, pollution, and rising prices of essential inputs like fuels has led to increased emphasis on development of technologies that are perceived to be renewable and sustainable. The twentieth century discovery of DNA and our increased understanding of the 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 paper aims to understand the basic forces that will shape the emergence of

¹ David Zilberman is a professor and Robinson chair at the University of California, Berkeley. Eunice Kim is a researcher at UC Berkeley. Sam Kirschner and Scott Kaplan are undergraduate students at UC Berkeley. This paper was supported by the Energy Biosciences Institute and Cotton Inc.

the bioeconomy, the challenges we face, and its implications for the macro-economy.

First, we review the economics of natural resources to understand where the bioeconomy fits within a larger production system, then we model it and identify some of the challenges and trade offs that face the emerging bioeconomy. Finally we will use this information to make policy recommendations and review its implications for agriculture.

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 non-renewable resources. Non-renewable resources, such as minerals and oil, have finite stocks, even though their availability may increase with discoveries in the short run their . 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 systems, for example, forest systems, fish, and other wildlife. Note that most renewable and non-renewable 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, 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 harvested 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 bioeconomy will replace products that are derived from non-renewable resources like fossil fuels with products derived from renewable resources, like 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 . Thus, 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.

Utilizing renewables vs non renewable resources

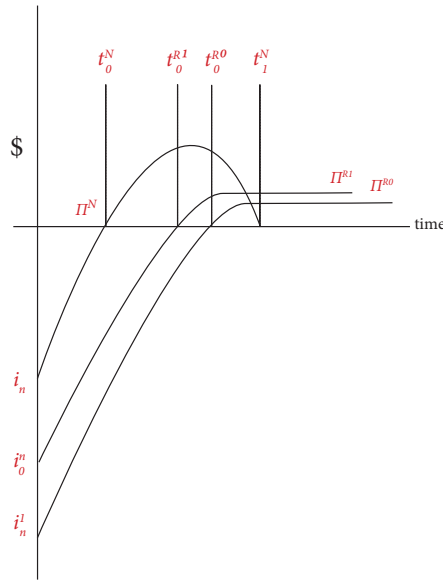
The transition from mining nonrenewable resources to harvesting renewable resources in order to produce an input can drastically change the economics of businesses that produce a product like energy. An oil company has high search costs and high initial investment, but once a well is discovered it will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

On the other hand, if fuel is produced with a renewable system, like biofuel, then there is an even larger initial investment, which goes towards expenses such as

purchasing of land and building of a refinery to convert the feedstock into fuel, but 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 Figure 1. The transition from a non-renewable to a renewable resource becomes more profitable as the search cost for new wells of non-renewable resources increases and the cost of conversion from renewable resources to a final product declines with research and development.

Figure 1: Profitability Per Unit of Time Under Both Systems.



Both systems require an initial period of investment followed by the period of production.

The (expected) net profit per unit of time under the non-renewable system is Π^N . Note that for an early period, where $0 \leq t < t_0^N$, Π^N is negative and when $t_0^N \leq t < t_1^N$, Π^N is

positive, and after t_1^N it is no longer profitable to mine the resource². Let us consider a traditional renewable resource system where profit per unit of time is Π^{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 non-renewable resources, and long life expectancy of non-renewable 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 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 non-renewable and renewable resources are utilized. Consider the case where a product can be obtained by renewable and non-renewable production. The non-renewable 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 non-renewable 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

² It may be profitable to mine the resource during periods of high resource prices, until the resource is exhausted.

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

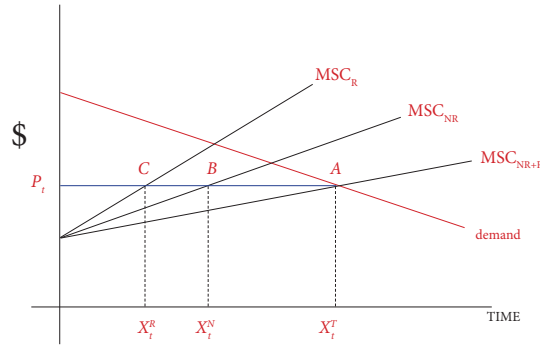
$$MSC_i(X_t^i) = MC_i(X_t^i) + MFC_i(X_t^i) + MEC_i(X_t^i) \text{ for } i = R, N$$

Along the optimal path, the quantities of the renewable and non-renewable 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

$X_t^T = X_t^N + X_t^R$. Thus along the optimal path

$$MSC_N(X_t^N) = MSC_R(X_t^R) = D(X_t^N + X_t^R)$$

Figure 2: Optimal Allocation between Renewable and Non-Renewable Resources



The optimal outcome is depicted in Figure 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 resource harvested and non-renewable mined are depicted at points B and C in Figure 2. Because of the decomposition of the marginal social costs, the externalities associated with the renewable and non-renewable 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.) are 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 used products increases over time, the importance of recycling increases.

Harvesting versus Farming

The transition from hunter-gatherer societies to farming systems is considered a major step in human evolution. There are tradeoffs when determining whether to obtain a product through harvesting of 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 between hunting activities is the efforts that are exerted by humans in the different stages of the production process. The fisherman or hunter only invest effort in the harvesting stage, while farmers invest in all stages. They plant the crop (breeding), fertilize it, and then harvest. The contribution of humans to these three stages vary 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 tradeoff 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 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 human population increases the demand for harvested goods, the amount harvested increases, which in turn leads to reductions in the size of wild life 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 vs. harvesting systems. There is a large and distinguished literature on the evolution of farming systems (Boserup 1963). Binswanger and McIntire (1987) and 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 by both farming and hunting. Optimal resource allocation suggests that the marginal net cost of breeding + feeding + harvesting in farming systems is equal to the marginal net cost of hunting, thus equating supply and demand. Thus, improved breeding technologies and improved efficiency of feeding will reduce the marginal cost of farming and will increase the share of crops and meats that are provided by farming rather than harvesting. One of the main byproducts of improved productivity of farming systems is the reduced reliance on hunting, actually leading to

expansion of wildlife populations. Similarly, increased productivity of farming through breeding has led to intensification and reduced land use in agricultural production while also increasing wildland.

While 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. In almost all cases, domesticated varieties of crops and animals are different than the wild varieties. Breeding efforts and improvements in breeding over time have increased the cost effectiveness of these techniques and have led to reductions in environmental footprints³. The transition to farm systems is leads to a substitution between land and labor used in harvesting and hunting systems with energy and human capital that are used in farming systems. One of the important byproducts of the introduction of aquaculture is the reduced pressure on fish populations. Advancements in biology are also likely to introduce farmable products like agar, an algae 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 represents another set of products that are being farmed and represent 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. 2012). The future of biofuels will depend on improvements in agricultural and in particular, biofuel technologies.

³ Aquacultural practices are still in their infancy and have much room to improve in terms of are efficiency and especially environmental impacts.

The Role of Technology

The key factor in the transition from hunting to farming is knowledge and development of new technologies, which may include improved feeding systems such as fertilizers, crop protection that reduces pest damage, as well as breeding of varieties that are more productive and less susceptible to disease. Alston, Norton and Pardey (1998) 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 basic principles of genetic and selective breeding associated with it has had immense impact and have been major contributors to the Green Revolution, the introduction of new biotechnologies that are based on better understandings 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 use of pesticides (Qaim and Zilberman [and Zilberman 2003](#)³). Sexton and Zilberman (2011) argue that adoption of 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 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, Zilberman, and Lichtenberg (1990) argued that output is a function of effective inputs consumed by the crop where effective input is the product of actual input and input use efficiency. Technologies that improve input use efficiency, for example 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 crop⁴, then a key element of this process is protection against diseases and pests. Lichtenberg and Zilberman (1992) introduced the notion that actual output is measured by potential output * (1 – damage), and pesticides are damage control agents that help increase yield. 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 results 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

⁴ One may consider the notion of ‘sustaining’ to incorporate both feeding and protection. However, we decided the narrow, yet more concrete term feeding.

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 eco-systems in which they could live (Zilberman and Kim 2011). Furthermore, alcoholic products were very valuable medicinally as well as nutritionally. These first generation products derived from fermentation were developed by artisans, 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 time tested, best management practices, but 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 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 1950's and is associated with ongoing scientific discoveries that have been made since. Applications for modern biotechnology are perhaps the most significant products the new educational industrial complex that emerged in the US and other Western countries in the second half of the 20th century (Graff, Heiman, and Zilberman 2002). To a large extent, universities supported by the public sector funds (NIH, NSF, etc) have been producing major innovations in the 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 enabled universities the right to patents supported by federal agencies, accelerated technology transfer from the public to the private sector. Graff, Heiman, and Zilberman (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 startup 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 startups are taken over by major established companies. Monsanto, for example, incorporated Cal-gene and several other agbiotechnology startups.

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, for example the Energy Biosciences institute, the research alliance between Stanford and Exxon Mobile, and the partnership between UC 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 vs social perspective . Private companies are less likely to develop technologies that meet the needs of specialty crops and the poor that is socially desirable. Development of technologies that meet the needs of the poor and specialty crops require resources from public sectors, both nationally and globally, as well as non-governmental 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 like a clearinghouse for intellectual property that would give rights to technology developers to use public sector IPRs for the purposes of specialty crops and the poor (Graff and Zilberman 2001)⁵. Indeed, several organizations including PIPRA

⁵ In many cases, rights to IP 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

(Public Intellectual Property Rights For Agriculture) and the ATF (African 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 further 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.

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 non-renewable (phosphorus). Intensification may also entail 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

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.

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 requires extra energy and generates 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 greenhouse gas effect of biofuels has utilized life cycle analysis and found that not all biofuels are alike. While both Brazilian sugarcane ethanol corn ethanol lead to reductions in GHG emissions relative to the fossil fuels they replace, biodiesel produced from soybeans may result in a greenhouse gas 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 US and Brazil, thus one of the challenges of the new biofuel sector and the bioeconomy is to reduce 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 non-market 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 non-renewable systems. This may be one reason why the transition to the bioeconomy will be gradual; frequently products (for example 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, but even still this transition will take time.

Even after the transition from non-renewable to farming systems, some non-renewable inputs may be used. It seems that an ideal renewable systems would only rely on renewable inputs, but this is not always socially optimal because some renewable inputs are abundant and their social costs are low. The transition of systems that relies on only renewable input requires innovations that will develop better management systems in terms of precise use of inputs, recycling, crop rotation, nutrient cycling, etc. It may require new products as well as different seed varieties, for example 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 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 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 like forests into land by 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 to what extent 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 the land of products that are farmed is 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 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 that embody high ecological and social value in non-agricultural use and movement towards ones 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.

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 and crops, including the plow, tractor, cotton gin, the potato, the tomato, and the germ theory of disease and pasteurization are just a few among many that 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, Swinnen, and Zusman 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 2003). Consumers that may benefit from low prices may not be aware of such benefits and may 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 towards 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 soybean primarily in the US and Latin America and in the production of cotton in many countries, GM 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 (NRC 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, Alston, and Zilberman 2006). Ingo Potrykus (2010) argues that the introduction of Golden Rice has been delayed by several years due to redundant regulation and Graff, Zilberman, and Bennett (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.

Conclusion

New discoveries in the life sciences and the need to reduce externalities like greenhouse gas 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 non-renewable resource to farming renewable ones. Furthermore, modern tools of molecular biology have expanded human capacity to breed new organisms and utilize them in order to increase productivity in agricultural production 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 eco-agriculture 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 lead to continuous private sector investment in development and commercialization of new products. One of the big challenges is the development of a regulatory framework that will control possible human and environmental externalities from new biotechnology products, and at the same time not suffocate innovation.

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