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Agricultural biotechnology and globalization: U.S. experience with public and private sector research

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Abstract

This paper examines the challenges and opportunities facing the agricultural biotechnology sector as it works to sustain innovations and further propagate its benefits into the new century. Drawing on US experience, we survey the milestones of technological, legal and economic precedence and discuss institutional mechanisms for public and private partnership that can help agricultural biotechnology fulfil its immense promise. In particular, we emphasize the importance of the public sector in facilitating private agency, via promotion of basic research, dissemination of innovations, and as a guarantor of property rights.

Keywords: public and private R&D; intellectual property rights

Introduction

We enter a new century equipped with remarkable tools for improving human circumstances; the most promising of these arising from biotechnology. Over the four decades since the discovery of DNA, extraordinary innovations have taken us to the brink of creation itself, conferring the ability to directly modify and even originate new organisms. There are inevitably controversial aspects of this technical revolution, and considerable research remains to be done on issues such as environmental risk and public health. Despite this, however, the economic potential of biotechnology is now firmly established in thriving life-science industries that are contributing to hundreds of aspects of medical therapy and also to the original life science, agriculture.

In establishing and sustaining this remarkable process of innovation, one of the most important factors was public–private partnership. In this paper, we examine the salient historical and present-day features of this partnership, with particular attention to the incentive properties needed to facilitate research and product development. In leading examples, such as the Green Revolution and medical biotechnology, we see how the right combination of economic institutions and legal precedence can deliver rapid and sustained innovation to the marketplace. Drawing upon these cases, we indicate how agricultural biotechnology (ag-biotech) can overcome a new set of challenges, posed mainly by globalization, in propagating its benefits across the greater part of humanity.

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The history of marketable scientific innovation, of which biotechnology is only one example, has special economic characteristics that merit restatement for the present discussion. Acting independently, both public and private agents tend to underinvest in research, albeit for different reasons. We give a brief overview of these conceptual issues in the next section. This is followed by a survey of recent history for indications of how public–private partnerships have evolved successfully, drawing lessons from the Green Revolution, medical biotechnology and ag-biotech itself. Then we discuss the special characteristics of biotechnology that relate to public–private partnership. The next section reviews the main institutional challenges to biotech proliferation, including imperfections in legal, educational and economic institutions, and discusses new initiatives for overcoming these. Most prominent among these is the Intellectual Property Rights (IPR) Clearinghouse; a new institutional mechanism that we believe can play an essential role in propagating the benefits of science in the service of mankind. The next section is devoted to a forward-looking discussion of the future of IPR in biotechnology, with implications for the wider agenda of technology and globalization. The a section reviews the special challenges and opportunities posed by globalization, including essential disparities in strategies for human-capital development. The final section of the paper presents concluding remarks.

The economics and role of public and private research: some theoretical considerations

There is a large body of literature on the economics of public and private research (Huffman and Evenson 1993; Alston, Pardey and Taylor 2001), including several lines of arguments that elucidate the role of research in the different sectors. In particular, we can distinguish between several major approaches to the problem. From the outset, we distinguish between innovations that are embodied in new products and those that are disembodied, including cultural practices etc. The private sector is more likely to conduct research and pursue development of embodied innovation. Our emphasis here is on this type of innovation, even though capturing the rents associated with improved seeds may be difficult and in some cases the private sector may underinvest.

Economic welfare analysis of research funding

Welfare economics attempts to identify resource allocations that improve overall societal economic welfare and compares them with choices made by the policymakers and the private sector. In particular, the public sector allocates resource funding with the putative aim of maximizing welfare for all sectors of society. Doing so, they strive to maximize the benefits to firms producing and using the technology and to consumers who utilize final products produced with this technology, minus the cost to generate and use the technology. On the other hand, the objective of firms generating the technology is to maximize their profits, i.e. revenues they obtain less the cost of the technology. Private-sector firms that engage in research and development (R&D) to generate new technologies take into account consumer interest only as it affects demand and revenues. However, consumers and users of publicly subsidized technologies are assumed to enjoy a surplus above what they pay for the technologies. Without this embodied surplus, their observed willingness to pay for new technology would be diminished.

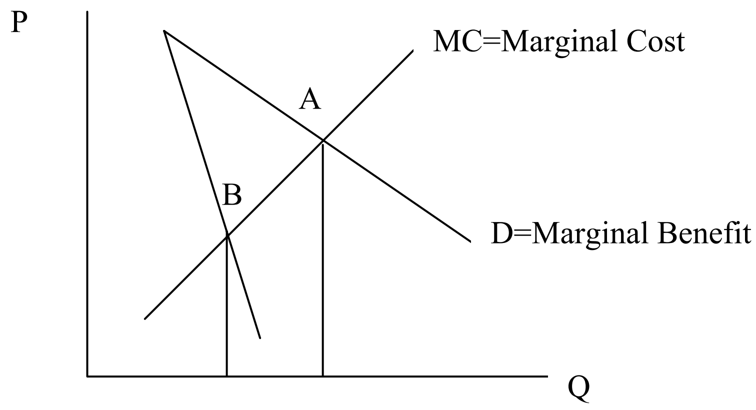

Figure 1a

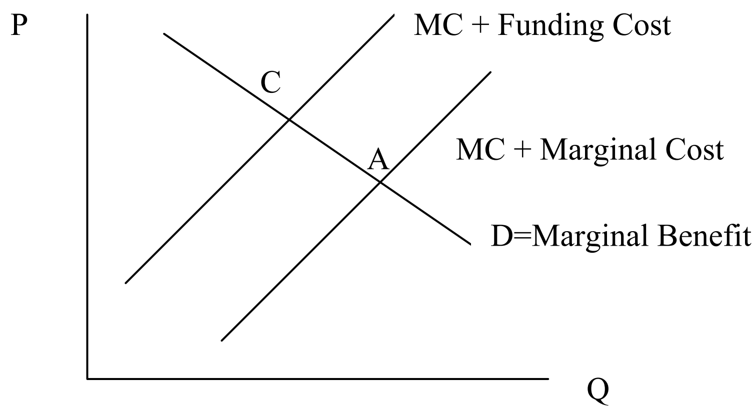

Figure 1b

Figure 1. (a) The private-sector under-investment in R&D due to monopoly power; (b) The public-sector under-investment in R&D due to resource constraint

However, these surpluses are not taken into account by producers, and this can lead to underinvestment by private agents who conduct R&D to generate technology products. Figure 1a illustrates this outcome. The private equilibrium is at point B (where marginal revenue is equal to the marginal cost of the technology), while the public optimum is at point A (where demand that is equal to the marginal benefit and combined consumer surplus is equal to the marginal cost of the technology).

Funding considerations

The private sector is assumed to finance investment and earn revenue only through the sale of products and services. Thus, they will invest in R&D activities seeking innovations that can be embodied in new products to be sold in the market. The best examples are mechanical innovations such as vehicles, chemical innovations such as new drugs or pesticides, etc. Private companies may also finance research that leads to patents with greater market potential than originally envisioned or than can be realized by the originating firm. The basic idea behind start-ups, for example, is to engage in high-risk research that may result in high-value patents that can then be sold to other companies that benefit from this type of research. On the other hand, private-sector companies are less likely to invest in research activities that result in knowledge and that cannot be protected by patents. Thus, imperfections in the patent system, in terms of both specificity and scope of protected intellectual content, are reflected by gaps (Black Holes) in the universe of marketable innovation because of what might be termed R&D aversion, unwillingness to invest because of incomplete IPR.

Public-funding considerations are also likely to limit the scope and absolute level of private-sector R&D activities. Private-sector research is financed for the most part by income. Willingness of the political system to impose taxes and the ability of governments to raise taxes can be expected to constrain investable funds available to the public sector, usually well below the level required to finance all activities whose social benefits exceed social costs. Therefore, in deciding how to invest the funds, public-sector decision makers must consider not only the explicit cost of each activity, but also the opportunity cost associated with their funding constraints. This opportunity cost arises because allocating an extra dollar to public research may entail reduction of public investment in other activities that are also socially beneficial.

We need to take into account that the opportunity cost of public funds results in significant reduction in public-sector investment in R&D (see Figure 1b). In an ideal case, where the opportunity cost of funding is zero, the optimal level of research will be determined at point A, but when the opportunity cost is high, it will be at point C. Thus, societies with weaker political systems will be less able to raise funds to support public research and will likely under invest in these activities.

One mechanism that will help public sectors to overcome the constraint associated with tax monies is direct assistance (e.g. donations). In developing countries, where research is generally targeted to support low-income populations and economic development, sources of funding include both taxation and aid. Again, aid is not sufficient to cover all the products that have positive net social benefits, and higher aid levels will reduce the opportunity cost of public project funding but not eliminate it.

Political economy and institutional considerations

There has been a growing realization among economists that public decisions are not necessarily made with the sole objective of maximizing social welfare, and political processes can result in choices that are less than optimal. To a large extent, these choices reflect the relative political power of social interests with varying degrees of influence over agencies that manage public allocation of resources. De Gorter and Zilberman (1990), for example, suggest that if farmers control the Department of Agriculture, which is the primary arbiter of funding of agricultural research, this may lead to underinvestment in research, regardless of the opportunity cost of public funds. By this reasoning, farmers only consider the impact of extra research on their own profit and not on consumer demand, except when it affects demand for agricultural products. The demand for food products is inelastic (namely, an increase in supply induces significant reduction in commodity prices). Thus, farmers who control research may not invest too heavily in supply-enhancing research, fearing drastic reductions in commodity prices that would harm producer profit, yet benefit consumers.

Having said this, agricultural research policies appear to differ across countries and even regions, but this can probably be accounted for by variations in the constituencies with salient influence over agriculture ministries and related policy institutions. In areas where consumers have a say about public research funding, we can expect to observe higher public (and subsidized private) investment because it may lead to increased supply and reduction in commodity prices. When agribusiness has significant influence on research funding, one can expect to see research with an emphasis on the supply and (especially) marketing and trade side. Because they can operate further downstream than farmers, agribusinesses are more tolerant of supply expansion if it can be translated into larger market capture.

As farmers remain the primary constituency in OECD agricultural policy, we can expect some degree of underinvestment relative to the optimum. One way to alleviate farmers' concerns about public research resulting in lower farm income is to subsidize farmers and increase their income. Agricultural policy in developed countries can be viewed as a package where public sectors have invested in research to increase the supply, and in return subsidize farmers to attenuate their induced losses. However, even this mechanism may not result in an optimal level of research because of the funding constraints faced by the public sector.

The organizational characteristics of public-sector research have important influences on the evolution of its agenda and priorities. Public-sector research is conducted in universities and research institutes. University professors produce joint products, teaching and research, and much day-to-day research at universities is conducted by PhD students. Both faculty and students are judged by their scholarship, which give primary recognition to originality. Thus, the nature of university research often leads to projects that are small-scale and self-contained, oriented toward conceptual breakthrough and relatively narrow intellectual outcomes. This line of research is essential for new innovations, but it is only part of a bigger picture.

In addition to conceptual origination, there is also an essential role for derivative or applied research that meets specific customer needs, e.g. testing for safety or conformity to other regulatory requirements. These types of research may be considered 'mundane' from a scientific perspective but they are essential for product development, i.e., to realize tangible social benefits from research investment. Partly for this reason, scientists and government research institutes are more oriented toward derivative research, and there is a division of labour within the public sector between the research conducted at universities and that at government research institutes. There are also significant and systematic differences between R&D done by universities and companies, as companies are much more interested in product development and revenues than enhancing general knowledge.

Systematic differences in institutional research emphasis lead to sorting of individual researchers based on their preferences and characteristics. They might be seen to pursue three ends: *fame, fortune and freedom.* Graff and Zilberman (2001) argue that universities may offer more fame and freedom, while the private sector may give more emphasis to the pursuit of fortune. Even within industries, there are differences in terms of risk and earning. Individuals who have both the temperament and opportunity to take more risk are more likely to be associated with start-ups financed by venture capitalists than to work in the secure and predictable environment of a major corporate research lab.

A thorough examination of the research environment, including organizational characteristics, economic incentives and political economy, can reveal much about the current landscape of research, how we arrived here, and what might be expected to appear on the near horizon of marketable innovation. To summarize for the present discussion, the results of research on research have several important implications.

Underinvestment both in public and private sectors

Research in both sectors is insufficient from a social perspective, and thus mechanisms to enhance investment in R&D and increase its productivity are likely to be valuable. These would include efforts to leverage complementarities between public and private research. The problem of underinvestment in research is much more severe in developing countries than in developed countries. The developed countries of the North have a larger capacity to finance public research, larger markets for agricultural producers, and more extensive commitments to human-capital development, all of which contribute to a good foundation for public and private agricultural R&D. In developing countries, aid can supplement public-sector research resources, but other challenges remain.

Complementarity of research characteristics conducted by the public and private sectors

The private sector will engage in R&D projects that will likely result in profitable products. Thus, R&D efforts should be directed at areas that are socially beneficial but are not profitable and not likely pursued by the private sector. Two categories for such research include research that has public-goods properties, namely, it results in outcomes that can be shared by others without the capacity to claim ownership, and research that may lead to 'orphan products'. This is research that ends up in products that have insufficient revenues and the potential to cover the costs. However, if one adds the consumer and social surplus to this revenue base, then the net social benefit exceeds social costs. Two typical 'orphan' markets are specialty crops in developed countries and subsistence crops in developing countries. The definition of orphan markets is evolving over time as the cost of R&D of new products declines and the private sector becomes more unlikely to engage in these research activities.

Importance of intellectual property rights protection

Since public investment in R&D depends on the earning capacity, mechanisms that enhance, for example, functions of well-defined property-rights systems with effective enforcement mechanisms and low transaction cost, are likely to induce the private sector to engage in research activities. However, since patents, in essence, generate monopoly rights, there may be excessive IPR protection, and patents and IPR may be abused. Patent rights owned by an incumbent firm may prevent new firms from entering the industry and producing new products that may require the use of innovations covered by the patents. Thus, design of the patent system has to balance social benefits associated with inducement of R&D by private companies with the social cost associated with the generation of extra monopoly power. In some cases, the patent system that aims for better utilization of knowledge 'commons' may result in constraints and transaction costs that will curtail future investment in research. This consequence of the patenting system is referred to by Heller and Eisenberg (1998) as the 'anticommons' problem.

Research and development as a dynamic phenomenon

The anticommons problem is one manifestation that R&D activities are part of the dynamic processes associated with build-up and utilization of the stocks of knowledge. While most of our theory is built on static assumptions, research is evolving. Within each research line, there is a transition from the laboratory to the factory, to the shop and to the field. The baton is handed down from researchers in the public sector who do conceptual work to private-sector actors who may do product-oriented R&D and engage in production and marketing efforts. Once the problem is solved, much of the research line that aims to address it may be redundant. But new research issues may rise. That suggests that we have cycles in research. Yesterday's solved puzzles are today's practices, and today's practices create tomorrow's problems.

The evolution of the research problems may cause continuous changes in the research system, and the allocation of public and private money to research efforts within fields is evolving over time. Productivity of the research line is changing and public-funding priorities must reflect it. As a problem, say, prevention of a disease, is solved, research in this area becomes a lower priority and thus funding should be reallocated to other areas where the benefit is higher. Similarly, introduction of new bodies of knowledge or techniques may open new fields of research and may lead to diversion of public money and corporate funding toward these new areas. Computer science did not exist 50 years ago, and now it is a major area of research investment (Mowery and Rosenberg 1989). We suggest that not only should allocation of public and private resources between private and public sectors be examined constantly and evaluated over time but, more importantly, allocation of resources within sectors and between fields and areas of research should also be constantly examined and re-evaluated.

Of course reallocation of resources between research lines is problematic. The skills of scientists are not malleable, and changes in research productivities and resulting research priorities of different research lines may be challenged and met with many objections. The basic discoveries in molecular and cell biology, which gave rise to genetically modified organisms, opened new avenues of research that may lead to reallocation of public research funding from areas that have been well established in the past. Furthermore, the use of genetically modified organisms and other technologies based on molecular and cell biology may also affect the nature of agricultural products and markets. Thus, to understand the challenge of the new technology, we have to view their place within a historical context.

Historical perspectives

Historically, most of the important innovations we all benefit from were generated by practitioners who identified a need and met it by exploiting knowledge resources that have accumulated in society. Many of the most important mechanical innovations in agriculture (the plough, tractor etc.) were such applications. Over time, as research in engineering has become more formulized and there is more reliance on university and other institutional research, yet most mechanical innovations are still developed by private sector companies. The most important chemical innovations (e.g., insecticides, artificial fertilizers) may have originated in scientific discoveries by people such as Haber and others. However, the rights to develop many of these technologies have moved to the private sector, and most research on new pesticides and improved agrochemical management (including fertilizer) have been done by the private sector. Of course, in many cases private agents relied on and took advantage of new knowledge developed in the public sector and incorporated it in their activities, sustaining a continuous public–private transfer of knowledge and (de facto or explicit) partnership.

While research may have been an indispensable starting point, from the user perspective (especially in the developed world), the source of chemical products has been the private sector. In developing countries, governments in some cases act as buyers and intermediary suppliers of fertilizers because of market failures, mainly lack of profitability and earning potential for the private sector. Such public-sector engagement in education and especially provision of inputs may reflect so-called orphan markets, where social benefits may justify intervention where private profit is not sufficient.

One area where the public sector was the dominant generator of technology and supplier of inputs has been genetic material. In the past, most of the research in seed development was conducted primarily by the public sector. Since it was difficult to appropriate benefits from development of new seeds, public-sector plant breeders, both in government and international research centres, developed the superior varieties. These were then disseminated to national research centres which, through selective breeding, adapted these improved breeds to local conditions. Seeds thus distributed to farmers became, through expanded agricultural productivity, one of the most important private contributions from public research (Evenson and Gollin 2003). What became known as the Green Revolution was an important example of how public-sector commitment to research led to immense improvements in global welfare.

As part of this process, public-sector provision of seeds led to an open system where breeders the world over could exchange gene plasm and other genetic materials, leading to increased efficiency. Within this system, however, elements of privatization already began to emerge. Once hybrids were established, private companies started making investments to differentiate this genetic material, adding some productivity/quality attributes and, more importantly, making it non-reproducible. Sterile hybrids conferred property rights that were sustainable, overcoming one of the essential incentive problems for private-sector investment in this area. Furthermore, Green Revolution varieties had been intensive users of fertilizers, and the introduction of these public-sector-generated varieties was co-ordinated with more intensive provision of private-sector-generated fertilizers and other inputs. Nevertheless, the public sector, through its direct and indirect control of genetic materials, retains significant responsibility for the evolution of crop systems.

Biotechnology: lessons from U.S. experience with rapid and sustained genetic innovation

Scientific innovation has a very long history, but for most of that time its relationship with the marketplace has been an occasional and less than faithful one. The ultimate economic potential of early scientific discoveries was rarely foreseen and material rewards usually eluded the discoverers. Beginning with Edison and Bell a century ago, however, the laboratory and marketplace established a mutually beneficial relationship that has now produced undreamed-of technological assets and enriched some of the world's largest private profit and non-profit institutions. This dramatic success was due not only to the inspiration of inventors and entrepreneurs, but also to an evolving relationship between public and private agencies in research and product development. In this section, we examine how this partnership accelerated and sustained technological innovation and product development.

In the context of agriculture, research and product development with biotechnology are different from those with selective breeding, and many of the principles and institutional systems that are applied to traditional plant breeding are of limited relevance to biotechnology. To some extent, the evolution of ag-biotech is more analogous to that of chemical innovation than of seed breeding with traditional methods. Some of the breakthrough innovations leading to the development of biotechnology tools and products have been made in public-sector institutions, but the private sector has dominated the effort to commercialize the technology. Several factors contribute to the privatization of ag-biotech:

1. The Bayh-Dole Act (which allows U. S. universities to sell the rights to patents generated with public funding).
2. The establishment of IPR on living organisms (the Chakrabarty case, Diamond vs. Chakrabarty 1980) and utility patents for seeds.
3. The proliferation of university offices of technology transfer.
4. The availability of venture capital funds for start-ups in biotechnology.

The main cause for the high degree of privatization of ag-biotech is the nature of innovation. Patents are statements of concepts that are novel and useful. Most patents are not applied and do not earn income. Commercialization of most patents requires significant extra investment. The patent system provides not only incentives for research but mostly for development and commercialization. Patent ownership is an asset essential for obtaining finance for further technology development. The offices of technology transfer served as a mechanism to reduce transaction costs in moving IPR from universities to the public sector. Biotechnology is typified by partnerships between university researchers, start-up companies and major corporations that allow sharing of risk and division of labour so each organization concentrates on tasks where they have relative advantage. Universities emphasize conceptual research, start-ups pursue early stages of risky commercialization, and major companies while having their own programmes in basic research and investing in risky development activities are dominant in product commercialization.

In the United States, the public–private partnership and privatization of ag-biotech have had several important consequences. The most salient characteristic is the emergence of an educational/industrial complex around biotechnology generally. Major companies are locating near research centres. The Silicon Valley is the most obvious example of a symbiotic co-evolution of an industrial hub and educational institutions. Industrial centres near research universities in the San Francisco Bay area (among others), Davis and San Diego in California, and in Saskatoon, Canada, have been crucial for the evolution of agbiotech.

Academics are joining the entrepreneurial community, providing deeper insight for capital markets into the process of innovation. A key to a successful commercialization of university innovation is sustained involvement of the innovator (Graff et al. 2003). Thus, successful technology transfer entails not only a transfer of IPR, but of innovation-specific human capital.

Universities are discovering that research can lead to substantial, diversified and sustained new income streams. The public sector gains from royalties, contracts and grants, as well as donations resulting from commercialization of its technology. As Graff et al. note, in the United States royalties hardly cover 1 percent of the research expenditures of the US universities, but they were concentrated in specific areas, in particular medicine. Some agricultural innovations generated a large stream of income. Overall, though, royalties are not likely to be a major source of income for universities, and intensive public support of research will be needed to maintain a viable public research system.

University research has emerged as an important mechanism of industrial competition. With technology transfer, established firms not only face competition from other firms but also from new innovations originated at universities and financed by venture capitalists.

Companies such as Monsanto and Novartis have spent billions of dollars to develop a viable technology package to generate new seeds and hybrids through genetic modification. We now have a foundation that can be advanced and improved to transfer genes to plants and to produce a diversified portfolio of seeds commercially at a reasonable cost.

It needs to be noted, however, that transferring control of enabling technologies to private hands may restrict access to innovations and impede new innovation. An important risk of privatization for ag-biotech is the emergence of an 'anticommons' problem. Wright (1998) provides some anecdotal evidence that lack of access to process innovation is preventing commercialization of genetically modified varieties of specialty crops. Even when access to technology is available eventually, it becomes very costly and the transaction cost associated with obtaining access may prevent undertaking many worthy projects. The case of Golden Rice, where access to more than 70 patents was needed in order to obtain 'freedom to operate' and develop the technology, is illustrative of this problem.

It is useful to distinguish between process innovations that are also referred to as enabling technologies (e.g., tools of genetic manipulation) and product innovation (e.g., functional genomic knowledge about the functions that certain genes may serve) in assessing the impact of privatizing IPR that was originated in the public sector. The anticommons problems may be especially severe with process innovations. When these technologies are patented and their use is restricted to research or banned altogether, the capacity to develop applications relying on this technology is limited. In some cases, Wright suggests that commercialization of public-sector innovations might have been blocked because of lack of access to patents that originated by public-sector researchers, but were transferred to the private sector. The extent to which access to public-sector innovations will be available in the future depends on licensing arrangements with the private sector.

The impact of licensing on the evolution of industries is illustrated by comparing the impact of the Cohen Boyer vs. *Agrobacterium* patents. The Cohen-Boyer patent (for the basic process of medical genetic engineering) has not been licensed exclusively. Its use has been licensed for a relatively small fee per application. It generated immense revenues to the University of California, Stanford, and the innovators. The affordable non-exclusive licenses enable fast diffusion of the technology and did not hamper their growth of medical biotechnology.

On the other hand, the rights for the *Agrobacterium* (a crucial process for planting genes in plants) were transferred exclusively to Monsanto from Washington University. Monsanto's restriction of use of the technology by researchers in other companies has been a source of much resentment (especially in Europe). Lack of access to this technology presumably thwarted commercialization of some innovations. Parker, Zilberman and Castillo (1998) argued, based on interviews, that innovators and offices of technology transfer wait for patents of enabling technologies to expire to issue dependent technologies (to avoid hold-up).

Privatization of ag-biotech has led to emphasis on the development of genetically modified technologies that served the needs of the North and targeted major crops. As theory predicts, companies like Monsanto have targeted the most profitable crops for genetic modifications. Monsanto and the other companies launched Roundup Ready and *Bt* varieties for major crops (soybeans, corn, cotton). Yet, these technologies are not applied for small crops or subsistence crops in developing countries. The major companies are not likely to apply these technologies for the orphan crops, and the public research institutions that will develop such technologies may be concerned about IPR availability.

Overcoming IPR constraints to spread the benefits of biotechnology

Thus far, ag-biotech innovation and product development have been confined largely to research systems in OECD countries, yet the economic and social potential of these technologies is global in scope. For example, *Bt* cotton has been widely adopted in the United States and conferred significant gains there in terms of reduced pesticide dependence and lower consumer costs. Recent studies of India (Qaim and Zilberman 2003) show even more dramatic per hectare gains, however, and research in China (Pray et al. 2002) also associates its adoption with improved worker health and reduced environmental side-effects. More generally, higher pest intensity in developing countries and more limited alternatives for pest control further amplify the relative benefits of pest-mitigating biotechnology, including collateral gains in terms of reduced chemical loading of soil, water and other resources.

Despite this emergent evidence, the world remains sharply divided when it comes to technological research, innovation and assimilation. Instinctive resistance to innovation might seem prosaic for everyday consumer technologies, but it has graver implications in the context of human health and nutrition. In the developing world, especially in some of the poorest countries, there has been precious little basic or applied research of the kind we are discussing, either of the public or private-sector variety[1]. Even in China and India, which have strong scientific traditions and many public and private laboratories, the trends we delineated in the above are only beginning to be established.

We believe that the potential of biotechnology is also underutilized in applications for minor crops that include fruits and vegetables in developed countries. Application of biotechnology generally in developing countries and to specialty crops in developed nations probably requires more intensive investment of the public sector in research, development and commercial licensing because such investment may not be profitable from a private perspective but may be desirable from a social perspective given benefits to consumers and users of the technology.

Indeed, the international research centres and public and private aid agencies are funding or considering investment to enhance biotech research and development capacity in developing countries. Commodity groups in the United States and developed countries are funding research and development activities to enhance the application of biotechnology for specialty crops[2]. In both cases, lack of access to intellectual property is one of the primary obstacles. One way to overcome these obstacles is the establishment of an Intellectual Property Rights Clearinghouse (IPRC); a new institution that can serve several purposes.

To understand some of the potential benefits of the IPRC, it is important to compare the way intellectual-property management differs between the private and public sectors. The private sector recognizes IPR constraints as part of the cost of doing business. New projects are not introduced without ‘freedom to operate”, i.e., the potential to capture rents from embodying a given technology in new products. In the course of their own research agendas, public-sector researchers do not have the information needed to foresee such downstream IPR constraints. This information gap can seriously limit the potential for future commercialization of their innovations. One objective of the clearinghouse is to provide researchers in the public sector with greater visibility on the freedom to operate issue, harmonizing their information set with that of their colleagues in the private sector.

Private-sector organizations use their IPR holdings to secure access to other needed components of intellectual property. One reason, for example, for merger arrangements and strategic alliances between firms is to enlarge and diversify IPR portfolios, thereby increasing their flexibility in research, development and commercialization. Graff et al. (2003) found that public-sector institutions actually have a significant share of the ag-biotech patents. These are concentrated in research universities in the United States and in the OECD countries. In 2000, private-sector entities owned 22 percent of value-weighted US agricultural biotechnology patents, and 44 percent of these private patents were owned by the "Big 5" (Monsanto, 19 percent; DuPont, 10 percent; Dow, 7 percent; Syngenta, 5 percent; and Aventis, 3 percent). The rest of the private sector, mostly start-ups and smaller companies, owned 34 percent of all ag-biotech patents. Similar proportions are observed in other OECD patent systems (EU, Japan and Patent Cooperation Treaty). Using cluster analysis in case studies, Graff et al. (2003) documented that private-sector organizations have patented broadly across the various technology classes necessary for most applications of ag-biotech. The range of research projects that can be supported by public-sector-owned IPR is also significantly enhanced by a wide range of unpatented innovations that are accumulating in the private-sector institutions.

While the public sector has a significant IPR ownership, it is diffused among many institutions. No individual institution has more than 2% of total patents, and the diffused ownership of IPR by public-sector institutions weakens the sector's power to negotiate and leverage greater public interest into biotech applications. The clearinghouse will provide mechanisms to combine public-sector IPR and, thus, make it a stronger block in possible technology negotiations.

While patent ownership is divided, the rights of use have largely been transferred to the private sector. To achieve more effective collective action among public-sector organizations, it is essential to know the actual portfolio of technologies controlled by the public sector. Information on the actual control of technologies is quite sensitive and, thus far, not available in one central location. This lack of transparency increases risk and transaction cost for potential entrants in both research and market development, seriously hindering the innovation and the realization of its benefits. Another role of the clearinghouse is to collect updated information about technology ownership and to advise individuals where to obtain technologies they need.

Private ownership of patents by corporations is perceived to be a major constraint of technology use in developing countries and for orphan crops. However, in some cases, obtaining the access to patents that are owned by universities may be as difficult or even more difficult. Some researchers in developing countries actually maintain that they have a harder time obtaining rights to utilize technologies from public offices of technology transfer than from private companies. Companies provide technologies to orphan markets simply for the sake of public-relations gains. Such goodwill motives may induce them to give away the rights to use the technology, especially in developing products that do not threaten established markets or other financial interests. For some university inventors, the income from use of technology is of major importance, and they may be reluctant to waive their rights to the revenues generated by their technology. One possible role of the clearinghouse is thus to establish arrangements for facilitating access to public-sector and especially university patents for orphan markets.

Greater transparency can also facilitate clear delineation of market scope, reducing risks of spill-overs to competing interests. In this sense, some barriers to technologies that originate in the public sector may be the result of imprecise marketing. Companies may obtain the rights of a patent for all markets, while in reality they may be interested in applying the patent to a small number of crops in OECD countries.

Once they own the rights, liability considerations, transaction costs and other factors may limit the capacity of researchers to utilize technologies for orphan markets. One possible role of the clearinghouse is to share knowledge and research cost to develop precise technology-transfer procedures that will lead to more efficient and socially beneficial IPR management. The above analysis suggests several objectives for an IPR clearinghouse for agricultural biotechnology:

1. Reduce transaction costs for the commercialization of innovations (Shapiro 2000).
2. Expand the universe of accessible technologies (for research and product development).
3. Improve efficiency of technology-transfer mechanisms and practices in public-sector institutions.
4. Increase transparency of IPR ownership.
5. Provide mechanisms to expedite IPR negotiation and access.
6. Consolidate the public interest in technology origination and development (Graff and Zilberman 2001).

There have been two recent attempts to develop IPRCs. The Rockefeller and McKnight Foundations are collaborating with 13 major universities in the United States to establish Public-Sector Intellectual Property Resource for Agriculture (PIPRA). This initiative aims to increase public-sector scientists' freedom to operate and provide access to IPR to develop technologies for orphan crops. The new organization will have two elements:

1. A database of IPR ownership and rights in ag-biotech (a team of experts will advise researchers, administrators and managers about practical intellectual-property management strategies and IPR ownership and access).
2. A mechanism such as a technology pool (the clearinghouse will consist of supporting public-sector institutions that will share technologies and users, i.e., researchers in developing countries). Institutional members who contribute to the pool will have access to it. Namely, the universities basically combine all technologies that they control into a pool available to subscribers. Actually, the technology can be sorted and arranged according to its function to ease access within the IPR maze. The pool will aim to provide a set of technologies that will allow pursuing a broad range of ag-biotech applications. The pool can also be used strategically to trade access to technologies from the private sector.

Another clearinghouse is the African Agricultural Technology Foundation (AATF). Also supported by the Rockefeller Foundation, it aims to facilitate research and the introduction of new sophisticated crop varieties (including biotechnology). It emphasizes technology transfer when using public research and will help scientists to overcome IPR and regulatory requirements. AATF aims to negotiate with the public sector directly to obtain licenses for technologies in Africa used for humanitarian causes. This organization will go beyond technology transfer, providing some funding for research, particularly to overcome IPR regulatory constraints. Its main emphasis, however, is to work with technology owners and project partners (including donors to negotiate overall licenses). The AATF will be the licensee, and then sublicensed to research teams and product developers.

In the medical arena, an interesting institution is the Management of Intellectual Property in Health (MIHR) R&D clearinghouse. Its motivation is to gain access to IPR and develop therapies for diseases (tuberculosis, AIDS, malaria) afflicting the poor. Its main areas of work include: (1) identification and codification of best practices for licensing to achieve the goals of the public sector; (2) provision of training to scientists, universities and research institutes in managing intellectual property to benefit the public sector in both developed and developing countries; and (3) consulting services to developed and developing country groups concerned with research and product development.

Since it embodies both the promise of sustained innovation and the risk of exploitation, private ownership of technology will remain a controversial subject for the foreseeable future. The responsibility of public entities is clearly to facilitate the former and mitigate the latter, and effective policies toward biotechnology will necessarily reflect this. Facilitating access to IPR is the primary impetus for the initiatives discussed above, but the following considerations are also important:

Clear delineation of patents

Designing optimal patents is a challenge. If patents are too broad, they may hamper future research and may undermine access to the commons of intellectual and scientific discovery. If they are too narrow, they will undermine incentives for private discovery and incentives to develop and commercialize discovery. The latter incentive effect may be even more important because it applies to both private and public discovery. Research to develop methodologies for precise patenting and licensing, as well as implementation of its findings as new knowledge accumulates, is of paramount importance.

Currently, genomic knowledge is patentable, and the discovery of a gene sequence and its use can confer monopoly power. However, genomic discoveries are no longer novel and, therefore, do not justify patents in most cases. Companies deciphering genetic codes now earn their primary income via information services (i.e. selling databases). On the other hand, functional-genomic discoveries, which identify the function of genes and their potential applications, are more logical candidates for patenting. The evolving distinction between genomic and functional-genomic innovations illustrates the importance of adjusting patent criteria as the state of knowledge advances.

Biodiversity and biotechnology: a two-way street

The relationship between biotechnology and biodiversity is a contentious one, and is generally not well understood. On the one hand, there is a public perception that biotechnology reduces biodiversity. On the other, there is a widely held sentiment that agricultural technology institutions (public and private) seek to appropriate biodiversity resources in developing countries.

On the first point, biotechnology actually has the potential to contribute to crop biodiversity (Qaim, Yarkin and Zilberman 2004). They argue that while classical breeding has narrowed crop diversity significantly, biotechnology could make possible retention of a large proportion of today’s crop varieties. *Bt* technology, for example, enables local varieties to be made pest resistant, obviating the need to adopt and adapt more homogeneous ‘global’ varieties, as was the norm during the Green Revolution. As a result, the US now has more than 1000 varieties of *Bt* soybean, most of which are single-gene variants of local legacy varieties. Far from homogenizing the gene pool, the introduction of ag-biotech in OECD markets has acted to protect and even increase biodiversity.

The issue of biodiversity and (implicitly) North-South property rights might seem more ambiguous. Genetic material from the developing world has certainly contributed to science and practical technology in OECD economies, but the productivity gains of technology transfer in the opposite direction have been enormous. There is a growing literature on the economics of biodiversity that shows it is, say, valuable at 'hot spots' with plants of apparent value (Rausser and Small 2000). However, for most locations, it is very low (Simpson, Sedjo and Reid 1996). The likelihood of discovery of new wonder drugs is a result of bioprospecting, which limits the capacity to change the access to biodiversity. Our discussion on technology transfer shows that universities' royalties are very low and cannot support their research. Similarly, biotechnology compensation will be low and should not be counted as a major source of income for developing countries.

Like the Green Revolution, public and private agencies will accomplish their primary objective (public interest and profit, respectively) only if they achieve their secondary mission, increasing agricultural productivity and food security in the developing world. From an economist's perspective, land is an immobile factor of production, and for this reason globalization of ag-biotech cannot succeed without local assimilation. Some observers see the advent of ag-biotech as a process of global consolidation, but the evidence on *Bt* reveals the opposite, a process of technology dispersal and localization. Instead of adapting innumerable farmers to a few varieties, ag-biotech appears to be adapting a few technologies to innumerable local varieties. This suggests not exploitation, but a partnership to overcome barriers to increased production for the world's majority enterprise, small farming, building upon the global legacy of biodiversity.

Having said this, the evolution and eventual success of such a partnership will depend critically on innovation and technology sharing, where the latter encompasses both man-made and natural technology (e.g. biodiversity). This in turn will depend upon clear delineation, ownership and market articulation of property rights, and much remains to be done in these areas. The IPRC can perform an essential service here, by increasing transparency and reducing transaction costs, but public institutions will have to fill many gaps in global standards for more complete markets to develop in this area.

Education - A North-South partnership and human-capital development

Biotechnology is in its infancy. This technology, using the tools of molecular biology, promises a future where biological solutions for many industrial problems will become more efficient and environmentally friendly. While most of the technology has been developed in the North, most of the world's genetic resources are in the South. At present, much of the research is developing tools to utilize genetic materials, but many of the opportunities in the future will arise from better understanding of functional genomics. Much of this research can be facilitated by North-South partnerships, and it is important for the South to participate more fully in this. Better intellectual capacity to take advantage of biodiversity will allow the South to take a better bargaining position to negotiate its role in partnerships.

Biotechnology is a modern technology that, to a large extent, was originated and sustained by university research, and many of the centres of this industry have been built in proximity of universities. It has thereby become apparent that, to succeed in biotechnology, a country needs to develop and maintain superior higher education, developing its own educational–industrial complex to generate human capital and marketable intellectual property. This observation alone defines an agenda for education-oriented development assistance, whether it be private or public, bilateral or multilateral[3]. Perhaps the greatest challenge, but ultimately the greatest opportunity, for fuller North-South partnership in biotech innovation is education.

Technology generally, and biotechnology in particular, are strong complements for human capital, and research and development are especially human-capital-intensive. The geographic and institutional symbiosis between modern universities and the technology sectors is an important example of this, and it is an example that developing countries have difficulty emulating for many reasons. A combination of underinvestment in education, private-capital insufficiency, and (in many cases) small market size have prevented the emergence of significant research capacity in most developing countries. Even those with large and long-established scientific traditions, such as China and India, are in the earliest stages of building the public–private research alliances that are hallmarks of dynamic technology sectors in OECD countries.

These facts reveal the need for expanded international partnership, both public and private, to develop capacity for biotech innovation and commercialization in the South. On the public side, aid agencies should reaffirm their commitments to human-capital development generally, and scientific capacity in particular, recognizing this as the key to sustained productivity growth and higher living standards. Private interests, for their part, should take new initiatives to leverage human resources in developing countries, transferring technology and capital into new markets and thereby gaining first-mover advantage in these emerging biotech markets. China, India and some other large and populous developing countries are already attractive candidates for this kind of entrepreneurship, while smaller and less advanced countries should be seen in a regionalized perspective.

The future of biotech

The majority of private investment in ag-biotech R&D has been accompanied by activities aimed at protection of IPR and development of proprietary applications of original scientific ideas. By its nature, scientific discovery is uncertain and requires significant initial financial commitments, followed by (often larger) investments for product development, testing and marketing. Generally speaking, neither public nor private agents would invest in development of a downstream research product without secure IPR at each stage. The decisive institutional reforms in the 1980s were legal precedents defining and protecting IPR, including the Bayh-Dole Act and decisions establishing the patentability of living organisms (the Chakrabarty case).

In this section, we give an overview of the salient issues that will influence the future evolution of biotech. After discussing necessary conditions for public–private research partnership, we examine emerging research priorities, and then close with a more speculative discussion about future trends in this dynamic sector.

Necessary conditions for public–private partnership in innovation

The inherent division of labour between public and private research reflects the substantive (and constructive) differences between the two. Universities and the scientific community place a high premium on originality and creativity, and in this way are more likely to come up with new paradigms and new research agendas. Within private companies, especially larger and more established ones, emphasis is on research that will enhance the bottom line. Their research is thus driven by a larger universe of criteria, including process efficiency, regulatory conformity and demand-driven design standards.

In principle, these differing objectives and priorities all represent socially (and individually) desirable product characteristics. Thus, the parallel agency of public and private research could yield significant complementarity, but of course this depends critically on the prevailing regime of incentives. The incentives, in turn, are strictly disciplined by the legal regime governing property rights and economic conditions of the destination market. As we have seen, these conditions have been quite virtuous for life-science research in OECD countries over recent decades, but much less so in poor countries.

In ag-biotech, new basic discoveries have emerged from public research and this new knowledge can be transferred to private agents because the legal regime allows them to acquire (appropriate) and retain partial or complete property rights. With ownership comes the incentive to invest in capacity to utilize this new technology and commercialize it. Thus the legal system enables faster technology transfer and commercialization because it recruits new (and arguably more appropriate private) resources to this task. Conversely, partial retention of property rights may sharpen the research incentives of the public partners. Meanwhile, other public dissemination institutions might further accelerate the process of technology transfer and, ultimately, promote more competitive innovation and commercialization.

As the research by Graff et al. (2003) suggests, it often happens that original innovators in public-sector research migrate (partially or completely) downstream to the start-up or industry stages, engaging directly in the development and application that allowed for commercialization of their technologies. These forays, while incurring some risks of conflict of interest, can have many benefits. The expertise of these individuals can facilitate much more effective transfer of the technology, significantly reducing the moral hazards associated with new technology acquisition. Considering the financial incentives sometimes offered to these ‘technology couriers’, risk reduction must be quite valuable to venture-capital entrepreneurs. Of course, these people also represent the human-capital component of the intellectual property in question, and thus are an investable asset in themselves. Whether or not they migrate back to basic-research institutions, their experience and continued contact will also influence the agendas of their former labs and those of their colleagues. In this way, migration of this kind influences both the basic research and the product-development environments.

As to incentives for public partners, this kind of technology transfer has certainly generated royalties for universities. As Graff et al. suggest, however, the order of magnitude of these royalties is relatively small and their relative impact on budgets even less significant. Nevertheless, new monies have been allocated to certain avenues of research that have not been highly funded before, such as medical biotechnology which has benefited significantly from these new resources. However, the main contribution of commercialization to the university, at least in the case of the United States, was through private-sector donations and contracts and grants. For example, Monsanto invested tens of millions of dollars into the University of St. Louis. Some of the new facilities in universities in California have been financed by contributions from companies and, especially, their owners. In addition to the formal transfer of funds, which were modest, there were also informal transfers that were more significant.

Despite largesse from private sources, earned or contributed, public-sector contributions far exceeded royalties and donations and have been the most important source of financing for ag-biotech. The data also suggest that, while investment in ag-biotech has increased in the public sector, most of it is being committed from the private sector. Certainly, there are important cases of public sector investment in ag-biotech, but this source is dwarfed by its private-sector counterpart.

The major concern about the increase in the use of genetically modified organisms for production of genetically modified materials in agriculture is fear that an important agricultural input, seeds, will transfer from the public to private sector. As we argued earlier, control of other important agricultural inputs as well as provision of medicines is the offering of private ends. In both cases, even though the private sector is the producer of most of the products, a large investment in research leading to the development of public policy has emerged to assure social optimality, and it will protect each individual and group that may be neglected if the private sector is left uncontrolled. Thus, the policy challenge is to develop similar institutions in the case of ag-biotech.

Emergent public research priorities

One perennial feature of research and its agenda, whether public or private, is continuous evolution. The primary drivers in the latter case are market-related, but the forces that animate public interest are more diverse. New societal problems and needs may instigate new priorities for investigation, in turn instigating new research agendas and even new disciplines. At the same time, once a research agenda has reached maturity, resources tend to shift from the frontier scientists towards practitioners.

Agricultural technology has gone through the same processes again and again. Much of the research in the last 100 years in the United States has focused on developing new varieties etc. This agenda resulted in improved high-yield varieties, chemical fertilizers, synthetic pesticides etc., but also in the discovery of new issues, such as the negative side-effects of DDT. In this case, the publication in 1962 of Rachel Carson's book *Silent Spring* gave rise to an environmental agenda that has become a major area of emphasis in both public and private sectors. For example, the recent NRC reports point out that integrated pest management, biological control and other biology-based technologies have become areas of emphasis in the private and public sector. Research in soil science and water has evolved an emphasis on issues of water quality and other environmental dimensions.

While the private sector has taken a leading role in the development of improved systems of production of livestock, university research has shifted its focus to environmental side-effects of these systems. To some extent, the increase in private funding of research has reflected maturity of technologies, and the emphasis on improvement of proprietary knowledge in established fields. At the same time, public research has emphasized some new avenues of research; some ultimately transferred and further developed by the private sector, or some addressing issues that have public-good properties. An example of the latter is measurement of the environmental impact and side-effects of new technologies that are not embodied in different products, and these type of technologies will continue to be emphasized by the public sector, since they do not promise significant return to private investment.

Salient future trends in agricultural biotechnology

As in any technological sector, the future ag-biotech is highly uncertain. Despite this, however, we feel it worthwhile to close the present discussion by highlighting a few salient issues that are sure to influence the course of future events. Each of these topics is worthy of its own research agenda, but we mention them only in passing to evoke deeper thinking and discussion about how to facilitate best the realization of biotech's enormous economic and human potential.

Resolution of IPR issues will reduce the costs and accelerate the introduction of new technologies when the economic conditions are ripe. The legal, political and economic universe of IPR is undergoing very rapid evolution, particularly with the impetus or public and private initiatives to promote globalization. With some exceptions, it is fair to say that most of these trends will lead to the goals embodied in the clearinghouse concept: greater transparency, lower transactions costs etc. This process will contribute decisively to the global proliferation and acceleration of innovation.

More stringent patent requirement will reduce IPR pressures. Like IPR issues generally, international policy toward patent law is changing fast, stimulated by the same public and private initiatives to establish economically rational international standards for tradable entitlement to innovation. Success in this area will be measured by how rapidly innovation progresses in both scope and depth.

As patent rights for basic technology expire, some tensions will be reduced. As we have seen in information technology, telecoms, and many other sectors, the usefulness of innovative technology generally outlives the right to own it, and in any case it usually makes contributions far beyond the boundaries of original property rights. For this reason, the natural process of rights expiration can be seen to contribute to a technology commons, enlarging mankind's stock of shared intellectual capital and broadening the basis for future innovation.

Public-sector institutions will develop technology pools and arrangements for swapping technologies with private-sector players. In terms of policy and market strategy, biotech can still be seen as a relatively new game, and the pubic sector is no more experienced than any of the other players. For this reason, one can expect to see public-sector strategy in this sector to evolve dramatically over the coming decade, much as it did with the advent of other path-breaking technologies (atomic energy, space travel etc.). Looking ahead, it is reasonable to expect more linkage between public policies in this area as governments strive for greater domestic and international policy coherence. It is also reasonable to expect progress in public–private partnerships, extending beyond basic regulatory duties to facilitating practices such as sponsorship of technology pools, clearinghouses and more complex incentive arrangements.

Private players will use their IPR assets to earn income and promote their technologies. From an investment and innovation perspective, the success of biotechnology is to an important extent self-fulfilling. Most biotech companies have very high rates of profit retention and reinvestment and, as the market success of today's innovations are consolidated, private resources dedicated to innovation will steadily expand. The semi-conductor industry provides a useful role model here, where multi-billion dollar R&D budgets have emerged from firms that were non-existent two decades ago.

Conclusions

Ag-biotech enters a new century with a remarkable set of accomplishments. The innovations of the four decades since DNA was decoded are revolutionary, and now we look to globalization to consolidate and expand the economic benefits which have until now been enjoyed primarily by the wealthy countries. If the promise of ag-biotech is to be fulfilled, the successes of public and private research partnerships in the OECD must be repeated around the world. Between the present and a bright horizon of opportunity, however, is a chasm of technological inequality between North and South. Bridging this gap will be one of the greatest challenges to lasting improvement of the human condition.

In this paper, we have briefly reviewed the lessons of biotech's successes in the United States, with particular reference to the way in which institutional factors facilitated partnership between public and private research interests. With these experiences in mind, we then discussed a series of ideas about how this success can be replicated elsewhere, both within the South itself and in partnership between North and South. Generally speaking, we believe the paramount considerations are appropriate institutions and incentives. If public interests can facilitate the development of these, we believe the private sector will identify society's unmet needs and provide solutions.

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[1] For more general discussion of market mechanisms in developing countries, see Sadoulet and De Janvry (1992)

[2]Alan Bennett, Director of Office of Technology Transfer, University of California, personal communication

[3] Development assistance to overcome the North-South technology gap is simply an example of the old 'giving a fish versus teaching to fish' adage, but with more profound growth implications because of endogenous growth externalities