Brian Wright and Tiffany Shih
“Agricultural Innovation”
Accelerating Energy Innovation: Lessons from Multiple Sectors

Agricultural Innovation

Brian Wright and Tiffany Shih

1. Introduction

Agricultural production is a highly decentralized and geographically dispersed activity, dependent upon a wide variety of technologies applied to a heterogeneous natural resource base that is changing over time. Its principal products are necessary inputs into consumer goods essential for life, and continuous availability at acceptable quality and price is vital.

The history of agricultural innovation is relevant to plans for accelerating energy innovation since energy production and use share many of the above characteristics. Many innovative energy technologies are becoming more similar to agriculture as they revert from depletable to renewable resource bases. Indeed, the principal currently commercialized biofuels technologies involve agricultural production. Like agriculture, energy production critically relates to greenhouse gas production. It is widely agreed that climate change will have a greater impact on agricultural production than on any other sector, while in the energy sector, its effect on investment is already significant.

The record of achievement in agricultural innovation over the past century is impressive. Increases in agricultural productivity have fueled rates of increase in food supply that outpaced the joint effects of growth in personal consumption and population, with only modest recruitment of new cropland (Pardey and Beintema, 2002). Better nutrition has, in turn, transformed life expectancies, labor productivity, and the rate of population growth. Agricultural research activities have spread around the globe with marginal social rates of return so high that they strain credulity. Patterns of participation and technology exchange demonstrate high interdependence both between countries and along the public-private spectrum (Table 1, Wright *et al*, 2007).

Agriculture has a long history of productive public research. Evenson’s 2001 survey of over forty studies between 1915-1999 gives a marginal real social rate of return to U.S. public agricultural research investments between 45-65 percent.[1] The development of an effective system for public investment in research and knowledge dissemination critically contributed to the observed pace of agricultural advancement. In addition, sharing of knowledge and innovation between farmers, input suppliers, and researchers, both within agriculture and beyond, has played an important role. For example, just as applied research in electronics, communications and nuclear energy have drawn from basic research funded by the U.S. Department of Defense, recent innovations in agricultural biotechnology owe much to projects on human health funded by the National Institutes of Health.

Compared to other sectors, agricultural research investments are more geographically dispersed, both within the United Stated and globally. Indeed, public investments in agricultural research from developing countries have recently overtaken public agricultural investment in developed countries as a whole (Wright *et al*, 2007). The fundamental influence of the natural features of the growth environment means that adaptive research is often needed to apply agricultural biotechnological innovations in a given local area. The U.S. institutional structure supporting agricultural research reflects this reality, employing state and local-level research institutions and experiment stations to meet the needs of local farmers. Since the primary benefit of innovation in agriculture is lower food prices, countries with large populations can internalize a larger share of the gains from more basic research.

Beginning in the United States in 1980, advances in biotechnology, combined with the extension of strong intellectual property (IP) protection to agriculture, have elicited such a great private investment response that it now exceeds public investment. The proliferstions of IP, however, has not been without consequences. There is mounting evidence of a negative effect on freedom to operate in public sector projects directed towards production of plant varieties and other technologies for use by farmers. The problem arises from fragmented IP claims to technology inputs and is especially prominent in the

---

[1] In a meta-analysis of nearly 300 relevant studies (including those derived from U.S. data or foreign data), Alston *et al* (2000) note that the estimates for annual rates of return range from -7.4 to 5,645 percent. The authors find significant variation in the estimates derives from the different rate of return measures used, potential analyst biases and methodologies used, and the type of research evaluated. Alston *et al* (2000a) estimate an 80 percent overall annual rate of return to agricultural research.

agricultural biotechnology field. The private sector responded to difficulties with arms-length licensing of IP with a series of industry purchases, leading to market concentration and the current dominance of the agricultural industry by the firm Monsanto.

Public interventions with other objectives also affect innovation. Direct, "uncoupled" public support for the incomes of farmers and other agricultural investors moderates their opposition to policies reducing commodity prices and revenues. Government regulations regarding food production and distribution, employment, environmental protection and intellectual property rights (IPRs) also affect the level and distribution of private research and development and technology investments on and off the farm, as well as the market structure of input industries.

Like the energy sector, the agricultural sector is facing continual challenges posed by a growing global population with changing demands on the amounts and kinds of resources being used, and by evolving concerns regarding global resources and environmental constraints. Awareness about global interdependence of the world's food supplies and concerns regarding environmental externalities such as global warming have motivated international efforts to harmonize regulations and share technologies. Recently, re-emergence food security as an international issue has engendered a flurry of private investment and strategic activity.

In this chapter, we provide an overview of innovation policies for agriculture with the purpose of highlighting aspects of interest to the energy sector. We proceed as follows. Section 2 provides a summary of global agricultural research investments with particular attention to public versus private investments and their distribution between developed and less developed countries. Section 3 provides a brief history of U.S. public investment in agriculture. We next discuss the main intellectual property mechanisms relevant to agriculture and their effects on research and innovation markets, followed by a short discussion of the extent and efficacy of public-private collaborations in Section 5. Section 6 considers government regulation and its dual responsibilities of ensuring public safety and promoting technological advances. We then describe the factors influencing technological adoption in agriculture, followed by a brief conclusion.

2. Agricultural research investments

According to the latest available figures, public and nonprofit funding accounts for about two-thirds of global agricultural research expenditures, while private investments account for the other third (Wright *et al*, 2007). These aggregate figures mask the fact that the *types* and *scope* of research performed by the two sectors are neither perfectly substitutable nor independent. In general, private investments are far more concentrated by crop and technology, and tend to rely on the latter for the basic science inputs in order to produce applied technology (Alston *et al*, 1998).

2.1 Research investment trends

Public spending on agricultural research experienced overall growth in the past few decades, from about $US 15.2 billion (at year 2000 prices) in 1981 to $23 billion in 2000 (Table 1). During the 1990s, public agricultural research expenditures by developing countries as a group exceeded those by developed countries for the first time. In no other sector does research expenditure by developing countries have comparable prominence.

China, India, Brazil, South Africa, and Thailand now undertake over half the investment in less developed countries. However research per capita or relative to agricultural output is far less concentrated. Similarly, public spending by developed countries is concentrated on a small set of countries: the U.S., Japan, France, and Germany. Developed countries spent about as much on public agricultural research ($US 12, 577M) in 2000 as developing countries spent on public research ($US 12,819M). Private spending in developing countries was only $US 819 million., as shown in Table 1. (Wright *et al*, 2007; Wright and Pardey, 2006)

As in energy, public and private research spending tends to increase in response to periods of high prices and go slack when low prices have restored a false sense of security. Public research spending, strong after the food price crises of the 1970s and early 1980s, declined during the 1990s in most areas. In developed countries, annual growth rates of 2.2% during the 1980s fell to 0.2% per year from 1991 to 1996. In Africa, growth in agricultural research spending ground to a halt in the 1990s, with some revival more recently. Spending in China and Latin America, on the other hand, grew in the early

1990s after stagnating in the 1980s. China has been particularly focused on the agricultural biotechnology field, increasing spending from $17 million in 1986 to nearly $200 million by 2003 (Huang *et al*, 2002; Huang *et al*, 2005).

Other measures of research investments reveal sharp contrasts between wealthy and poor nations. Both developed and less developed countries increased spending on public agricultural R&D per dollar agricultural output in the past few decades. In developed countries, spending on public agricultural R&D per dollar agricultural output increased to $2.64 per $100 agricultural output in 1995 from $1.53 per $100 of output in 1975. In the developing world over this interval, growth in research intensities also increased on average, but the level was much lower and varied between countries. Growth was constant in China, increasing in other parts of Asia and in Latin America, but decreasing significantly in Africa.

While the rates of research expenditures are informative about recent policies, researchers have found the accumulated stock of research capital to be a more relevant determinant of research capabilities. Pardey and Beintema (2001) calculate that the agricultural research resource stock, as a proportion of the value of agricultural output, is at least 12 times larger in the United States than in Africa, given reasonable rates of interest and depreciation.[2]

2.2 International funding organizations

International funding agencies have been established to direct more research resources toward more efficiently serving the needs of poorer nations. Most notably, 1971 saw the establishment of the Consultative Group on International Agricultural Research (CGIAR), an international partnership between governments, private foundations, and civil society organizations that fund and influence the research of 15 international agricultural research centers (IARCs). CGIAR’s roots are in the 1943 International Agriculture Program, a cooperative effort initiated by the U.S. and Mexican governments with significant support from the Rockefeller Foundation. The Mexican Program became the CIMMYT,

---

[2] For further details, see Wright *et al* (2007) and Wright and Pardey (2006) from which this section is largely drawn. See also Pardey *et al* (2006) for a discussion of agricultural research investments in less developed countries.

The International Center for the Improvement of Maize and Wheat. The relatively simple funding and managerial structure proved superior to the less focused activitiessponsored by the Food and Agricultural Organization (FAO) of the United Nations in producing major agricultural innovations. It developed high-yielding semi-dwarf wheat varieties that were more responsive to nitrogen fertilizer. Contemporaneous innovation in the fertilizer sector enabled production of cheaper nitrogen fertilizer from natural gas. The technology package offering cheaper nitrogen fertilizer and the wheat varieties that could exploit it laid the basis for the Green Revolution in wheat in Mexico and Asia. To broaden the scope of yield increases to other crops,similarly-structures research centers were established in Colombia, Nigeria, and the Phillippines by 1971.

The need for a broader funding base to support the new centers led the International Agriculture Program to enlist the participation of a large range of other donors, including several national aid organizations, the United Nations Food and Agriculture Organization, the International Fund for Agricultural Development, the United Nations Development Program, and the World Bank, in the establishment of the CGIAR (CGIAR, 2008). After establishment, the annual spending of the members of the CGIAR grew rapidly, from $1.3 million supporting four centers in 1965, to $141 million supporting eleven centers by 1980, and $305 million supporting thirteen centers by 1990. Growth slowed in the 1990s, so that spending per center during this decade declined. Between 1994-2002, total CGIAR funding dropped in real terms, reflecting the influence of popular critiques of the Green Revolution, complacency regarding food supplies, and the conflicting agendas and diverse interests of the increased number of funding sources. Investments in germplasm enhancement research, the original core mission ofmembers of the CGIAR, declined at 6.5% per year during this time. This trend was accompanied by similar declines in agricultural aid and research funding from the European Community, the World Bank, and USAID from the mid-1980s through the 1990s. More recently, in response to high agricultural prices and a renewed recognition of the importance of an adequate food supply, funding has begun to trend upward again. CGIAR funding was over $495 million in 2007, and World Bank agricultural lending increased from an annual average of $1.5 billion in 2002 to $4.6 billion between 2006-2008. (Wright *et al*, 2007; Lele 2003; Lele *et al*, 2003; CGIAR Independent Review Panel, 2008; World Bank Group, 2009)

3. A history of US public agricultural support

The U.S. made an early commitment to agricultural research in the form of agricultural institutional innovations adopted from Europe. Economists have emphasized the success of the land grant college system (National Research Council, 1995; Huffman and Evenson, 2006; Ruttan 1980; Ruttan 1982), noting its contribution to lowered food costs, rural development, and the prominence of U.S. agriculture globally (Adelaja, 2003). A lesson embedded in the long history of U.S. public support for agriculture is the importance of a large buildup of research capital stock through sustained investment. In addition, the nationwide adoption of agricultural innovations was encouraged by a decentralized institutional system capable of adapting technology to local environmental conditions, as was incorporated in the land-grant colleges and state agricultural experiment stations.

3.1 The establishment of U.S. agricultural institutions

Spatial environmental variation forms the context in which technology and resources determine agricultural productivity. The expansion of arable land followed by mechanical innovations produced by farmers and blacksmiths drove early increases in U.S. agricultural output (Huffman and Evenson, 2006; Sunding and Zilberman, 2001). Major increases in yields *per acre* were not achieved until the advances in hybrid seed and agrichemical technology in the 1930s. Until that time, biological innovation focused on disseminating and adapting crops to unfamiliar frontier environments (Olmstead and Rhode, 1993).

Human efforts to locate and distribute plant genetic material appropriate for given production environments or meeting particular consumer needs originated long before the groundbreaking discoveries of Mendel and Darwin, not to mention recent work in genetically engineered crops.[3] Heightened recognition of the economic value of plants in the context of the Industrial Revolution, and their scientific documentation and classification, encouraged the spread of botanic gardens across Europe

---

[3] Juma (1989) gives several examples of early plant-collecting expeditions and gardens spanning Ancient Egypt to Japan to colonial explorations of the Americas.

in the 18th and 19th centuries. In particular, Britain's Royal Botanic Gardens at Kew excelled in the acquisition, development, and dissemination of economically important plants (Juma, 1989). A physician's experimentation with urban plant cultivation in the polluted atmosphere of London during the Industrial Revolution led to the invention of the Wardian case or terrarium, an enclosed container that vastly increased the reliability of international transportation of live plants between the new and old worlds (Schoenermarck, 1974).

In the U.S., prominent figures such as George Washington, Benjamin Franklin, and Thomas Jefferson all recognized the benefits of acquiring diverse plant resources and endeavored to introduce improved plant varieties into the country. Jefferson himself once wrote, "The greatest service which can be rendered any country is to add a useful plant to its culture,"[4] and went so far as to smuggle rice from the Piedmont region of Italy into the U.S., sewn into the lining of his coat pockets, when such a crime was punishable by death (Fowler, 1994). His enthusiasm for the importance of plant resources was shared by Henry Ellsworth, the first commissioner of the Patent Office and founder of what ultimately became the United States Department of Agriculture. Without Congressional approval, Ellsworth distributed seeds and plant material from other lands in order to test and promote their benefits. The U.S. Patent Office thus became the main repository for plant genetic material in the country, relying on the U.S. Navy to import foreign seed and the U.S. Post office to distribute seeds to farmers through the mail. Producing a number of documents on proven and potential economic benefits of plant resources, Ellsworth championed federal support for agriculture and the creation of an independent national agricultural research bureau. As a result, in 1839 Congress began to formally support seed collection, distribution, and research efforts by establishing the Agricultural Division of the Patent Office, which became the Department of Agriculture in 1862. (Harding, 1940; Huffman and Evenson, 2006).

This widespread recognition of plant resource benefits plus the dominance of the U.S. farmer population created a favorable political climate in support of the passage of the foundational 1862 Morrill

---

[4] Thomas Jefferson, *The Works of Thomas Jefferson*, Federal Edition. New York and London: G.P. Putnam's Sons, 1904-5. Vol. 8. Accessed from http://oll.libertyfund.org/title/805 on 6 September 2009.

(Land Grant Colleges) Act (7 U.S.C. § 301 et seq) and the 1887 Hatch Act (7 U.S.C. § 361a et seq). The Morrill Act allotted federal land to each state to support the development of a college focused on instruction in "agriculture and the mechanic arts." (7 U.S.C. § 304). Originally blocked by southern states where education was viewed as a threat to the cheap labor supply, the Morrill Act was passed after the South seceded. The Hatch Act provided additional federal lands to conduct and disseminate research in SAESs associated with land grant colleges. In recognition of the importance of technology transfer mechanisms for realizing the benefits of research, the 1914 Smith-Lever Act established the Cooperative Extension Service to distribute knowledge relevant for the local adoption and application of innovations. These key acts balanced federal and state roles by combining federal financial support with state management for the administration and direction of research. The resulting structure provided an avenue to address local research needs while also exploiting interstate competition to motivate fruitful research. As early as 1888, states began to establish substations that addressed needs distributed at even finer geographic scales. (Huffman and Evenson, 2006; Ruttan, 1982)

The case of hybrid corn exemplifies the advantage of regionally-focused agricultural research that benefited both local farmers and consumers generally. This innovation, which originated as a by-product of basic research in genetics conducted at Harvard decades earlier (Troyer, 2009), required additional decades of adaptive research before it spread across the states in which it was ultimately established, after its initial adoption in the heart of the mid-west corn belt (Griliches, 1957).

The establishment of the SAES system in the U.S. borrowed heavily from European developments that firmly established the central role of universities and scientists in agricultural development. Justus von Leibig, a German chemist who founded the first modern chemistry laboratory, became one of the forefathers of agricultural science with his 1840 publication, *Organic Chemistry in Its Relation to Agriculture and Physiology* (Brock, 1997). During this time, agricultural research institutions in the states that eventually formed Germany demonstrated the potential power of a group of experts working on a focused field, highlighted the importance of consistent funding, provided valuable experience navigating the link between science and practice, and demonstrated the merits of inter-institutional competition. By the time of Liebig's death in 1873, the newly united Germany had 25 agricultural research stations. The German development of successful university-based agricultural chemistry research laboratories and experiment stations became the model followed throughout the U.S. and Europe, where numerous agricultural experiment stations were also established during the second half of the nineteenth century. In particular, Rothamsted Agricultural Experiment Station in England, currently the oldest continuously operating agricultural experiment station, was founded by a fertilizer manufacturer in 1843. (Huffman and Evenson, 2006; Finlay, 1988).

The first U.S. stations continued the heavy emphasis on agricultural chemistry established in Germany, and Samuel W. Johnson, the first director of a U.S. agricultural experiment station, was trained by a founder of the German system. By the time the Hatch Act was passed, 15 primarily state-funded experiment stations were already in operation.

Major benefits of public research for agricultural productivity in the U.S. began to accrue only after the research establishment had accumulated a substantial stock of knowledge. Evenson (1980) found that during 1870-1925, agricultural productivity was strongly correlated with the total real public-agricultural research spending over the preceding 18 years. Early advances in U.S. agriculture were largely borrowed from progress made in Europe. It took several decades of development and learning before the U.S. land grant/SAES system had acquired the scientific capacity and research base necessary to become an efficient system of innovation (Huffman and Evenson, 2006). Subsequent research has confirmed that stable agricultural funding promotes persistent gains in agricultural productivity (White and Havlicek (1982).

3.2 Private interests and the allocation of public funding

Since private research focuses mainly on commercializable technologies with appropriable benefits, the onus is on the public sector to produce basic science and undertake research that may be high in risk, have long development lags, or create unpredictable and non-excludable benefits (Alston *et al*, 1998; Stokes, 1997; Huffman and Evenson, 2006; Just and Huffman, 1992). High rates of return to investments in different types of agricultural technologies persist, implying that those investments have overall made excellent use of public funds, but also that the level of funding has been inadequate (Judd *et al*, 1986; Huffman and Evenson, 2006). In addition, in cases where public support for research has declined and there are private incentives or IPRs for innovation, some observers have concluded that public research funds have been increasingly directed toward the development of private goods (for example, Knudson and Pray, 1991). Economists have warned that heightened private influence over public research agendas may further erode public support for research, thus damaging the system by which basic science and public goods research is produced (Just and Huffman, 1992). However, Foltz *et al* (2007) found evidence of economies of scale and scope in life science research production of patents and journal articles, particularly in land grant universities.

A number of empirical studies suggest that interregional externalities in the U.S. significantly affect state research investment levels (Guttman, 1978; Huffman and Mirankowski, 1981; Rose-Ackerman and Evenson, 1985). For example, citing unpublished work, Alston (2002) finds that, across U.S. states, over half the measured within-state productivity gains may be derived from the benefits of research investments made elsewhere. Such spillovers, both within and among nations, may discourage investments in research. Moreover, studies by Hayami and Ruttan (1971) and Binswanger and Ruttan (1978) conclude that nationally or globally, consumers are the main beneficiaries of agricultural research since low price elasticity of demand for agricultural products means that higher productivity achieved by innovation will translate into lower prices (Guttman, 1978). In a world of highly efficient global transportation, the relatively small share of benefits from lower prices that accrues to consumers in a single state tends to limit within-state consumer support for agricultural research that increases national or global productivity (Rose-Ackerman and Evenson, 1985).

For region-specific production-oriented research (especially on crops as opposed to animals), the negative price response on international markets may be negligible. Local farmers tend to get a substantial share of the benefits of this type of research, given the level of other research activity. Political support tends to be high for region-specific innovation, suggesting that farmers have substantial influence on relevant research spending. Empirical studies indicate that U.S. state spending on agricultural research significantly and positively correlates with state characteristics such as per capita income, the share of rural population, the number of large farms, the political influence of farmers, and the number of firms producing agricultural inputs, while spending is negatively influenced by the ability to adopt technology produced in other states (Rose-Ackerman and Evenson, 1985; Guttman, 1971; Huffman and Mirankowski, 1981). In developing countries, on the other hand, underinvestment in regionally specific crops such as cassava and sweet potatoes in the 1970s relates to the relatively low influence of staple food producers and small farmers on research agendas (Judd *et al*, 1987).

4. Intellectual property for agricultural innovations[5]

4.1 Methods for protecting intellectual property rights in agriculture

Beginning with the 1930 Plant Patent Act, the United States has created a number of institutional innovations in the form of intellectual property rights, to accommodate the needs of different agricultural technologies. The eligibility criteria, duration, and nature of rights conferred vary across these IPRs, and a single innovation may be protected under multiple mechanisms under the same or different legal jurisdictions. The first IPR specifically for plants was introduced by the 1930 Plant Patent Act, allowing plant patents for new and distinct varieties of most asexually propagated plants, while the USDA administers the separate Plant Variety Protection Certificates (PVPCs) for sexually reproduced plant varieties, in accordance with the 1970 Plant Variety Protection Act (PVPA). U.S. legislators based the PVPA on the International Convention for the Protection of New Varieties of Plants (UPOV) – an agreement established in 1961 by a group of Western European countries that lays out a model system for plant breeders' rights, which was itself influenced by the United States Plant Patent Act of 1930.

Subsequently, the landmark ruling by the Supreme Court the 1980 *Diamond v. Chakrabarty* case (*Diamond v. Chakrabarty* 447 US 303, 1980) confirmed the eligibility of novel living organisms for utility patents in the U.S. Since the decision, utility patents have been applied to plant varieties, animals, genetically engineered organisms, processes for genetic transformation, and genes. The 2001 *J.E.M. v. Pioneer* Supreme Court case confirmed the legality of joint protection of an invention under utility

---

[5] This section draws heavily on Wright (2009).

patents and a PVPC or a plant patent (*J.E.M. AG Supply v. Pioneer Hi-Bred International* 122 S. Ct. 593, 2001).

Trade secrets, trademarks and geographical indications (GIs) may also apply to agricultural innovations. Legally a right based on state common law, trade secrecy can be invoked by firms that can demonstrate sufficient efforts to protect proprietary information of commercial value. It is frequently relied upon by innovators prior to obtaining a patent or other IP protection (Friedman *et al*, 1991), but has high value independent of patenting; important surveys have shown that innovators in most industries rank secrecy higher than patenting for effectively appropriating commercial value (Levin *et al*, 1987; Cohen *et al*, 2000). The model trade secret law, known as the Uniform Trade Secrets Act, has been adopted by 46 states. Trade secrecy has been more important recently in agricultural biotechnology research, since advances in biotechnology have improved detection of infringement (Boettiger *et al*, 2004).

To the extent that bioenergy development relies upon plant innovation, we can expect most of the above mechanisms (and their drawbacks, discussed below) to be relevant for energy technology. A common area of confusion concerns the jurisdiction of IPRs. It is important to note that a patent or PVPC can be enforced only in the jurisdiction in which it is granted.[6] While the Trade-Related Aspects of Intellectual Property Rights agreement (TRIPs) among the World Trade Organization (WTO) members mandates minimal standards for all types of IPRs, only copyright has virtually global reach, under the Berne Convention for the Protection of Literary and Artistic Works, which is largely incorporated in the WTO TRIPs agreement.

4.2 The private sector response

The private sector response to the new opportunities and incentives in agricultural biotechnology has been focused and forceful. Since 1987, over 55% of all field trials for genetically modified ("GM") crops have

---

[6] The well-publicized case of "Golden Rice," transformed to include pro-vitamin A, has been characterized as subject to scores of widely-held patents and as an excellent example of private-sector collaboration in licensing these patents for use in poor rice-consuming countries. In fact, few if any of the

been on corn and soybean varieties. Global GM crop value and planted area is almost entirely in soybeans, corn, cotton, and canola (James, 2008). Monsanto has become the dominant firm in generation and diffusion of agricultural biotechnology, concentrating its activities on corn, soybeans, and cotton incorporating herbicide resistant “Roundup Ready” technology and pest-resistant traits based on crystal proteins derived from samples of Bacillus thuringiensis (*Bt*). It is unlikely that public research institutions could have matched the efficiency and scale of Monsanto and other leading firms in these activities. For example, in 1998, Monsanto spent $1.26 billion in agricultural biotechnology research and development, eclipsing the total CGIAR investment of $25 million in agricultural biotechnology that same year (Pardey and Beintema, 2005).

4.3 IPR limitations and drawbacks

The most popular modern rationale for granting IPRs is that they motivate technological innovation and dissemination by at least partially privatizing associated social benefits. The experience in agriculture shows both the strengths and the limitations of IPRs in a well-balanced system of dynamic, creative research. First, private research has not been (and likely never will be) a complete substitute for public agricultural research (Alston *et al*, 1995). While the recent strengthening of intellectual property rights in the U.S. opened the way for increased private participation in basic plant breeding research by major firms such as Monsanto and Pioneer (Falck-Zepeda and Traxler, 2000), the private sector primarily performs applied research with the goal of producing a profitable technology or product. Private sector research critically depends on the public sector to produce the “building blocks” for technology. (Alston *et al*, 1998; Stokes, 1997; Huffman and Evenson, 2006; Just and Huffman, 1992)

Economists have recognized that the intellectual property protection of research at public institutions might erode the provision of and access to such public goods. For example, Just and Huffman (2009) note that while the 1980 Bayh-Dole Act led to a jump in university patenting (from less than 400

---

patents were relevant to production or use of the technology in major poor rice-consuming countries; licenses related mainly to material transfer agreements. (See Binenbaum et al, 2003).

patents per year before Bayh-Dole to 1100 per year by 1989 and over 3000 per year in the 1990s), the act may have reduced the pool of basic research supporting private research, shifting the focus of public research towards shorter-term incentives such as patents, at the expense of future public goods research.

Furthermore, there appears to be great variation in private responses to different forms of intellectual property. While Fuglie et al (1996) found that in the U.S., private investments in agricultural biotechnology increased fourfold (nominal) in the first twelve years after the *Diamond v. Chakrabarty* ruling, Alston and Venner (2002) were unable to find evidence of increased private-sector investments in wheat breeding as a response to the PVPA, which they conclude is more relevant to marketing than research.

4.3 Freedom to operate in agricultural research and market concentration

There is mounting evidence that multiple, mutually blocking intellectual property claims on inputs are hindering access to research tools that can be incorporated in the marketed products of agricultural research (Wright and Pardey, 2006; Pardey et al, 2007). The rising application of IPRs to plant components and processes imposes high transaction costs for researchers who must acquire or license fragmented proprietary inputs to develop and commercialize a single downstream innovation.

Agricultural economists have long been concerned that patents on locked-in but otherwise non-crucial genetic technologies have been retarding innovation and affecting the market structure of private research. In the field of plant biotechnology in particular, where ownership of the genes, markers, or promoters incorporated in a single innovation is fragmented, upstream IPR-holders, unwilling to allow commercialization of varieties using their property, have in some instances foreclosed university development of new crops or technologies.[7] The broader economics profession has become focused on

---

[7] For example, the cases of the GE tomato and herbicide-resistant strawberry at the University of California at Berkeley, an herbicide tolerant barley, and an herbicide tolerant turf grass at the University of Michigan (Wright, 1998; Wright *et al*, 2007; Erbisch, 2000). More recently, commercialization of transgenic hypoallergenic wheat technology has been blocked by a combination of patent protection and regulatory costs. (P. Lemaux, personal communication) Generation of further examples is unlikely, given

these issues more recently, due to growing problems with blocking patents on embedded software (Besen and Hunt, 2004; Lemley and Shapiro, 2005; Lemley and Shapiro, 2007; Cohen et al, 2000). The Supreme Court appears to have acknowledged this problem in its eBay decision (*eBay Inc v. MercExchange, L.L.C.*, 547 U.S. 388 (2006)), which reduced the ability of holders of blocking patents to use the threat of injunction to extract high royalties from infringers.

In a 2003 *Science* article signed by fourteen university presidents, chancellors, and foundation presidents, the authors highlight the negative effect of intellectual property rights on “freedom to operate” in agricultural research (Atkinson *et al*, 2003). In fact, universities themselves appear to have contributed to the problem by insisting on the use of material transfer agreements (MTAs) governing exchanges of research materials between researchers, to protect university intellectual property rights and limit university liability.

A recent survey indicates that, for scientists focused on their own research goals rather than commercialization of innovations, the problems associated with MTAs are more salient than concerns about patent infringement. Over a third of agricultural biologists at Land Grant Universities reported delays in obtaining access to research tools in the five years preceding the survey, with a mean of two delays and a mean duration of over eight months (Lei *et al*, 2009). They attributed the vast majority of these delays to problems experienced by university administrators in negotiating MTAs. Researchers reported responding to hold-ups by substituting tools, sometimes of lower efficacy, and in some cases by abandoning the project altogether. Although a substantial portion of the sample were patentees, most respondents view intellectual property protection as a net negative for progress of research in their fields.

Follow-up interviews revealed that scientists view university administrators as principally concerned with protecting their institutions’ financial interests including protecting claims to potential intellectual property value and reducing exposure to potential liability. Indeed, Glenna *et al*’s 2007 survey

---

that independent university implementation of new transgenic technologies is widely regarded as economically infeasible due to the combined effects of blocking patents and regulatory costs and delays.

reveals that land-grant university administrators, on average, rate the provision of new funds and research support as the greatest advantage of university-industry research collaborations, but believe that scientists choose projects based on research enjoyment and scientific curiosity.

Private firms in agricultural biotechnology, unlike bench scientists, cannot ignore infringement issues. Often, firms have to commit to commercializing a product involving many patents, subject to time-consuming development and regulatory approval processes, and thus exposed to holdup even by owners of non-essential technologies that become "locked in" as innovation progresses. Major firms have established freedom to operate largely by merger and acquisition of patentees, rather than by in-licensing.

Since the mid-1990s, a relatively dramatic series of industry purchases led to concentration of the agricultural biotechnology sector. As a result, a relatively modest number of private hands controls a major portion of patents in the field (Murray and Stern, 2007; Marco and Rausser, 2008). In effect, the possibility that an injunction might stop a line of development and commercialization in its tracks was avoided by a strategy that does not rely solely on in-licensing, but instead deals with potential hold-ups by acquisition or merger. The European conglomerate AgrEvo acquired Plant Genetic Systems (PGS) for $730 million, $700 million of which accounted for the estimated value of PGS-owned patents on plant traits. Monsanto in 1997 purchased Holden's Foundation Seeds for $1.1 billion, when Holden's gross revenues were just $40 million. In 1998, Monsanto paid $2.3 billion to acquire the 60% of DeKalb Genetics Corporation which it did not already own. DeKalb, the owner of a major corn transformation technology, had a 1997 total revenue of $450 million (United States Department of Justice, 1998; Marco and Rausser, 2008). The following year, DuPont Co. purchased the remaining 80% of Pioneer Hi-Bred International that it did not already own for $7.7 billion (Marco and Rausser, 2008).

Based on USDA data for 1988-2000, Brennan *et al* (2005) found that when including mergers and acquisitions, the top ten firms (rated by number of patents held) owned more than half of the agricultural biotech patents granted through 2000, whereas if patents acquired via purchases and mergers are excluded, the share owned by the top ten firms would be only one third. One firm (Monsanto) currently accounts for almost two-thirds of all public and private plant biotech field trials in the United States. King and Schimmelpfennig (2005) show that by 2002, six firms (Monsanto, Dow, Dupont, BASF, Bayer, and Syngenta) controlled over 40% of the agricultural biotech patents owned by the private sector, with the subsidiaries acquired by these firms through mergers and acquisitions responsible for 70% of their total patent stocks. Concentration in the innovation market has continued to increase; USDA data on field releases of new genetically modified organisms show Monsanto’s dominance in the testing of new GM products (Figure 1).

Thus the need to ensure freedom to operate in an environment of initially fragmented and decentralized proprietary claims enhanced the normal tendency of firms in a new industry to consolidate in order to avoid transaction costs, exploit increasing returns to scale, and establish market power (Rausser, 1999). Notably, Marco and Rausser (2008) empirically show that in the plant biotechnology industry, the enforceability of a firm’s patent portfolio is a good predictor of participation in consolidation. Additionally, the authors note that a number of mergers, including Monsanto-Calgene and Monsanto-DeKalb, occurred in the context of patent infringement litigation.

It appears to be true that IP-induced consolidation in agricultural biotechnology is negatively affecting the very same innovation and dissemination incentives that justified IPRs in the first place. By blocking new firms from entering, market consolidation may suppress future innovation (Barton, 1998; Wright 1998; Graff *et al*, 2004). Lack of freedom to operate particularly affects nonprofit research institutions, which cannot solve the problem by merger or acquisition of blocking firms, and can scarcely afford the expense of a lawsuit.

4.4 Attempts to ensure freedom to operate for public and nonprofit research: BiOS and PIPRA

Early recognizing the threat from lack of freedom to operate, public and nonprofit parties have formed institutions which endeavored to construct alternative technologies that could circumvent patents blocking key transformation technologies. These include the Biological Innovation for Open Society

(BiOS) and Public-Sector Intellectual Property for Agriculture (PIPRA) initiatives, which have both attracted widespread attention from biologists in the biomedical sector.

Inspired by the successful open source models in software, BiOS, an open source initiative arising out of the nonprofit biotechnology firm Cambia, was formed to license rights to use protected innovations, including those that could substitute for technologies protected by blocking patents, in exchange for a commitment to share any downstream technologies with all BiOS members (Jefferson, 2006). It appears that this bold initiative has not functioned as anticipated. Participants willing to access Cambia technologies offered by BiOS are apparently reluctant to follow the lead of Cambia and offer their own technologies under an “open source” license.[8] A more fundamental problem might be that any success achieved in open source software using copyright licenses to prevent appropriation of the core technology might be difficult to replicate in a system that relies on patent protection (Boettiger and Wright, 2006).

PIPRA, founded with support from the University of California and the Rockefeller and McKnight Foundations, was intended to act as a clearinghouse for information about patenting and licensing of technologies originating in the public and nonprofit sector. The goal was to facilitate commercialization and adoption of new technologies in less developed countries and of “minor” crops such as the fruits and vegetables produced in California. The common problem of both target groups was that their markets were too small to attract much interest from the major agricultural biotechnology corporations. PIPRA’s intellectual property strategy, similar to that of CAMBIA, was to protect proprietary claims for commercial use in developed countries (consistent with federal policy expressed in the Bayh-Dole Act of 1980 and with the aims of university licensing objectives), while simultaneously providing access to users in less developed countries and producers of minor crops, and reserving public and nonprofit institutions’ rights to use the inventions in developing country applications.

---

[8] Stricly speaking the license was not open source as participants are charged on a sliding scale based on size.

While these initiatives yielded notable scientific advances (see for example Broothaerts *et al* 2005), neither has yet furnished an efficient and completely unencumbered biotechnology package that is a good substitute for proprietary blocking technologies that received wide market acceptance. Indeed, the experience of these initiatives constitutes strong evidence of the blocking capacity of proprietary claims over key elements of plant transformation. The lack of attractive unencumbered alternative technology sets may be the main reason why efforts to encourage collaboration in open-source type ventures have not made more headway. However, had they already succeeded at this level, the regulatory hurdles would still have loomed large.

Although attempts to offer unencumbered alternatives to key technologies are continuing, both CAMBIA and PIPRA are currently emphasizing provision of easily accessible information to researchers in developing countries and non-profit institutions regarding freedom to operate within the context of patenting as the dominant paradigm. They offer other services that can assist public and nonprofit research institutions in navigating patent thickets and identifying intellectual property issues before they become serious problems. PIPRA provides educational and informational services to facilitate navigation of the IP landscape and promote innovation-enabling collaboration, as well as a valuable IP handbook. CAMBIA offers, among other services, its “Patent Lens” to provide accessible guidance as to the patent landscape relevant to the plans of researchers in biotechnology (Graff *et al*, 2001; Atkinson *et al*, 2003; Delmer *et al*, 2003).

5. Public-private collaborations

Channeling fruitful basic research from the public sector into applied research efforts by the private sector is a key, though problematic, step in the innovation “pipeline.” Economists have often highlighted the potential for public-private collaborations to bridge this gap and have argued for their critical role in spreading agricultural biotech innovations for consumers in developing countries (Rausser *et al*, 2000; Byerlee and Fischer, 2002; Tollens *et al* 2004; Parker and Zilberman, 1993). In light of declining federal research support between 1980 and 2000, collaborations with the private sector have become increasingly attractive for public sector researchers. However, public-private collaborations do not currently account for a large portion of agricultural research in practice. A few examples illustrate of the potential benefits and drawbacks of these agreements.

Overcoming conflicts between private sector interests and public responsibilities is a key challenge to fruitful public/private collaboration. In their 1986 analysis of the Canadian malting barley industry, Ulrich *et al* (1986) find that the availability of grants from and collaborative work with the brewing industry led the public sector to pursue traits to improve malting quality. Although the research yielded both public and private benefits, the collaboration siphoned public resources away from yield-related traits. Ulrich *et al* calculate social gains would have been 40% higher or more had public researchers focused only on yield-related traits. Note that this example is drawn from an era when intellectual property protection had yet to strongly influence the direction of research activity in agriculture.

The subsequent proliferation of patenting in universities has increased the potential for diversion of the university agenda toward private monetary returns and away from the direct public interest. Such a real or apparent shift in focus of public institutions away from public goods research might further reduce public support for universities (Just and Huffman, 2009), even if the ultimate motive is to ensure survival of the institution in an era of public cutbacks. Supporting this argument are Glenna *et al*’s (2007) findings that land grant university administrators rate further support for research and increased funding as the main benefits from university-industry collaborations, and potential for conflicts of interest as their main drawback.

An innovation in private support for public agricultural research was established by the 1998 agreement between the University of California at Berkeley and the Novartis Foundation. The latter was selected by Berkeley as partner after eliciting competitive bids from several firms. The agreement generated much controversy, motivated by opposition to the genetic transformation technologies involved in the research to be funded, by objections to the decision-making procedures that led to the partnership, and by concern that the university was selling its plant biology agenda to the highest bidder, distorting the direction of university research. The Novartis Foundation had the right to a vaguelyspecified subset of the research results in plant and molecular biology and had a minority of seats on the committee allocating project resources. (Busch *et al*, 2004; Rausser, 1999)

In hindsight, the $25 million received from the Novartis (later Syngenta) Foundation appears to have been associated with an increase in the level and the diversity of funding of Plant and Molecular Biology at Berekeley, with little if any affect on research direction. It appears that no valuable patents were obtained by the funder. Indeed a similarly generous arrangement is unlikely to be achieved in future public-private partnerships in biotechnology. Nevertheless an ex post review (Busch *et al*, 2004) concluded, among other things, that the agreement did affect the processes leading to the initial denial of tenure (later reversed) to a prominent critic of the agreement. Even relatively hands-off funders, it seems, can affect the operation of procedures relevant to protection of academic freedom in the university.

Subsequently, Berkeley has become the lead partner (with Lawrence Berkeley National Laboratory and the University of Illinois at Urbana-Champaign) in the $500 million Environmental Biosciences Initiative (EBI), funded by British Petroleum and aimed at developing means of converting cellulosic biomass to a substitute for petroleum. Some of the intellectual property provisions of this agreement are more favorable to the funder than in the Berkeley-Novartis agreement, but the EBI has not generated the same degree of opposition, on campus or beyond.

In another model of public-private collaboration known as Cooperative Research and Development Agreements (CRADAs), the U.S. provides research funds to national laboratories contributing non-financial resources in order to produce a commercial technology in collaboration with a private firm. Any proprietary material may be owned by both parties, but the private collaborator gets priority in licensing (Day-Rubenstein and Fuglie, 2000). Since 1987, the USDA has formed at least 700 CRADAs with private firms. CRADAs have produced and commercialized at least a handful of important innovations (Day-Rubenstein and Fuglie, 2000).[9] In accordance with the goal of connecting the basic and

---

[9] Most notably, a CRADA is responsible for production of the anti-cancer drug Taxol, based on the bark of the Pacific yew tree, and involving the USDA and its Forest Service (Koo and Wright, 1999). This highly successful drug is used in treatment of ovarian and breast cancers. In the agricultural field, CRADAs have been associated with the development of a number of pest and disease controls, a chicken

applied ends, CRADA research focuses on a “middle ground” between public and private goods (Day-Rubenstein and Fuglie, 2000). However, concerns that CRADAs and other public-private collaborations divert funds from public goods or basic research to more applied research highlight the need to carefully design collaboration agreements and to consider the unintended effects of undertaking collaborations (Just and Rausser, 1993). In addition, claims that CRADAs provide unfair advantages for the private partner (even if, as in the case of Taxol, the contract was awarded by auction), illustrate that any agreement mechanism providing profits high enough to incentivize private investment in a risky enterprise will be met with critical political comment if the CRADA succeeds.[10]

On the other hand, research consortium models such as those adopted by the Latin American Maize Project (LAMP) and the Germplasm Enhancement of Maize Project (GEM) have been lauded for productively balancing public goods research with commercial viability (Knudson, 2000). Initiated by then Pioneer CEO William Brown, LAMP was established in 1987 as a cooperative effort to regenerate and utilize maize landraces, supported by funding from Pioneer and resources from the U.S., 11 Latin American countries, and the International Maize and Wheat Improvement Center (CIMMYT) (Knudson, 2000; CIMMYT, 1997). Of the 12,000 accessions evaluated by LAMP, 51 accessions plus 7 donated from DeKalb formed the source material for the USDA-ARS GEM Project. Jointly funded by an array of private, public, and non-profit collaborators and utilizing research from federal programs, state programs, and private industry, GEM’s structure recognized needs from the local to national levels and maintained industry support through appropriate IPR provisions (Knudson, 2000).

6. Government regulation

From an economic perspective, government regulation is necessary to correct for externalities such as those related to environmental quality, food safety, and public security. Aside from immediate social,

---

vaccine for Marek’s disease, and a chemical compound to reduce soil erosion (Day-Rubenstein and Fuglie, 2000).

[10] Even prominent economists will make such comments. See for example the claim by Boldrin and Levine (2008, Chapter 1) that any returns above “break-even” were superfluous to the incentive needed for Boulton and Watt to produce their celebrated steam engine.

environmental, and economic costs, past regulatory disasters and their aftermaths demonstrate that ineffective or disingenuous government practices create a secondary problem of reduced public confidence and support. On the other hand, the costs of regulatory compliance can discourage innovation and technology adoption. The challenge to government is to strike a balance between supporting technological improvement and protecting public safety.

6.1 Public trust

Experience in agriculture demonstrates that a poor track record or a handful of extreme cases may durably erode public confidence in the government's ability to prudently select and monitor new technologies. The U.S. Three Mile Island incident and the Ukrainian Chernobyl disaster caused significant curtailment of nuclear power projects in Sweden and Italy, respectively, and weakened public trust in government officials and scientists alike (Weingart, 2002). Studies of government regulation and public perceptions drew parallels between the cases of nuclear power and agricultural biotechnology (Sjoberg, 2001; Poortinga and Pidgeon, 2005). Indeed, Chernobyl's contamination of European foods was initially denied by many governments, and the consequences for public perceptions of technological risks, government competence, and the reliability of public assurances has contributed to the prohibition of genetically modified foods in Europe (Vogel, 2001; Lusk *et al*, 2003).

Past crises in food safety have also demonstrated the consequences for public health, government reputation, and industry. After the BSE outbreak was recognized in Britain, European regulatory systems were further discredited by the British Ministry of Agriculture's insistence that BSE posed no threat to human health and the French government's slow response to BSE (Vogel, 2001; Daley, 2001). The direct effects of BSE on beef consumtion and the subsequent trade bans caused heavy losses to beef producers. The containment costs borne by the British government reached £700 million per year in 1996, or about 0.1% of GDP (Gollier *et al*, 2001). Another example is the release by the European multinational firm Aventis of genetically engineered corn, StarLink, into the U.S. food supplies, when the corn was approved only for feed. Fortunately no health damage to consumers was detected. Aventis agreed to pay $110 million plus interest to farmers whose crops were contaminated (O'Hanlon, 2004; Pollack, 2001;

Shuren, 2008) to compensate for adverse effects on prices of exports due to fears of harmful contamination.

The StarLink case not withstanding, the lack of major food-related regulatory disasters in recent U.S. experience likely has contributed to greater public acceptance and employment of agricultural biotechnology in the U.S. relative to Europe (Vogel, 2001; Nelson, 2001). However the effects on public perception are not confined by national boundaries and can become confounded with strategic market maneuvers. For example, China changed its plans to approve GM foods when the StarLink incident cooled demand for GM corn by importers Japan and South Korea (Cohen and Paarlberg, 2004). In North America, the U.S. wheat industry compelled the agricultural biotech firm Monsanto to release the first genetically engineered spring wheat in the U.S. and Canada, or not at all. The technology was shelved in both countries when Canada rejected the product (Berwald *et al*, 2006).

Considering the commonalities of the above cases, we would expect public trust problems to be most influential for technologies related to foods, with uncertain but potentially widespread and irreversible risks, and in cases where the benefits are dubious from the consumer viewpoint (Arrow and Fischer, 1974; Brush et al, 1992). Bioenergy products, especially if they are not related to foods or feeds, might be better accepted due to the widespread recognition of the benefits of a cleaner and more secure energy supply.

6.2 Non-adaptive regulatory systems and unintended consequences

While negligent regulatory systems can precipitate public safety disasters, the costs of extremely restrictive regulatory systems are less transparent but may also be severe. They can impede the application of technology, implying missed opportunities to realize the benefits of research and innovation. Cases in various countries show that both lack of regulatory capacity and public distrust may lead to regulatory procedures that slow adoption of technology. In addition, relatively stringent regulatory standards for a particular set of technologies create an advantage for substitutes.[11] Thus,

---

[11] Graff and Zilberman (2007) argue that the interests of European pesticide and herbicide producers have influenced the development of negative attitudes on that continent to agricultural biotechnology.

government safety standards have indirect but important effects on market structure and environmental externalities.

The case of U.S. agricultural chemical regulation illustrates some of the tradeoffs related to standard setting. Ollinger and Fernandez-Cornejo (1995) found that between 1972 and 1989, in response to three amendments tightening regulatory requirements, industry-wide research spending increased, but the share of regulatory costs in total R&D increased from 18% to an astounding 60%. The authors also found that each 10% increase in regulatory costs corresponded to a 2.7% reduction in the number of new pesticides products, but also decreased the negative environmental qualities of the pesticides produced. Regulatory costs affected the market by increasing foreign capture of market share, reducing the number of small firms and broadening opportunities for biological pesticides and GMOs. As this example shows, the net effects of regulation are hard to pin down.

Many governments have recently enacted regulatory standards for the release of agricultural biotechnology to address concerns about potential ecological and food safety risks. While some scientists fear the standards for transgenic crops do not adequately inform us about potential risks, economists have argued that these regulations hinder implementation of important technologies (Fuglie *et al*, 2006; Zilberman, 2006; Pardey *et al*, 2007; Cohen and Paarlberg, 2004). For example, lack of mutual recognition of regulatory standards and test results requires duplication of field trials for transgenic crops in some East and South African countries, without generation of new information between test trials, and has slowed commercialization (Pardey *et al*, 2007; Thomson, 2004).

In India, regulatory authorities approved the first field trials for Bt transgenic cotton in 1998. Although the crop had been grown as early as 1996 in countries such U.S., Australia, South Africa, Mexico, Argentina, and China, outcry by NGO groups claiming to represent India’s farmers influenced regulatory officials to delay final approval for *Bt* cotton until 2002 – about six months after authorities discovered some 500 Gujarati farmers had already illegally planted *Bt* cotton seeds. A public edict to destroy the standing crop were abandoned after demonstrations by thousands of farmers. Another example of obstructive Indian regulation is that of a transgenic mustard variety which underwent successful field trials in India for at least nine years (Cohen and Paarlberg, 2004), but is yet to be commercialized. If biofuel technology utilizes transgenic crop innovations, inflexible and inefficient regulatory systems could significantly defer this alternative fuel's production and utilization.

For transgenic food crops in the U.S., the Food and Drug Administration, Environmental Protection Agency, and USDA Animal and Plant Health Inspection Service have regulatory authority concerning potential risks related to food safety, pesticidal properties (if applicable), and field testing, respectively (Vogt and Parish, 1999; Fuglie *et al*, 1996). While public opinion and government policy create a less hostile environment for GMOs relative to the regulatory environments in areas such as Europe and Africa, some economists maintain that U.S. regulation for transgenic crops is unduly restrictive, relative to regulations for competing technologies (Miller and Conko, 2005).

In industries subject to market concentration, such as the agricultural biotech industry, insights from capture theory suggest pushes for regulatory reform are likely not forthcoming. High compliance costs associated with stringent regulatory standards may even be preferred by firms with market power since such standards create barriers to entry and build consumer approval (Zilberman, 2006). For example, in 1925 California adopted the One-Variety Cotton Law, requiring nearly all California cotton growers to plant a single USDA-controlled cotton variety in the interests of quality control. In their 1994 analysis of the regulation, Constantine *et al* (1994) argue that any initial benefits were lost over time due to unforeseen technological changes, institutional reforms, and regulatory cost increases. While the industry was partially deregulated in 1978, private beneficiaries of the regulation successfully resisted further reform for a number of years, despite the regulation's large social costs.

Economists have critiqued the precautionary principle (cited by European GMO regulators) for failing to respond to new information (Gollier *et al*, 2001; Vogel, 2001). In agricultural biotechnology, the firm bears the costs of regulatory compliance. Although farming of biotech food crops has grown rapidly in recent years, the still narrow breadth of the market may be influenced by regulations slowing commercialization of new transgenic traits beyond herbicide tolerance and Bt-based insect resistance in corn, soybeans, canola and cotton (Pardey *et al*, 2007).

7. Technology adoption

Timely adoption is necessary in order to realize the benefits of innovation. The most relevant aspect of adoption in the agricultural sector is the dispersed application and management of technologies adapted to local environments. The period between technology development and widespread adoption by farmers can be quite long (and infinite for technologies that never take hold). Griliches’ (1957) work on hybrid corn adoption and subsequent empirical studies[12] showed that the rate of technology diffusion increased with profitability from its adoption. A multitude of economic studies has taught us that factors such as risk and heterogeneity are crucial determinants of adoption. In addition, the canon of relevant political economic work highlights the dependence of adoption on consumer preferences, political interests, and the appropriateness of technology. With respect to energy innovations, we might expect analogous issues to arise for technologies with similarly dispersed applications. Again, production of biofuel crop technologies is a clear example, but prior adoption research might also be relevant for technologies like cookstoves for less developed countries, mini or micro hydroelectric systems, wind farms and building efficiency innovations, all of which could well have user-dependent outcomes affected by the heterogeneity of regulations and of the natural environment.

7.1 Profitability and heterogeneity

The recent increases in market concentration due to strengthened IPRs in agriculture (as discussed above) might well imply oligopoly pricing that reduces adoption of technologies integrating proprietary components. However, the dispersed use of agricultural technologies in heterogeneous environments constrains the extent of non-competitive pricing if spatial price discrimination is costly. Thus, even firms exercising market power may have to employ low-price policies in order to encourage rates of technological exposure and adoption that make the discounted value of the innovation positive and attractive to investors. The empirical study by Falck-Zepeda *et al* (2000) on markets for transgenic soybeans and cotton estimated that firms Monsanto and Delta & Pine Land (D&PL) adjust price to keep about 21% of the benefits generated from these innovations, while about 59% of these benefits flow to

---

[12] Feder, Just, and Zilberman (1985) provide a summary of empirical work

farmers, despite essential monopoly power by Monsanto and D&PL. A follow-up study by Oehmke and Wolf (2004) estimated heterogeneity in technology adopters to account for 80% of farmer rents. Although the question has yet to be addressed in depth, it appears that if “degraded” lands are favored for biofuels production due to low carbon release upon cultivation, their heterogeneity could well reduce the speed of technology adoption, thus reducing monopoly rents and perhaps investment in optimizing the technology.

When the newest technology is a substitute for their current technology, farmers will not adopt the new technology unless the net benefits of switching are positive, leading to an additional constraint on oligopoly pricing for the new technology (Pray and Fuglie, 2001). If the current rate of innovation is rapid, the loss of the option to wait and use an even better prospective technology may increase the cost of adopting the current best technology when the sunk costs of learning or complementary investment are significant.

A large body of research on heterogeneity and adoption demonstrates that a number of other factors moderate the profitability of adoption at a given time. While a full review is beyond the scope of this paper, we briefly provide a few examples to illustrate the diversity of this work. Studies such as those by David (1969), Feder (1980), and Ruttan (1977) discuss the influence of farm size (perhaps as a proxy for wealth or increased access to credit, information, or production inputs) on the rate of technology diffusion or level of individual adoption, for various types of technology and institutional frameworks (Feder, Just, and Zilberman 1985). A recent paper by Fernandez-Cornejo *et al* (2005) finds that small U.S. farms that supplement farm income with off-farm activities are more likely to adopt time-saving technologies such as herbicide-tolerant crops or conservation tillage. Examples of research evaluating the effect of heterogeneity in land quality on adoption decisions include Caswell and Zilberman’s (1986) analysis of water-holding capacity and irrigation technology and Rahm and Huffman’s (1984) article relating soil quality to adoption of corn varieties. Recently, access to information and social capital have been highlighted as determinants of adoption of crop varieties such as hybrid corn and wheat, mechanical innovations such as tractors, and livestock technologies, to name a few (Skinner and Staiger, 2005;

Matuschke et al, 2007; Abdulai and Huffman, 2005). Finally, a plethora of research discusses the role of risk and uncertainty associated with adopting new technologies.

Another important insight is that technologies that reduce input use per unit output may, via price effects, increase total input demand with respect to the efficiency-adjusted unit, as observed in studies of water or energy use in modern irrigation technology (Caswell and Zilberman, 1986). Thus, yield-enhancing varieties of biofuels crops may increase, rather than reduce, the area planted to such crops.

7.2 Policy implications

Given the heterogeneity of the myriad of moderating factors, the adoption of agricultural technologies over extensive geographic areas is enhanced by directed local efforts and adaptations (Knowler and Bradshaw, 2007). Key decisions for government are whether and how to alleviate risks and high fixed costs associated with adoption. The relevance of risk is dependent upon farmer perceptions and the type of technology (for example, see Fernandez-Cornejo *et al*, 1994). The adoption of crop technologies is scale-neural in the sense that farmers can test the new crop on a small portion of land, thus reducing risk problems and allowing farmers to learn through use (Feder, 1982; Feder, Just, and Zilberman, 1985). This strategy might be less relevant for biofuels, if their introduction depends upon a large investment in local processing facilities. In this case, extra attention should be paid to spatially dispersed adaptive and evaluative research (Judd *et al*, 1986), and appropriate extension services, public or private.

Agricultural extension systems are designed to provide farmers information about new technologies and thus facilitate technology transfer or adoption. Researchers have estimated high rates of return to extension work in the U.S. and have demonstrated that, provided there are attractive technologies awaiting adoption, contact between farmers and extension agents promotes technology adoption in some less developed countries (Huffman and Evenson, 2006; Abdulai and Huffman, 2005; Polson and Spencer, 1990).

In industries requiring high up-front investments in infrastructure or regulatory compliance, adoption may be retarded by lock-in of old technologies. In agricultural biotechnology, regulatory requirements for testing a new variety, and fragmented IP claims on inputs for a single new technology, create high costs of entry for followers once a leading innovation has become approved established. Private firms owning IP might raise their prices for access to proprietary technology after strategically pricing low to induce diffusion and dependence.[13] This issue is akin to a problem of patented technology incorporated in regulatory standards, familiar from the literature in electronics and communications technology, although the connections between the relative literatures have not, as far as we are aware, been fully explored.

Note, however, that if farmers perceive a technology to be extremely attractive or to provide significant benefits, they will not only adopt at impressive rates but may also perform adaptive innovation themselves, regardless of the policy regime in place. A case in point is the exchange and development of unapproved genetically modified seeds by Gujarati farmers, and the success of these farmers' opposition to federal attempts to destroy the unapproved standing crop (Pray et al, 2005). The case of "no-tillage" agriculture in the U.S., one of the prominent agricultural innovations in the late twentieth century, is also a striking example of users innovating and adopting in response to prices and practical environmental problems. The first no-till planting is credited to Kentucky grain grower Harry Young, an extension specialist who successfully applied his knowledge of scientific trials for new herbicides to develop this new method of crop growing in 1962 (Coughenour and Chamala, 2001). Due to such benefits as increased yield and reduced requirements for labor, water, fuel, and machinery, the word about no-tillage spread rapidly between farmers, who traveled from neighboring states to learn about Young's technique. The ensuing years saw rapid diffusion of the technique between farmers,[14] who adapted the technology

---

[13] For example, in the years before United States patents were generally published 18 months after application, Monsanto encouraged widespread use of their 35S promoter in plant transformation. The fact that Monsanto had a patent on the technology was revealed only after 35S had been diffused widely, when the patent was granted and published. Innovators could commercialize their technologies incorporating the promoter only if they had a license from Monsanto, since switching promoters would have required producing new transgenic technologies using a non-infringing promoter, followed by transformation of relevant cultivars, testing, and dissemination (Joly and de Looze, 1996), an alternative so time-consuming as to preclude serious consideration.

[14] By 1970, 35% of farmers in southwest Kentucky had tried no-tillage for corn (Coughenour and Chamala, 2001)

for other crops such as soybeans. In view of the many complex legal and institutional innovation systems developed by governments, these examples are important reminders of the time-honored role of practitioners participating in technological development, with motivations ranging from necessity to curiosity.

8. Conclusion

In both the energy and the agricultural sectors, the demand for the services and goods produced extends across all the populated areas of the world, where heterogeneity in consumer preferences, environmental conditions, economic structures and governmental policies mediate the applicability and appropriateness of innovations. For agriculture, the need for local adaptive technology has created global dispersion of research efforts and support. However, investments are by no means evenly dispersed across the globe. Instead, the majority of global spending comes from large countries that can internalize the benefits of research. The high rates of return to agricultural research in the United States were achieved through sustained, though less than optimal, public investment oriented by a clear mission. The establishment of institutional mechanisms in the 19th Century created a public commitment to agriculture, but the extent and direction of public investments has been and will continue to be influenced by interest groups operating at multiple geographic scales.

The experience in agriculture should be of interest to those assessing the appropriate roles of public and private research. In agriculture, strengthening of intellectual property protection has been associated with a surge in private research expenditures in developed countries. Further, it appears that leading firms in the private sector have been particularly efficient in developing, promoting and disseminating commercial technology packages, relative to what one might reasonably expect of a typically competent public or non-profit entity, especially in the context of a disruptive and controversial technology.

On the other hand, the last fifteen years have demonstrated the limits of the role of IPRs in a balanced research system. (1) IPRs have not strongly encouraged the private production of basic, essential research that is risky and often only pays off in the long run, (2) IPRs on key research inputs can impede freedom to operate in public research, and (3) IPRs on research inputs have led to market concentration and price markups, which should discourage or delay adoption.

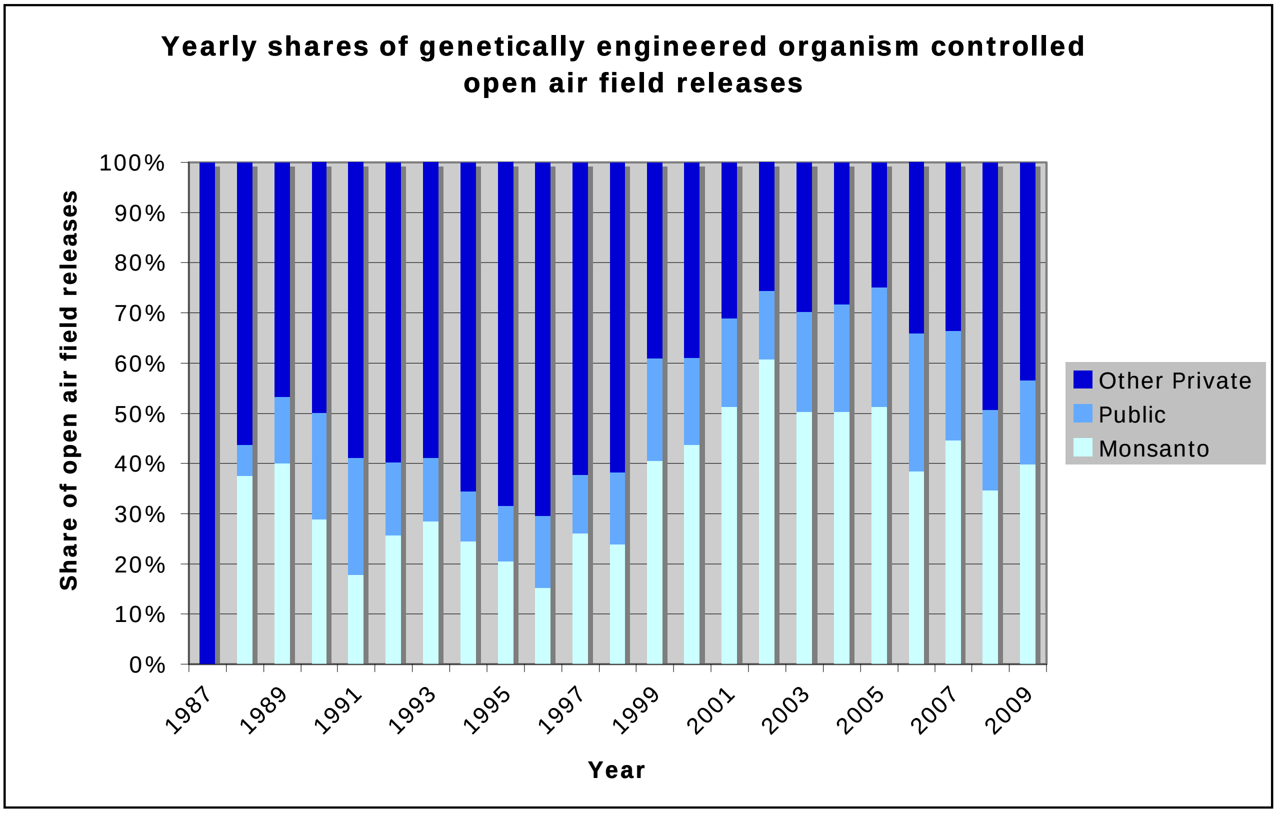
For governments, experience in agriculture illustrates the importance of effective consumer protection, administration of standards and grades, and antitrust. With respect to innovations, governments face the challenge of balancing public trust and safety with exploiting the advantages produced by a changing technological environment. Critiques of the shortcomings of regulatory performance in the United States and elsewhere draw attention to the need for further scientific study directed to the achievement of effective and dynamically adaptive regulation.

9. Appendix

Table 1: Estimated global public and private agricultural R&D investments, 2000

	Agricultural R&D spending (million 2000 intl. dollars)		*Shares in global total (%)*	
	1981	*2000*	*1981*	*2000*
Public				
Asia and Pacific (28)	3047	7523	20.0	32.7
Latin America and Caribbean (27)	1897	2454	12.5	10.8
Sub-Saharan Africa (44)	1196	1461	7.9	6.3
West Asia and North Africa (18)	764	1382	5.0	6.0
Subtotal, less developed countries (117)	6904	12819	45.4	55.8
USA	2533	3828	16.7	16.6
Subtotal, High Income Countries (22)	8293	10191	54.6	44.2
Total (139)	15197	23010	100.0	100.0
Private				
Developing	-	869	-	6.5
High Income	-	12577	-	93.5
Total	-	13446	-	100.0
Public and private				
Developing	-	13688	-	37.5
High Income	-	22767	-	62.5
Total	-	36456	-	100.0

Source: Pardey *et al.* (2006a)



Source: Source data from U.S. Department of Agriculture, Animal and Plant Health Inspection Service. Available http://www.aphis.usda.gov/biotechnology/status.shtml. Accessed 17 July 2009.

10. References

Abdulai A, WE Huffman. (2005) “The diffusion of new agricultural technologies: the case of crossbred-cow technology in Tanzania.” *American Journal of Agricultural Economics*, 87(3): 645–659.

Adelaja AO. (2003) “The 21st century land grant economist.” *Agricultural and Resource Economics Review*, 32(2): 159–170.

Alston JM. (2002) “Spillovers.” *The Australian Journal of Agriculture and Resource Economics*, 46(3): 315-346.

Alston JM, C Chan-Kang, MC Marra, PG Pardey, and TJ Wyatt. (2000) “A meta-analysis of the rates of return to agricultural R & D: ex pede herculem?” Washington DC, IFPRI.

Alston JM, MC Marra, PG Pardey, and TJ Wyatt. (2000a) “Research returns redux: a meta-analysis of the returns to agricultural R&D.” *The Australian Journal of Agricultural and Resource Economics,* 44(2): 185-215.

Alston JM, PG Pardey, and J Roseboom. (1998) “Financing agricultural research: international investment patterns and policy perspectives.” *World Development* 26(6): 1057-1071.

Alston JM, GW Norton, and PG Pardey. (1995) *Science under scarcity: Principles and practice for agricultural research evaluation and priority setting*. Ithaca, N.Y.: Cornell University Press.

Alston JM, and PG Pardey. (1999) “The economics of agricultural R&D Policy.” In JM Alston, PG Pardey, VH Smith (eds) *Paying for Agricultural Productivity*. Baltimore: John Hopkins University Press, pp. 6-30.

Alston JM, and RJ Venner. (2002) “The effects of the US Plant Variety Protection Act on wheat genetic improvement.” *Research Policy* 31: 527-542.

Atkinson RC, RN Beachy, G Conway, FA Cordova, MA Fox, KA Holbrook, DF Klessig, RL McCormick, PM McPherson, HR Rawlings III, et al. (2003) “Intellectual property rights: public sector collaboration for agricultural IP management.” *Science*, 301(5630): 174–175.

Barton, J. (1998) “The impact of contemporary patent law on plant biotechnology research.” In SA Eberhardt, HL Shands, W Collins, and RL Lower (eds) *Intellectual Property Rights III, Global Genetic Resources: Access and Property Rights.* Madison, WI: Crop Sciences Society of America.

BBC News. (26 October 2000). “Ministers ‘misled’ public on BSE.” BBC News. Available: http://news.bbc.co.uk/2/hi/uk_news/992020.stm. Accessed 10 July 2009.

Berwald D, CA Carter, and GP Gruère. (2006) “Rejecting new technology: the case of genetically modified wheat.” *American Journal of Agricultural Economics*, 88(2): 432–447.

Bessen J, RM Hunt. (2003) “An Empirical Look at Software Patents.” Working Paper No. 03-17, Federal Reserve Bank of Philadelphia. Available at http://www.researchoninnovation.org/swpat.pdf.

Binenbaum E, C Nottenburg, PG Pardey, BD Wright, P Zambrano. (2003) “South-north trade, intellectual property jurisdictions, and freedom to operate in agricultural research on staple crops.” *Economic Development and Cultural Change,* 51(2): 309-336.

Binswanger HP, VW Ruttan. (1978) *Induced Innovation: Technology, Institutions and Development*, Baltimore: The Johns Hopkins University Press.

Boettiger S, GD Graff, PG Pardey, E Van Dusen, BD Wright (2004) “Intellectual property rights for plant biotechnology: International Aspects.” In P Christou, H Klee (eds) *Handbook of Plant Biotechnology*. Chichester: John Wiley & Sons, Ltd. Chapter 56, pp. 1089-1113.

Boettiger S, and BD Wright. (2006) “Open source in biotechnology: Open questions.” *Innovations: Technology, Governance, and Globalization*, 1(4): 45–57.

Boldrin M, and DK Levine. *Against Intellectual Monopoly*. Cambridge University Press. Available: http://www.dklevine.com/general/intellectual/againstfinal.htm.

Brennan M, CE Pray, A Naseem, and JF Oehmke. (2005) “An innovation market approach to analyzing impacts of mergers and acquisitions in the plant biotechnology industry.” *AgBioForum*, 8(2&3): 89–99.

Brock WH. (1997) *Justus von Liebig: The Chemical Gatekeeper*. Cambridge: Cambridge University Press.

Brookes G, and P Barfoot. (2005) “GM Crops: the global economic and environmental impact: the first nine years 1996-2004.” *AgBioForum*, 8(2&3): 187-196.

Broothaerts W, HJ Mitchell, B Weir, S Kaines, LMA Smith, W Yang, JE Mayer, C Roa-Rodriguez, RA Jefferson. (2005) “Gene transfer to plants by diverse species of bacteria.” *Nature*, 433: 629-633.

Busch L, R Allison, A Rudy, BT Shaw, T Ten Eyck, D Coppin, J Konefal, C Oliver, and J Fairweather. (2004) *External review of the collaborative research agreement between Novartis Agricultural Discovery Institute, Inc. and the Regents of the University of California*.

Byerlee, D, and K Fischer. (2002) “Accessing Modern Science: Policy and Institutional Options for Agricultural Biotechnology in Developing Countries.” *World Development*, 30: 931-48.

Caswell MF, and D Zilberman. (1986) “The effects of well depth and land quality on the choice of irrigation technology.” *American Journal of Agricultural Economics*, 68(4): 798–811.

CGIAR. (2008) “The origins of the CGIAR.” Consultative Group on International Research. Available: http://www.cgiar.org/who/history/origins.html.

CGIAR Independent Review Panel. *Bringing Together the Best of Science and the Best of Development. Independent Review of the CGIAR System*. Report to the Executive Council. Washington, DC. Available: http://www.cgiar.org/externalreview/

CIMMYT. 1997. *CIMMYT in 1995-1996: The Next 30 Years*. Mexico, D.F.: CIMMYT.

CNN. (18 January 2001) “French police in BSE government raid.” CNN News. Available: http://premium.asia.cnn.com/2001/WORLD/europe/france/01/17/france.madcow.02/index.html. Accessed: 10 July 2009.

Cohen JI, R Paarlberg. (2004) “Unlocking crop biotechnology in developing countries – a report from the field.” *World Development*, 32(9): 1563-1577.

Cohen WM, RR Nelson, and JP Walsh. (2000) “Protecting their intellectual assets: appropriability conditions and why U.S. manufacturing firms patent (or not).” NBER Working Paper no. 7552.

Constantine JH, JM Alston, and VH Smith. (1994) “Economic impacts of the California One-Variety Cotton Law.” *The Journal of Political Economy*, 102(5): 951-974.

Daily S. (18 May 2001). “French report faults response to mad cow crisis.” *The New York Times*. Available: http://www.nytimes.com/2001/05/18/world/french-report-faults-response-to-mad-cow-crisis.html. Accessed 10 July 2009.

David PA. (1969) *A Contribution to the Theory of Diffusion*, Stanford Center for Research in Economic Growth, Memorandum no. 71.

Day-Rubenstein K, and KO. (2000) “The CRADA model for public-private research and technology transfer in agriculture.” In KO Fuglie and DE Schimmelpfennig (eds) *Public-Private Collaboration in Agricultural Research: New Institutional Arrangements and Economic Implications*, Chapter 8, pp. 155–174. Ames: Iowa State University Press.

Delmer DP, C Nottenburg, GD Graff, and AB Bennett. (2003) “Intellectual property resources for international development in agriculture.” *Plant Physiology*, 133: 1666–1670.

Erbisch FH. (2000) “Challenges of plant protection: how a semi-public agricultural research institution protects its new plant varieties and markets them”, presented at the workshop on *The Impact on Research and Development of Sui Generis Approaches to Plant Variety Protection of Rice in Developing Countries*, International Rice Research Institute, Los Baños, The Philippines, 16-18th February.

Evenson, RE. (1980) “A century of agricultural research and productivity change research, invention, extension, and productivity change in U.S. agriculture: an historical decomposition analysis.” In AA Araji (ed) *Research and extension productivity in agriculture*. Moscow, ID: Department of Agricultural Economics, University of Idaho.

Evenson RE (2001). “Economic impacts of agricultural research and extension.” In BL Gardner, GC Rausser (eds) *Handbook of Agricultural Economics*. Vol. 1A (Agricultural Production), New York: Elsevier Science/ North Holland.

Falck-Zepeda JB, and G Traxler. (2000) “The role of federal, state, and private institutions in seed technology generation.” In KO Fuglie, DE Schimmelpfennig (eds) *Public-Private Collaboration in Agricultural Research: New Institutional Arrangements and Economic Implications*, Chapter 6, pp. 99–115. Ames: Iowa State University Press.

Falck-Zepeda JB, G Traxler, and RG Nelson. (2000) “Surplus distribution from the introduction of a biotechnology innovation.” *American Journal of Agricultural Economics*, 82(2): 360-369.

Feder G. (1980) "Farm Size, Risk Aversion and the Adoption of New Technology under Uncertainty." *Oxford Economic Papers*, 32(July): 263-83.

Feder G. (1982) "Adoption of Interrelated Agricultural Innovations: Complementarity and Impact of Risk, Scale, and Credit." *American Journal of Agricultural Economics*, 64(February): 94-101.

Feder G, RE Just, and D Zilberman. (1985) “Adoption of agricultural innovations in developing countries: a survey.” *Economic Development and Cultural Change*, 33(2): 255-298.

Fernandez-Cornejo J, Ed Beach, W Huang. (1994) “The adoption of IPM techniques by vegetable growers in Florida, Michigan, and Texas.” *Journal of Agricultural and Applied Economics*, 26(1): 158-172.

Fernandez-Cornejo J, C Hendricks, A Mishra. (2005) “Technology Adoption and Off-Farm Household Income: The Case of Herbicide-Tolerant Soybeans.” *Journal of Agricultural and Applied Economics*, 37(3): 549-563.

Fisher AC, and WM Hanemann. (1998) "The impact of global warming on agriculture: rethinking the Ricardian approach." CUDARE Working Paper Series 842, University of California at Berkeley, Department of Agricultural and Resource Economics and Policy.

Friedman DD, WM Landes, and RA Posner (1991). “Some economics of trade secret law”. *Journal of Economic Perspectives*, 5(1): 61-72.

Finlay MR. (1988) “The German agricultural experiment Stations and the beginnings of American agricultural research.” *Agricultural History*, 62(2), Publicly Sponsored Agricultural Research in the United States: Past, Present, and Future: 41-50.

Foltz JD, BL Barham, and K Kim. (2007) “Synergies or Trade-Offs in University Life Sciences Research.” *American Journal of Agricultural Economics*, 89(2): 353-367.

Fowler C. (1994) *Unnatural Selection: Technology, Politics, and Plant Evolution*. Yverdon, Switzerland: Gordon and Breach.

Fuglie K, N Ballenger, K Day, C Klotz, M Ollinger, J Reilly, U Vasavada, J Yee. (1996) *Agricultural research and development: public and private investments under alternative markets and institutions.* Agricultural Economic Report Number 735. Washington, DC: Economic Research Service, U.S. Department of Agriculture.

Glenna, LL, R Welsh, WB Lacy, and D Biscotti. (2007) “University administrators, agricultural biotechnology and academic capitalism: defining the public good to promote university-industry relationships.” *The Sociological Quarterly*, 48: 141-63.

Gollier C, B Moldovanu, T Ellingsen. (2001) “Should we beware of the precautionary principle?” *Economic Policy*, 16(33): 303-327.

Graff GD, SE Cullen, KJ Bradford, D Zilberman, and AB Bennett. (2003) “The public–private structure of intellectual property ownership in agricultural biotechnology.” *Nature Biotechnology*, 21(9): 989–995.

Graff GD, BD Wright, A Bennett, and D Zilberman. (2004). “Access to intellectual property is a major obstacle to developing transgenic horticulture crops.” *California Agriculture*, 58(2): 120-126.

Graff GD, and D Zilberman. (2007) “The political economy of intellectual property: reexamining European policy on plant biotechnology.” In J Kesan (ed) *Agricultural Biotechnology and Intellectual Property: Seeds of Change*. Washington D.C. and London: CAB International. Chapter 17, pp. 244-267.

Griliches Z. (1957) “Hybrid corn: an exploration in the economics of technological change.” *Econometrica*, 25(4): 501-522.

Guttman J. (1978) “Interest groups and the demand for agricultural research.” *Journal of Political Economy*, 86: 467–484.

Harding TS. (1940) “Henry L. Ellsworth, commissioner of patents.” *Journal of Farm Economics*, 22(3): 621-627.

Hayami Y, and VW Ruttan. (1971) *Agricultural Development*. Baltimore MD: Johns Hopkins University Press.

Huang J, S Rozelle, C Pray, and Q Wang (2002) “Plant biotechnology in China.” *Science*, 295: 674–677.

Huang J, R Hu, S Rozelle, and C Pray. (2005) *Development, policy, and impacts of genetically modified crops in China: A comprehensive review of China’s agricultural biotechnology sector*. Paper for the Belfer Center for Science and International Affairs, Kennedy School of Government at Harvard University, 1–58.

Huffman WE, and RE Evenson. (2006) *Science for Agriculture: A Long-Term Perspective*. Ames: Iowa State University Press.

Huffman WE, and JA Miranowski. (1981) “An economic analysis of expenditures on agricultural experiment station research.” *American Journal of Agricultural Economics*, 63(1): 104-118.

James C. (2008) *Global Status of Commercialized Biotech/GM Crops: 2008*. ISAAA Brief No. 39. ISAAA: Ithaca, NY.

Jefferson R. (2006) “Science as social enterprise: the Cambia Bios initiative.” *Innovations: Technology, Governance, and Globalization*, 1(4): 13–44.

Joly P, and M de Looze. (1996) “An analysis of innovation strategies and industrial differentiation through patent applications: the case of plant biotechnology.” *Research Policy*, 25: 1027-1046.

Judd MA, JK Boyce, and RE Evenson. (1986). “Investing in agricultural supply: the determinants of agricultural research and extension investment.” *Economic Development and Cultural Change*, 3(1): 77-113.

Judd MA, JK Boyce, and RE Evenson. (1987) “Investment in agricultural research and extension.” In VW Ruttan and CE Pray (eds) *Policy for Agricultural Research*. Boulder, CO: Westview Press. Chapter 1, pp. 7–38.

Juma C. (1989) *The Gene Hunters: Biotechnology and the Scramble for Seeds*. Princeton, N.J.: Princeton University Press.

Just RE, and WE Huffman. (1992) “Economic principles and incentives: structure, management, and funding of agricultural in the United States.” *American Journal of Agricultural Economics*, 74(5): 1101-1108.

Just RE, and WE Huffman. (2009) "The economics of universities in a new age of funding options." *Research Policy*, 38(7): 1102-1116.

Just RE, and GC Rausser. (1993) "The governance structure of agriculture science and agricultural economics: a call to arms." *American Journal of Agricultural Economics*, 75(October): 69-83.

King JL, and D Schimmelpfennig. (2005) "Mergers, acquisitions, and stocks of agricultural biotechnology intellectual property." *AgBioForum*, 8(2&3): 83-88.

Knowler D, and B Bradshaw. (2006) "Farmers' adoption of conservation agriculture: a review and synthesis of recent research." *Food Policy*, 32(1): 25-48.

Knudson MK. (2000) "The research consortium model for agricultural research." In KO Fuglie and DE Schimmelpfennig (eds) *Agricultural Policy in an Era of Privatization*. Iowa State University Press: Chapter 9, pp 175–198.

Knudson MK and CE Pray. (1991) "Plant variety protection, private funding, and public sector research priorities." *American Journal of Agricultural Economics*, 73(3): 882–886.

Koo B, and BD Wright. (1999) "The role of biodiversity products as incentives for conserving biological diversity: some instructive examples." *The Science of the Total Environment*, 240(1-3): 21–30.

Lee D. (2005) "Agricultural Sustainability and Technology Adoption: Issues and Policies for Developing Countries." *American Journal of Agricultural Economics*, (87)5: 1325-1334.

Lei A, R Juneja, and BD Wright. (2009) "Patents vs. Patenting: Implications of Intellectual Property Protection for Biological Research." *Nature Biotechnology*, 27: 36-40.

Lele U. (2003) "Biotechnology: opportunities and challenges for developing countries." *American Journal of Agricultural Economics*, 85(5): 1119-1125

Lele U, C Barrett, CK Eicher, B Garnde, C Gerrard, L Kelly, W Lesser, K Perkins, S Rana, M Rukuni, and DJ Speilman. (2003) *The CGIAR at 31: an independent meta-evaluation of the Consultative Group on International Agricultural Research*. Operations Evaluation Department, the World Bank, Washington D.C.

Lemarié S. (2001). "How will US-based companies make it in Europe? An insight from Pioneer and Monsanto." *AgBioForum*, 4(1): 74-78. Available on the World Wide Web: http://www.agbioforum.org.

Lemley MA, and C Shapiro. (2005) "Probabilistic Patents." *Journal of Economic Perspectives*, 19(2): 75-98.

Lemley MA, and C Shapiro. (2007) "Patent Hold-Up and Royalty Stacking." *Texas Law Review*, 85(7): 1991-2049.

Levin RC, AK Klevorick, RR Nelson, SG Winter, R Gilbert, and Z Griliches. (1987) "Appropriating the returns from industrial research and development." *Brookings Papers on Economic Activity*, 1987(3) Special Issue On Microeconomics: pp. 783-831.

Lusk JL, J Roosen, and JA Fox. (2003) "Demand for beef from cattle administered growth hormone or fed genetically modified corn: a comparison of consumers in France, Germany, the United Kingdom, and the United States." *American Journal of Agricultural Economics*, 85(1): 16-29.

Marco AC, and GC Rausser. (2008) "The role of patent rights in mergers: consolidation in plant biotechnology." *American Journal of Agricultural Economics*, 90(1): 133–151.

Matuschke I, RR Mishra, and M Qaim. (2007) "Adoption and Impact of Hybrid Wheat in India." *World Development*. 35(8): 1422-1435.

Mendelsohn R, W Nordhaus, and D Shaw. (1994) "The Impact of Global Warming on Agriculture: A Ricardian Approach" *American Economic Review*, 84(4): 753-771.

Miller HI, and G Conko. (2000) "The science of biotechnology meets the politics of global regulation." *Issues in Science and Technology*, (Fall): 47-54.

Murray F, and S Stern. (2007) "Do formal intellectual property rights hinder the freedom of scientific knowledge? An empirical test of the anti-commons hypothesis." *Journal of Economic Behavior and Organization*, 63(4): 648-687.

National Research Council. (1995) *Colleges of agriculture at the land grant universities: a profile*. Washington, D.C.: National Academy Press.

Nelson CH. (2001) "Risk perception, behavior, and consumer response to genetically modified organisms: toward understanding American and European public reaction." *American Behavioral Scientist*, 44(8): 1371-1388.

Oehmke JF, and CA Wolf. (2004) "Is Monsanto leaving money on the table? Monopoly pricing and Bt cotton value with heterogeneous adopters." *Journal of Agricultural and Applied Economics*, 36(3): 705-718.

O'Hanlon K. (23 August 2004) "Starlink corn settlement also to include interest." USA Today.

Ollinger M, and J Fernandez-Cornejo. (1995) "Regulation, innovation, and market structure in the U.S. pesticide industry." AER-719. Economic Research Services, U.S. Department of Agriculture, June 1995.

Olmstead AL, and P Rhode. (1993) "Induced innovation in American agriculture: a reconsideration." *The Journal of Political Economy*, 101(1): 100-118.

Pardey PG, JM Alston, and RR Piggott, eds. (2006) *Agricultural R&D in the Developing World: Too Little, Too Late?*. Washington, D.C.: International Food Policy Research Institute (IFPRI).

Pardey PG, and NK Beintema. (2001) *Slow magic: agricultural R&D a century after Mendel*. Food Policy Report. Washington, D.C.: International Food Policy Research Institute (IFPRI).

Pardey PG, NK Beintema, S Dehmer, and S Wood. (2006a) *Agricultural research: a growing global divide?* Food Policy Report. Agricultural Science and Technology Indicators Initiative. Washington, D.C.: International Food Policy Research Institute (IFPRI).

Pardey PG, J James, J Alston, S Wood, B Koo, E Binenbaum, T Hurley, and P Glewwe. (2007) *Science, Technology, and Skills [International Science and Technology Practice and Policy (INSTEPP)*. Rome: CGIAR and Department of Applied Economics, University of Minnesota, for FAO.

Park CC. (1989) *Chernobyl: the long shadow*. London and New York: Routledge.

Parker DD, and D Zilberman D. (1993) “University technology transfers: impacts on local and U.S. economies.” *Contemporary Policy Issues*, 11(2): 87-100.

Pollack A. (4 September 2001) “Altered corn surfaced earlier.” New York Times.

Pollak LM. (2003) “The history and success of the public-private project on germplasm enhancement of maize (GEM).” *Advances in Agronomy*, 78:45–87.

Polson RA, and DSC Spencer. (1991) “The technology adoption process in subsistence agriculture: the case of cassave in southwestern Nigeria.” *Agricultural Systems*, 36(1): 65-78.

Poortinga W, and NF Pidgeon. (2005) “Trust in Risk Regulation: Cause or Consequence of the Acceptability of GM Food?” *Risk Analysis*, 25(1): 199-209.

Pray CE, P Bengali, and B Ramaswami. (2005) “The cost of biosafety regulations: the Indian experience.” *Quarterly Journal of International Agriculture*, 44(3): 267-289.

Pray CE, and K Fuglie. (2001) *Private Investment in Agricultural Research and International Technology Transfer in Asia*. Economic Research Service Technical Report 805, Washington, D.C.: US Department of Agriculture.

Qaim M, A Subramanian, G Naik, and D Zilberman. (2006) “Adoption of bt cotton and impact variability: insights from India.” *Review of Agricultural Economics*, 28(1): 48–58.

Rausser G. (1999) “Private/Public Research: Knowledge Assets and Future Scenarios.” *American Journal of Agricultural Econonomics*, 81(5): 1011-27.

Rausser G, L Simon, and H Ameden. (2000) “Public-Private Alliances in Biotechnology: Can They Narrow the Knowledge Gaps between Rich and Poor?” *Food Policy*, 25: 499-513.

Rogers E. (1962) *Diffusion of Innovations*. New York: Free Press of Glencoe.

Rose-Ackerman S, and RE Evenson. (1985) “The political economy of agricultural research and extension: grants, votes, and reapportionment.” *American Journal of Agricultural Economics*, 67: 1-14.

Runge CF, and BM Ryan. (2004) *The Global Diffusion of Plant Biotechnology: International Adoption and Research in 2004*, Department of Applied Economics, University of Minnesota, St. Paul.

Ruttan V. (1977) "The Green Revolution: Seven Generalizations." *International Development Review*, 19 (December): 16-23.

Ruttan V. (1980) "Bureaucratic productivity: the case of agricultural research." *Public Choice*, 35: 529-49.

Ruttan V. (1982) *Agricultural Research Policy*. Minneapolis: University of Minnesota Press.

Schoenermarck H. (1974). "Nathaniel Bagshaw Ward: How a Sphinx Moth altered the ecology of earth." *Garden Journal*, 24: 148-154.

Sen AK. (1981) *Poverty and Famines: An Essay on Entitlement and Deprivation*, Oxford: Clarendon Press.

Shuren J. (2008) "Guidance for industry on the food and drug administration: Recommendations for sampling and testing yellow corn and dry-milled yellow corn shipments intended for human food use for cry9c protein residues; withdrawal of guidance." Docket No. FDA-2008-D-0229, April 2008.

Sjöberg L. (2002) "Limits of knowledge and the limited importance of trust." *Risk Analysis*, 21(1) 189-198.

Stokes D. (1997) *Pasteur's quadrant: basic science and technological innovation*. Washington, D.C.: The Brookings Institution.

Sunding D, and D Zilberman. (2001) "The agricultural innovation process: research and technology adoption in a changing agricultural sector." In BL Gardner and GC Rausser (eds) *Handbook of Agricultural Economics*, Vol. 1. Elsevier, Chapter 4, pp. 201–261.

Taylor MR, and J Cayford. (2002) "The U.S. patent system and developing country access to biotechnology: does the balance need adjusting?" Discussion Paper.

Tollens E, M Demont, and R Swennen. (2004) "Agrobiotechnology in Developing Countries: North-South Partnerships are the Key." *Outlook on Agriculture*, 33: 231-8.

Troyer AF. (2009) "Development of hybrid corn and the seed corn industry." In JL Bennetzen and S Hake (eds) *Handbook of Maize - Volume II: Genetics and Genomics*. New York: Springer Science + Business Media, LLC.

United States Department of Justice. (1998). *Justice department approves Monsanto's acquisition of DeKalb Genetics Corporation* (press release 98-570). Washington, DC: USDOJ. Available on the World Wide Web: http://www.usdoj.gov/atr/public/press_releases/1998/2103.htm.

Venner RJ. (1997) *An economic analysis of the U.S. Plant Variety Protection Act: the case of wheat.* Ph.D. dissertation, Department of Agriculture and Resource Economics, University of California at Davis, Davis, California, U.S.A.

Vogel D. (2001) *The New Politics of Risk Regulation in Europe*. London: Centre for Analysis of Risk and Regulation, London School of Economics and Political Science.

Vogt DU, and M Parish. (1999) “Food biotechnology in the united states: science, regulation, and issues.” Congressional Research Service Reports and Issue Briefs, Domestic Social Policy Division, U.S. Department of State.

Weingart P. (2002) “The moment of truth for science.” *European Molecular Biology Organization*, 3(8) 703-706.

White FC, and J Havlicek. (1982) “Optimal expenditures for agricultural research and extension: implications for underfunding.” *American Journal of Agricultural Economics*. 64: 47-55.

World Bank Group. (30 July 2009). *Implementing Agriculture for Development, the World Bank Group Agriculture Action Plan: FY2010-12.* Available: http://web.worldbank.org/WBSITE/EXTERNAL/TOPICS/EXTARD/0,,contentMDK:22273089~pagePK:210058~piPK:210062~theSitePK:336682,00.html

Wright BD. (1998) “Public germplasm development at a crossroads: Biotechnology and intellectual property.” *California Agriculture*, 52(6): 8–13.

Wright, BD. (2009). “Agricultural Biotechnology: The Quest for Freedom to Operate in the Public Interest.” University of California, Berkeley.

Wright BD, and PG Pardey. (2007) “Changing intellectual property regimes: implications for developing country agriculture.” *International Journal of Technology and Globalization*, 2(1/2):93–114.

Wright BD, PG Pardey, C Nottenburg, and B Koo. (2007) “Agricultural innovation: Investments and Incentives.” In R Evenson and P Pingali (eds) *Handbook of Agricultural Economics*, Vol. 3, Elsevier B.V., pp 2535–2605.

Zilberman D. (2006) “The economics of biotechnology regulation.” In RE Just, JM Alston, and D Zilberman (eds) *Regulating Agricultural Biotechnology: Economics and Policy*, Vol. 30 of *Natural Resource Management and Policy*, U.S.: Springer. Chapter 12, pp. 243–261. Springer, U.S.