Public Sector Plant Breeding in a Privatizing World. By Paul W. Heisey, C. S. Srinivasan (University of Reading, U.K.), and Colin Thirtle (Imperial College, University of London, U.K.), Resource Economics Division, Economic Research Service, U.S. Department of Agriculture. Agriculture Information Bulletin No. 772.

Abstract

Intellectual property protection, globalization, and pressure on public budgets in many industrialized countries have shifted the balance of plant breeding activity from the public to the private sector. Several economic factors influence the relative shares of public versus private sector plant breeding activity, with varying results over time, over country, and over crop. The private sector, for example, dominates corn breeding throughout the industrialized world, but public and private activities in wheat breeding differ widely in Western Europe, different regions of the United States, Canada, and Australia. Public sector involvement in plant breeding may have benefits to society that the private sector's activities may not, fostering greater sharing of information and more work on traits of plant varieties (such as environmental suitability and nutritional characteristics) that may be under-researched by private breeding programs.

Keywords: Plant breeding, economics, public sector, private sector, research policy, biotechnology, and intellectual property.

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Contents

Summary

Intellectual property protection, globalization, and pressure on public budgets in many industrialized countries have shifted the balance of plant breeding activity from the public to the private sector. This balance has differed over time, over country, and over crop for a number of economic reasons, including private firms' ability to earn returns on their research investments. However, public sector involvement in plant breeding may have benefits to society that the private sector's activities may not. Furthermore, society benefits when there is public access to scientific knowledge that, when developed by the private sector, is subject to intellectual property protection. Intellectual property rights in life sciences are likely to be subject to debate and policy changes.

Arguments for public sector investment in plant breeding include:

- Furthering scientific knowledge, which may be a "public good" or benefit to society as a whole, but may not be a major research goal of private firms if it is not financially profitable
- Conducting long-term research, which private firms may avoid in their desire to earn profits in the near term
- Thoroughly researching traits of plant varieties (such as environmental suitability and nutritional characteristics) that are under-researched by private breeding programs
- Public sector plant breeding will yield the largest social returns if it continues to focus on research directed at carefully identified problem areas, with clear "public good" components

Areas that public research might pursue include:

- Educating and training plant breeders
- Refining and testing methodology for variety selection
- Increasing public sector commitment to germplasm preservation and development
- Attending to minor crops
- Solving technological bottlenecks
- Identifying problems and limitations of existing agricultural technology, including existing crop varieties

More economic analysis is necessary to improve both theoretical and empirical models of the influence of intellectual property rights on both private sector plant breeding investment and the public sector's freedom to operate and collaborate with the private sector.

Public Sector Plant Breeding in a Privatizing World

Paul W. Heisey, C.S. Srinivasan,[1] and Colin Thirtle[2]

". . . it cannot be now very many years, if the investigations go on at the present rate, before the breeder will be in a position not so very different from that in which the chemist is: . . . when he will be able to do what he wants to do, instead of merely what happens to turn up."

— William Bateson, "Practical Aspects of the New Discoveries in Heredity," address to the International Conference on Plant Breeding and Hybridization, New York City, Aug. 30-Sept. 2, 1902

Introduction

Public sector agricultural research in general, and public plant breeding research in particular, is in trouble in both industrialized and developing nations. For a variety of reasons, budgets are stagnating in the public sector. In contrast, over the last 30 or more years, private sector agricultural research investment has grown dramatically, and an increasing proportion of this investment has been directed to plant breeding. This is certainly true in the United States (Fuglie and others, 1996) and may apply to industrialized countries in general. As a result of this trend, many attempts have been made to identify and analyze the future role of public sector plant breeding.

In this report, we analyze some of the major forces for change in plant breeding research over the past 30 or 40 years. We also present empirical evidence of the current level of public versus private sector investment in plant breeding, including which types of plant varieties they favor. In addition, we consider some of the major recommendations for the public sector's future role in plant breeding.

Factors Influencing Private and Public Sector Investment in Plant Breeding

During the first two-thirds of the 20th century, various events in the areas of applied genetics, plant breeding, and seed production and marketing set the stage for the current discussion of the role of private and public agricultural research and development (R&D). Even before the significant changes in the science applicable to plant breeding and the application of broader plant varietal protection over the last third of the 20th century, the factors influencing private and public investment in plant breeding could already be defined in economic terms.

Factors Determining Private Sector Plant Breeding Investment

Agricultural input firms that provide inputs to farmers, the marketing industry for food and fiber, and the retail food sector are all highly concentrated, relative to individual farmers. Individual farmers are highly unlikely to have either the incentives or the capital to carry out the socially optimal level of agricultural research and development (Alston and Pardey, 1996). Therefore, investment is needed from outside sources.

In the case of plant breeding, many factors determine the level of investment by private sector input suppliers. Many of these factors were first identified by Zvi Griliches in his pioneering study of the diffusion of hybrid maize in the United States (Griliches, 1957). Some of these factors relate primarily to seed production and marketing. Building on Griliches' work, we argue that for most private companies, the decision to begin a plant breeding program depends on the cost of research innovation, market structure, the organization of the seed industry, and the ability to appropriate the returns to research. Furthermore, seed industry profitability depends on farmer profitability. Even for a monopolist innovator, the choice of input price is constrained by the alternative technology. In other words,

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a price must be set that will provide incentives for the farmer to adopt a new plant variety (Moschini and Lapan, 1997).

Cost of Research Innovation

The cost of research innovation is receiving increasing attention in current debates over "new" vs. "old" economies. According to the Schumpeterian model, innovation is viewed as a constant progression of drastic changes that create new products and new markets (Schumpeter, 1942). In other situations, innovation may involve improvement of existing products. In this case, analysis often focuses on whether or not there are economies of scale in the research process (see Byerlee and Traxler, 2001, for the case of plant breeding), or on the cumulative nature of innovation (Scotchmer, 1991; Bessen and Maskin, 2000). Combining these two perspectives has not been easy.

We might speculate that for plant breeding, major innovations such as application of modern genetics, creation of hybrid varieties, introduction of semidwarf characteristics, and, perhaps, genetic engineering, fit the Schumpeterian model. They actually may appear to increase the costs of research. Their long-term impact, however, is to decrease the costs of the normal, cumulative research process.

Major innovations may sometimes appear to lead to markedly higher yields, or markedly lower costs of production, for agricultural producers. In many important instances, normal cumulative research has also resulted in impressive yield gains over time (see Duvick, 1992, and Byerlee and López Pereira, 1994, for hybrid maize; Byerlee and Moya, 1993, and Rejesus and others, 1999, for semidwarf wheat).

The success of a modern plant breeding program depends, among other things, on the following: access to a large pool of germplasm agronomically suited to the target area, ability to tap new genetic resources as the need arises, and the capacity to recombine large amounts of genetic material and efficiently evaluate the resulting progeny over a wide variety of conditions. In many circumstances, plant breeding programs aimed at developing finished varieties can rely on other institutions to store and test genetic resources and incorporate these resources into agronomically adapted material. In fact, when plant breeding programs concentrate on producing finished varieties, and leave storing and testing to other institutions, they reduce their costs. A good example is the use of hybrid maize worldwide. The techniques for creating hybrid maize varieties are well known. In the developing world, however, less work has been done on testing genetic resources and developing agronomically adapted superior maize cultivars in lowland tropical environments. As a result, other things equal, there has been less success in producing hybrid maize varieties for these environments, which in broad agroecological terms are very different from the temperate environment of the U.S. Corn Belt, in which hybrids had their earliest success (Heisey and others, 1998).

Market Structure

The influence of market structure on entry into plant breeding is somewhat more straightforward. Both the analyses following Griliches (1957) and the opinions of seed market professionals suggest that the larger the perceived size of the potential market, the greater the probability of entry. Another factor determining entry, particularly in the early stages of seed market development, is the composition of the market. If there are fixed costs in marketing new varieties to individual farmers, then the larger the average farm size, the more profitable market participation will be for seed companies.

Organization of the Seed Industry

Market organization, in theory, should also influence the profitability of individual firms engaged in plant breeding. Standard industrial organization suggests that the more concentrated a seed market, the greater the potential profitability of individual firms. Newer approaches to industrial organization argue that the key issue is the contestability of the relevant market, which is related to ease of entry. The Schumpeterian model implies that in a technically dynamic industry, a monopoly in one market, based on R&D breakthroughs, is replaced by a new monopoly in a new and different, but related market, stemming from a new breakthrough.

Given recent changes in the agricultural inputs industry, new interest has arisen in its industrial organization. Analysis of the industrial organization of R&D-intensive industries in recent years has concentrated primarily on pharmaceuticals, semiconductors and computers, or software. Studies of plant breeding and seed industries are only in their infancy.

In the United States, the four-firm concentration ratio for maize seed has risen from around 50 percent in the 1950s to almost 70 percent today, and seed prices relative to maize grain prices have also risen. Nonetheless, maize seed companies appear to have shared some of the benefits from advances in varietal performance resulting from conventional breeding with farmers and consumers (Fuglie and others, 1996; Byerlee and López-Pereira, 1994; Morris, 1998).

Ability to Appropriate the Returns to Research and Distribution of Benefits

The distribution of benefits among plant breeders, farmers, and consumers leads directly to the question of ability to appropriate the returns to research innovation. This is another area receiving renewed attention. Plant breeders' rights in industrialized countries have been strengthened in the past several decades, dating back to the late 1960s and early 1970s, and further expanded from the 1980s onward. Before this, the key factor determining the ability to appropriate returns was whether the crop was amenable to the development of hybrid varieties that could be priced low enough to encourage widespread farmer adoption. Self-pollinated crops such as wheat or soybeans were far more resistant to the creation of economically viable hybrid varieties than were open-pollinated crops like maize or sorghum. As a result, the ratio of private sector plant breeding investment to public sector investment was far higher in the open-pollinated crops such as maize and sorghum (Fuglie and others, 1996; Fuglie, 2000).

Other technical factors, however, may have weaker but still noticeable effects on the degree to which private firms can appropriate the returns to their plant breeding innovations. In the United States, for example, cotton breeding has moved with much less fanfare than maize from the public sector to the private sector over the past 40 years or so. Cotton is a self-pollinating crop and to date, most varieties grown by farmers are not hybrids. To plant cotton, the seed must be ginned and de-linted, making it far more practical for a farmer to rely on a seed company for seed every year, rather than attempt to manage the ginning and de-linting of seed from his or her own crop (S. MacDonald, 2000; L. Meyer, 2000; J. Radin, 2000).

One market-related phenomenon also appears to influence private sector plant breeding investment. This is the degree to which crops are related in the same cropping system. In the United States, for example, the maize-soybean rotation is commonplace throughout the Corn Belt, and maize-soybean-wheat rotations are often found farther east. Farmers who are customers for maize seed are more likely also to be customers for seeds of the rotation crop, such as soybeans or wheat, than farmers who are growing that other crop in different systems.

In the United States, soybeans are usually grown in rotation with maize, but most wheat is grown without a maize rotation. This link between soybeans and maize, coupled with changes in intellectual property rights (discussed in greater detail below), has allowed seed companies to price soybean seed at a higher level. This has allowed them to appropriate some of the returns from seed saved by farmers and replanted in subsequent years (Hansen and Knudson, 1996). In wheat, this indirect appropriation has been less common (Knudson and Hansen, 1991). U.S. soybean breeding, as well as wheat breeding in the soft red winter class, the class most commonly grown in eastern U.S. rotations, has moved substantially to the private sector.

Further, as might be anticipated by the arguments of Fuglie and others (1996), as well as those of Hansen and Knudson (1996), seed company representatives will sometimes state privately that their maize seed business is more profitable than their soybean seed business, which in turn is more profitable than their wheat seed business. Wheat, they sometimes argue, is not profitable at all, but breeding and seed distribution in the soft red winter wheat areas is done as a "service" to their customers (G. Vocke, 1999).

Public Sector Plant Breeding

Public sector plant breeding research is, in some respects, the inverse image of private sector plant breeding research. The one factor we have already addressed, scientific advance and the cost of research innovation, applies equally to private and public sector breeding. However, public sector breeding programs are likely to be affected far less directly, if at all, by market structural conditions and the organization of the seed industry than private sector firms.

The most direct contrast comes in the area of ability to appropriate returns to research. For crop varieties that farmers or other seed companies can easily duplicate, the divergence between private and social returns from plant breeding can be particularly great. Because farmers can replant seed that may perform as well as seed purchased from private companies, private breeders often cannot charge a price high enough to allow them to finance their research programs. Yet, as numerous economic studies have shown, the social returns to any breeding program, public or private, can be very high. Even more fundamentally, knowledge is an "impure" public good, so any research can produce some social benefits that may not be financially profitable to the innovating firm. The potential of breeding programs to have high social returns has resulted in the development of public sector efforts characterized by cumulative innovation and an ethos of "the free exchange of germplasm."

Certainly, there are still areas in which plant breeding has other public good components besides knowledge. Nutritional characteristics or environmental suitability of plant varieties may take the form of impure public goods (Alston and Pardey, 1996; Shoemaker and others, 2001). Disease resistance in plants is a particular example of an impure public good (Heisey and others, 1997). In some instances, these considerations may be quite important and need to be addressed, if not through public plant breeding, then through other mechanisms.

Finally, private individuals or firms might discount the future more heavily than society would, or might have different levels of risk preferences than society as a whole. This might lead to situations in which some public agricultural research, including plant breeding, is justified. Although this argument is often expressed, it has usually been based more on theoretical than empirical grounds. Nonetheless, despite the apparent recent interest of some private firms in areas such as plant genomics (Traxler, 1999), there are other areas such as germplasm conservation and preservation where the private sector has made more forceful arguments for a public role (Day-Rubenstein, 1999). The contention that private research has become directed toward more "basic" research in certain instances is not equivalent to the claim that the private sector will in some sense provide the "optimum" amount of basic research in all areas.

Forces for Change—The Late 20th Century

The last third of the 20th century was marked by an acceleration in the rate of privatization of plant breeding in industrialized countries. Two forces have been widely credited for driving this privatization: changes in science and increased intellectual property protection for plant varieties (Fuglie and others, 1996; Klotz-Ingram and Day-Rubenstein, 1999). Here, we consider these changes along with other institutional changes that function like de facto changes in intellectual property. Other forces have also influenced the pace of privatization, including the stagnation or tightening of public agricultural research budgets (Alston and others, 1999).

Changes in Science

The fundamental discoveries of Darwin and Mendel in the 19th century laid the groundwork for an increasingly rapid succession of biological advances in the 20th century. These included the rediscovery of Mendel's laws, identification of genetics with subcellular chromosomes, proof that DNA embodies heredity material in most living organisms, discovery of the molecular structure of DNA, and discovery of the role of the genetic code in protein synthesis (Lander and Weinberg, 2000). These advances led to the development of recombinant DNA, molecular marker technology, genome mapping, and other techniques now included under the heading of biotechnology.

In plant breeding, the biotechnology most widely recognized today is genetic engineering, including the insertion of DNA from one species to another that is widely separated in evolutionary history. Biotechnology may also refer, however, to clonal propagation, rescuing an embryo from an interspecific cross, constructing doubled haploid lines, monitoring recombination throughout the genome, or augmenting the efficiency of selection in plant improvement. A large part of what biotechnology represents today is new knowledge about the natural processes of DNA replication, breakage, ligation, and repair that has paved the way for a much deeper understanding of the mechanics of cell biology and the hereditary process itself (McCouch, 2000).

With the rapid spread of genetically engineered crops (particularly in the United States), the excitement over new areas such as genomics, and the constant parade of mergers and acquisitions within the so-called "life sciences" industry, many analysts assume that plant breeding has entered into a new era of "creative destruction," with innovation following upon innovation in rapid succession. Ultimately, developments in plant breeding may resemble the earlier cycle that followed the rediscovery of Mendel's laws and the development of hybrid maize. In other words, initial scientific breakthroughs will be followed by a stream of steady but less spectacular scientific improvement, with plant breeders using a vastly enlarged toolkit. Just as with hybrid crops, many implications of new molecular biology techniques may not reveal their full impact for many years. It is likely, however, that the use of these techniques has already had a few major impacts on plant breeding. It has made research alliances a more attractive institutional arrangement in many cases, and may also have increased economies of scale.

Changes in Intellectual Property

Most Western European countries passed plant breeders' rights legislation in the 1960s and 1970s. In the United States, the Plant Variety Protection Act (PVPA) was adopted in 1970. Australia and Canada adopted plant breeders' rights around 1990 (Pray, 1991; Butler and Marion, 1985; Gray and others, 1999). The main variants of plant breeders' rights legislation concerned the following: the definition of a distinct variety (as opposed to an "essential derivative"), the rights of farmers to save seed for their own use (or to re-sell it), the research exemptions for use in other breeding programs, and the time period covered by the grant of a certificate.

In 1980, the U.S. Supreme Court ruled that utility patent protection, based on criteria of utility, non-obviousness, and novelty, could be applied to a living organism. In 1985, utility patent protection in the United States was extended to plants (Fuglie and others, 1996). Other industrialized countries have been more reluctant to grant patent protection to living organisms, although the European Patent Office in 1999 finally moved to grant patents on genetically engineered crops.

In many countries, institutional innovations in the funding of plant breeding research have also changed the degree to which public or private plant breeders can appropriate some of the gains resulting from their research. In other words, changes in funding mechanisms have also subtly modified de facto property rights. These funding alternatives include mandatory or voluntary levies on producers, which are often matched by funds from government agencies. In some cases, levies are collected through end-point royalties collected by crop marketers. Recently, the European Union moved to collect royalties on farmer-saved seed and to pass these back to the breeders of the varieties in question.

Just as with changes in science, the overall changes in intellectual property protection appear to have stimulated greater private sector investment in plant breeding, but the quantitative impact has been extremely hard to determine (Pray, 1991). An early assessment (Butler and Marion, 1985) of the U.S. Plant Variety Protection Act (PVPA) found that it did encourage greater development of new varieties of soybeans and wheat. Butler and Marion also concluded that the PVPA had not significantly affected public sector crop breeding, when all crops were considered. At the time of their assessment, they felt that neither the costs nor the benefits of the PVPA were particularly striking. More recently, Alston and Venner (2000) further analyzed effects of the first version of the PVPA on wheat. They concluded that the PVPA appears to have contributed to increased investment by State agricultural experiment stations in developing new wheat varieties, but that private sector efforts in developing non-hybrid wheat varieties had not increased. Furthermore, the PVPA did not appear to have contributed to greater technical progress in wheat breeding. We speculate that conclusions might be somewhat different if equivalent analysis were applied to the case of U.S. soybeans.

In the United Kingdom, however, somewhat stronger plant breeders' rights legislation did appear to lead to market entry by seed firms (Pray, 1991; Thirtle and others, 1998). In Canada, a variety of mechanisms, including plant breeders' rights, private contracts, gene patents, and hybrid varieties, have contributed to a marked shift from public to private breeding for canola (Gray and others, 1999).

To the best of our knowledge, no studies have analyzed the influence of utility patenting on plant breeding. Given the uncertainties surrounding the exact level of the economic impact of utility patenting on R&D in general (Cohen and others, 2000; Jaffé, 2000), it is quite likely that for plant breeding, too, the impacts may eventually be substantial, but difficult to characterize and measure. To date, it appears that patenting in the United States, rather than stimulating further private sector interest in crops still bred in the public sector, has tended to follow current patterns of private sector investment. The number of patents issued appears to be correlated with the degree to which the private sector is involved in the breeding of the crop, the value of the crop, and (particularly in the case of tobacco and potatoes) the current level of technological possibilities for genetic engineering (fig. 1).

Public and Private Plant Breeding: Levels of Investment and On-Farm Varietal Use

In this section, we present some of the available estimates on investments in public and private plant breeding in industrialized countries. We also describe some preliminary attempts to estimate areas planted to public and private varieties for major field crops.

Plant Breeding Investment

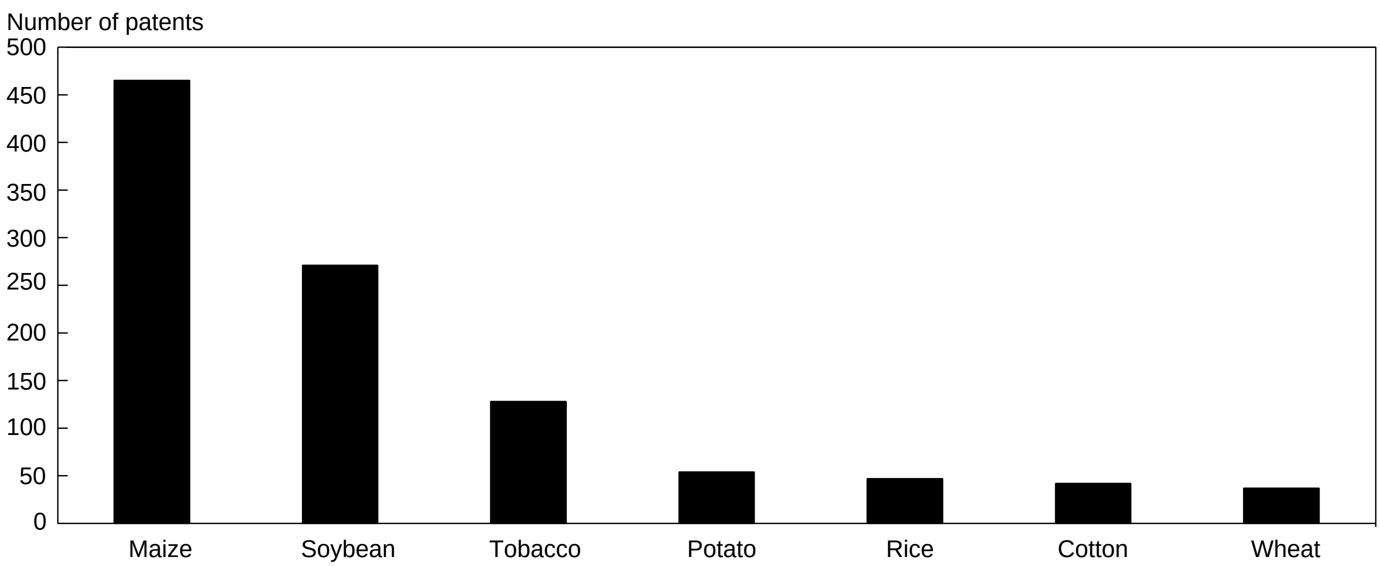
Data on investment in disaggregated research areas such as plant breeding are hard to come by, even for the public sector. Available data for several industrialized countries are discussed here. Methodology is discussed in the Appendix. Although comparisons across time and across countries must be treated with caution, we have converted all estimates to 1996 U.S. dollars to facilitate such comparisons.

United States

Figures 2 and 3 present continuous estimates of U.S. public sector plant breeding expenditures for field crops only, based on Current Research Information System (CRIS) data. These estimates present one time series for research problem area 307, "Improved Biological Efficiency of Field Crops;" and another for two research problem areas—207, "Control of Pests in Field Crops," and 208, "Control of Diseases in Field Crops." A third series combines all three problem areas, 307, 207, and 208. For comparative purposes, total expenditures on public sector field crops research are also depicted. Figures 2 and 3 also show time series for private sector plant breeding for all crops, based on data from Fuglie and others (1996), Kalton and others (1989), and current ERS data on private expenditures on agricultural research over time. In addition, for comparative purposes, Frey's (1996) point estimates for public and private plant breeding expenditures for all crops in 1994 are included.

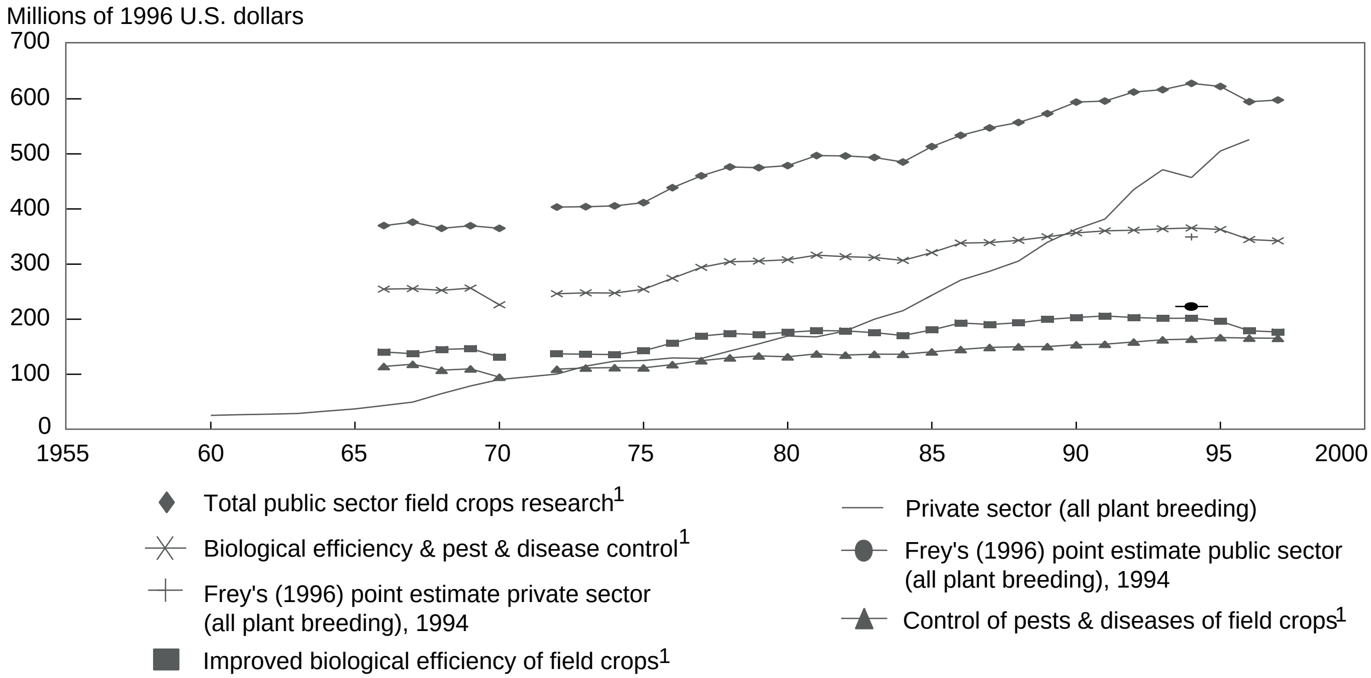
Several things are apparent from the data. First, in the United States, public sector plant breeding research expenditures for field crops appear to have started to decline in real terms from the mid-1990s. Using an ERS research deflator (fig. 3), they appear to have been essentially level from the late 1970s to the mid-1990s; using the GDP deflator (fig. 2), they appear to

Figure 1
U.S. patents issued for field crops, 1998



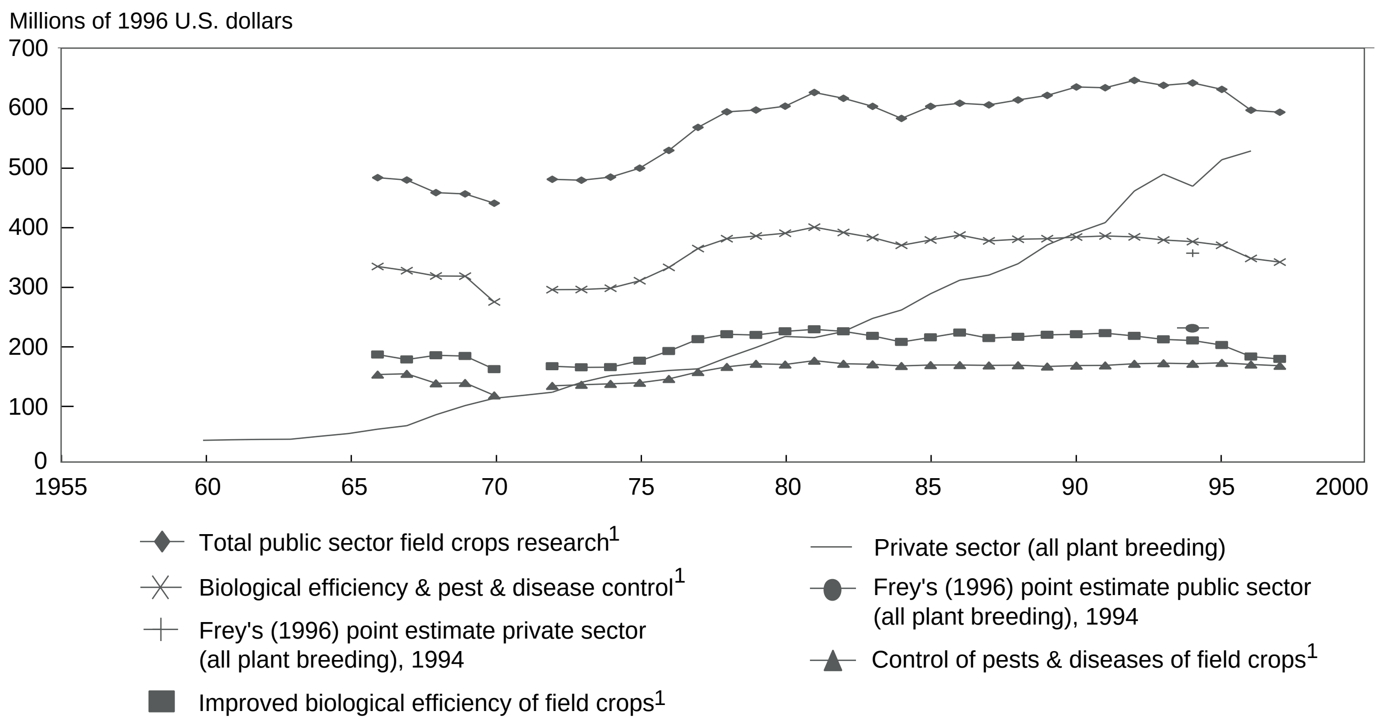
Source: Data compiled by C. Klotz-Ingram from U.S. Patent and Trademark Office, http://www.uspto.gov

Figure 2
Real public and private sector expenditures on plant breeding, U.S. GDP deflator



[1]Data not available for 1971.

Figure 3
Real public and private sector expenditures on plant breeding, U.S. agricultural research deflator



[1] Data not available for 1971.

have grown slowly over that period. In contrast, private sector plant breeding investment appears to have grown extremely rapidly. Maize may comprise around 33 percent of all private plant breeding and breeding for field crops may comprise 80 percent of the private sector effort (Frey, 1996). Furthermore, our public plant breeding series may overstate somewhat the "true" amounts invested in plant breeding. Thus, it is likely that, for field crops alone, private plant breeding expenditures now surpass public expenditures by a considerable margin. Note, too, that the estimates based on Frey (1996) are somewhat lower than the other estimates, illustrating the contention that estimates based on number of scientists are usually lower than estimates based on aggregate expenditure data. It must also be remembered that Frey did not attempt to measure investment in biotechnology, nor do our other time series estimates contain all biotechnology investments related to plant breeding. Biotechnology research should have already been considerable in the private sector by the time of Frey's survey (Klotz and others, 1995).

Table 1 indicates the number of private sector plant breeders in the United States in 1982 and 1994, and public sector breeders for 1994. Clearly there was an increase in the number of private sector breeders over that period. The true increase would be greater, since Frey's (1996) criteria for counting scientists as breeders were stricter than those of Kalton and Richardson (1983). Frey's survey also suggested that the total number of public sector plant breeders declined over the same period, although at a slower rate than the rate of increase in the number of plant breeders in the private sector. Note the dominance of private breeders for maize and sorghum, two crops comprised almost completely of hybrid varieties, and also for cotton and soybeans, for which we argued private sector plant breeding became dominant for other technical and market reasons. On the other hand, there were still more public than private breeders for wheat, other small grains, forage crops, and potatoes; although for most of those crops, the number of private breeders was significant. Maize has more than three times the total number of breeders than any other crop.

Table 1—Scientist years in plant breeding, U.S. field crops, 1982 and 1994

	1982		1994		
	Private sector (Ph.D.)	Private sector (M.S. & B.S.)	Public sector	Private sector	Total
	Years				
Maize	155	302	35	510	545
Soybeans	36	58	55	101	156
Cotton + other fiber	17	30	33	103	136
Wheat	23	46	77	54	131
Forage crops	34	49	71	51	122
Other small grains	7	8	36	29	65
Grain sorghum	22	44	15	41	56
Potatoes	na	na	41	9	50
Rice	7	6	20	22	42
Other field crops	32	38	90	193	283
Total	333	581	473	1,113	1,586

Source: Frey (1996); Huffman and Evenson (1993), based on Kalton and Richardson (1983).

Australia

Australian investment in plant breeding in the early 1990s is presented in table 2 (see also table 4). As in the United States, private sector investment was relatively strong in oilseeds, grain sorghum, and maize, although the latter two crops are relatively unimportant in Australia. The public sector still dominated breeding for wheat and other cereals, primarily barley. Even in wheat, one of Australia's most important agricultural exports, Australia's plant breeding investment was several times smaller than that in the United States.

Table 2—Australia's research investment and scientist years in plant breeding: cereals, grain legumes, and oilseeds, 1991-92 (single crop year)

	Research expenditures		Scientist years	
	Public sector	Private sector	Public sector	Private sector
	Million 1996 U.S. dollars			
Wheat	11.6	0.1	27	4
Other cereals	5.6	<0.1	29	0
Grain sorghum	0.9	0.7	2	4
Maize	0.5	0.5	4	3
Multi-cereals	2.3	0.0		
Grain legumes	4.7	0.0	16	0
Oilseeds	2.9	1.9	13	12
Multi-crop	1.4	0.0		
Total	29.9	3.3	91	23

Source: Clements, Rosielle, and Hilton (1992).

Canada

Table 3 shows plant breeding expenditures in Canada for the late 1990s. Wheat research expenditures for that period were roughly comparable to those for Australia in the early 1990s, and were also primarily in the public sector. In Canada, however, canola breeding investment by both private and public sectors far surpassed the amount spent on wheat. Even public sector investment in canola improvement research was nearly triple the amount spent on wheat. The composition of funding sources for Canadian public sector wheat and barley breeding at the leading institutions in Canada's prairie heartland are indicated in figure 4. Producer check-off funding constitutes over a quarter of the total for wheat, a little under a quarter for barley. For both crops, traditional funding from the general treasury makes up just less than half the total. Federal sources are more important for wheat, and provincial sources are more important for barley.

United Kingdom

In the United Kingdom, the Plant Breeding Institute (PBI) was the main public sector breeding institute for wheat and barley until it was privatized in 1987. The PBI also did some breeding for oats and potatoes. Though the PBI developed considerable capacity in genetics and molecular biology, another institution, the John Innes Institute (JII), concentrated on basic research pertinent to plant breeding (Pray, 1996; Thirtle and others, 1998).

Real research expenditures for the PBI and the JII are shown in figure 5. Post World-War II successes with barley paved the way for rapid budget increases at PBI over the 1970s, much of which were directed to wheat (Thirtle and others, 1998). Real expenditures at the PBI appear to fall even in advance of privatization, although Pray (1996) argues that the immediate result of privatization was an increase in both capital and recurrent expenditures on plant breeding and plant biotechnology. Pray indicates that the overall effect of several related privatization moves on research budgets for plant breeding and biotechnology was indeed negative, and the change shifted some of the burden of research from taxpayers to farmers.

Table 4 indicates alternative estimates of early 1990s plant breeding expenditures across four industrialized countries for a single crop, wheat. Wheat is a good crop for comparison across industrialized countries, since it is an important crop in many of them. It is also a crop with a complicated genome that has so far resisted widespread use of commercial hybrid varieties. Therefore, comparisons for wheat can also help to illustrate the influence of factors, other than the trade secrets protection offered by hybrids, on the division of plant breeding efforts between public and private sectors. Note that in these estimates by Bohn, Byerlee, and Maredia (1999), scientist years for the United States and Australia, two countries for which we have alternative sources, are considerably higher than those presented in tables 1 and 2. This is because Bohn, Byerlee, and Maredia attempted to count all individuals working in wheat breeding who had a Bachelor of Science (B.Sc.) degree or higher, and because they also made a conscious effort to include non-breeder scientists whose major efforts were devoted to wheat improvement.

Varieties in the Field

Even in industrialized countries, though some seed production or certification data may be available, data on individual crop varieties grown in farmers' fields are usually not consistently or routinely collected

Table 3—Canada's research and development costs (primarily cultivar development) late 1990s[1]

Crop	Year	Sector	Research & development costs
			Million 1996 U.S. dollars
Canola	1999	Private	76.4
Canola	1999	Public	33.4
Wheat	1998	Public	12.0
Pulses	1999	Public	11.1

[1]Totals for canola include a small amount of funds spent outside of Canada toward the development of Canadian cultivars.

Source: Stavroula Malla, University of Saskatchewan, personal communication

Table 4—Annual wheat improvement research investment and scientist years in plant breeding, early 1990s

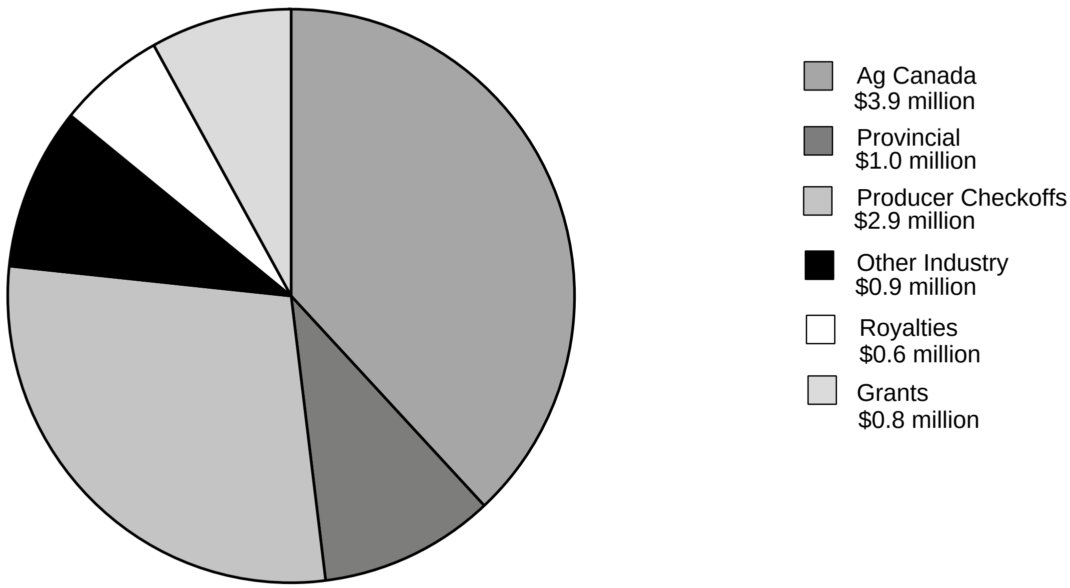
	Total research expenditure	Scientist years
	Millions 1996 U.S. dollars	
Australia	10.1	109
Germany	10.8	50
U.K.	19.7	128
United States	50.9	278

Source: Bohn, Byerlee, and Maredia (1999).

Figure 4

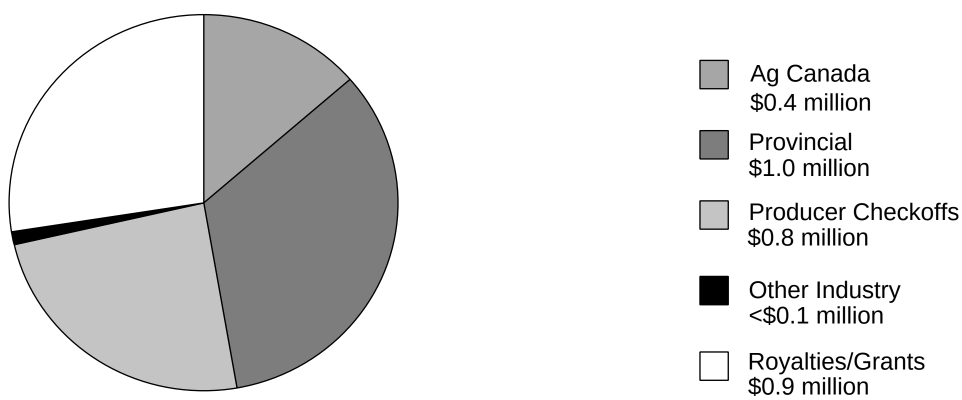
Composition of funding sources, public sector wheat and barley breeding programs, major Canadian prairie institutions

1999 wheat breeding expenditures, major prairie institutions, Canada



Total: $10.1 million (1996 U.S. dollars)

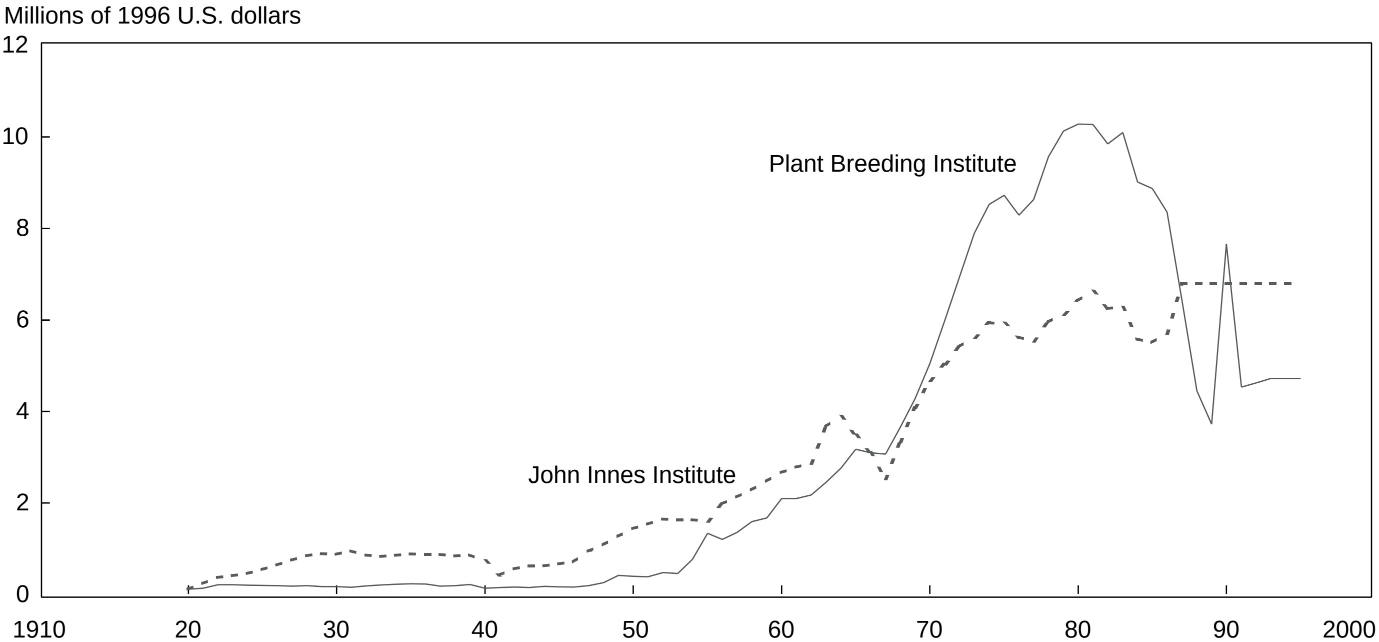
1999 barley breeding expenditures, major prairie institutions, Canada



Total $3.1 million (1996 U.S. dollars)

Source: Calculated from data reported by Western Grains Research Foundation, http://www.westerngrains.com/

Figure 5
Research expenditures, Plant Breeding Institute (PBI) and John Innes Institute (JII), United Kingdom



Source: Thirtle and others (1998).

across entire countries. Where possible, estimates may be based on seed sales or possibly marketing data; but in some cases, it is practical to rely on expert opinion.

Table 5 shows estimates of areas planted to public and private varieties in different crops and different countries. Maize area, as expected, is dominated by the United States and by private sector hybrids. Public sector inbreds, which are combined to form hybrids, continued to play an important role in U.S. private sector hybrids until the 1970s, after which their direct influence declined precipitously. Soybeans and cotton in the United States, and canola in Canada, illustrate cases in which there have been notable shifts from the planting of public sector to private sector varieties over the past 20 to 40 years. Though some of these changes have been caused partially by increased intellectual property protection of plant varieties, each crop illustrates the influence of other factors as well—soybeans' presence in the maize-soybean rotation, the growing impracticality of farmer-saved seed in cotton, and the importance of early research sponsorship by the product output industry in canola. Canola is also interesting because of the relatively large number of types of intellectual property that have been used to protect varieties grown in the field (Gray and others, 1999).

Wheat is a study in contrasts. Most Australian and Canadian wheat area is still planted with public sector varieties, although a rapidly growing percentage (around 10 percent in Australia, just under 40 percent in Canada) is sown with varieties subject to some sort of intellectual property protection. In contrast, European wheat acreage is increasingly dominated by private varieties, largely reflecting the different breeding histories and stronger plant variety protection of European countries. In the United States, the current situation is somewhat intermediate. An increasing proportion of the wheat area is planted to private varieties. However, use of private varieties is far more important in the soft red winter wheat areas, where wheat is grown primarily as a rotation crop, than in the major hard red winter, hard red spring, and white wheat growing areas (Sears, 1998).

In summary, across industrialized countries and across crops, the general trend has been toward relatively greater private sector investment in plant breeding, and greater use of private sector varieties in farmers' fields. Complete dominance by private sector breeding and complete adoption of private sector varieties are by no means universal. This suggests that a complex web of crop-specific and country-specific factors will influence the practice of plant breeding, including different

Table 5—Estimates of percentage cropped acres planted with private sector seed varieties, various years

Crop	Year	Country/ region	Percent of area planted with private sector varieties
Maize	1980	United States	100[1]
	early 1990s	United States	100
		EU	97
		Canada	95
		Total industrialized	99
	1997	United States	100
Wheat	1980	United States	5[2]
	late 1990s	United States	24
		Australia	1
		Canada	3[3]
		EU (preliminary)	71
		Total industrialized	27
Soybeans	1980	United States	8[4]
	1997	United States	70-90[5]
Cotton	1980	United States	72
	1998	United States	93
Canola	before early 1980s	Canada	<10
	after late 1980s	Canada	>80

[1] Butler and Marion (1985) estimated 23 percent of U.S. maize area was planted to "unknown" varieties in 1980. We attributed this area to the private sector.

[2] Butler and Marion (1985) estimated that more than a third of U.S. wheat area was planted to "unknown" varieties. We attributed this area to the public sector. We also assumed private sector area for durum wheat was equivalent to private sector area in the hard red spring class.

[3] Prairie shares were estimated from data available from the Canadian Wheat Board (http://www.cwb.ca/) and Saskatchewan Agriculture and Food (http://www.agr.gov.sk.ca/). Prairie wheat accounts for around 97 percent of total Canadian wheat area. Private sector shares for the other 3 percent, mostly in eastern Canada, were assumed to be equivalent to shares for the U.S. soft red winter class.

[4] Butler and Marion (1985) estimated 22 percent of U.S. soybean area was planted to "unknown" varieties. We attributed this area to the public sector.

[5] Lower estimate assumes most farmer-saved seed is from public sector varieties. Higher estimate assumes planted areas are roughly proportional to seed sales. About 25 percent of soybean seed planted in 1997 was estimated to be farmer-saved.

Source: Butler and Marion (1985); Hayenga (1998); Sears (1998); CIMMYT (1994); Gray and others (1999); Canadian Wheat Board (http://www.cwb.ca/); Saskatchewan Agriculture and Food (http://www.agr.gov.sk.ca/); J. Brennan (personal communication); W. Pfeiffer (personal communication); USDA Agricultural Marketing Service, as reported by G. Traxler (personal communication).

intellectual property rights regimes and different potential applicability of new breeding methods.

Future Roles for the Public Sector in Plant Breeding

Public and private sector plant breeding have coexisted in industrialized countries over the past 100 years, or in other words, since the beginning of modern scientific plant breeding. We have argued that private investment in plant breeding is affected by the cost of research innovation, the market structural conditions, the organization of the seed industry, and the appropriability of the returns to research, along with the constraint that seed must be sold at a price that will make its use profitable to the farmer. Public plant breeding is also strongly affected by the cost of innovation. In contrast to private plant breeding, economic justifications for public plant breeding include several arguments. Knowledge, as an impure public good, may not always be produced at the socially optimal level by private firms. Private and social returns from plant breeding may diverge due to appropriability problems. Divergence in discount rates and risk preferences may lead private firms to use a shorter time horizon than is socially optimal. And there may be other impure public good characteristics of plant varieties (environmental suitability, including disease resistance; other environmental consequences of varietal choice; and nutritional characteristics) that are produced in insufficient amounts by private breeding programs.

The parameters defining the relative roles of public and private plant breeding have varied by country and region and have changed over time as well. Today, despite differences in the dominance of private plant breeding across crop and country, mixed systems are the rule rather than the exception. Funding mechanisms, as well as institutional cooperation and competition in plant breeding, are often quite complex.

The last third of the 20th century witnessed an acceleration both in biology applicable to plant breeding and in the availability of intellectual property protection for plant varieties. This has led to considerable discussion of the appropriate roles for public and private sector activity. This is, however, not an entirely new phenomenon either; similar debate occurred when public sector maize breeding activity in the United States was drastically reduced (Duvick, 1998).

Here, we will examine some of the main arguments concerning the future role of public plant breeding. In a number of recent papers, several authors—often plant breeders themselves—have addressed this issue (these include Coffman, 1998; Herdt, 1999; Fischer, 2000; Duvick, 2000; and, especially, Frey, 2000). Although they differ in emphasis, and sometimes in the points covered, the degree to which they address the same issues is remarkable. With a few exceptions, they focus on research and training activities relevant to plant breeding. For the most part, they do not consider the other public policy instrument, the ability to define or change the intellectual property regime, that has a major effect on plant breeding. This is natural given their background in the sciences. We will, however, also attempt to touch on the latter topic.

Education and Training of Plant Breeders

There appears to be a general consensus that the public sector must continue to play a major role in the training of plant breeders. The range of skills necessary to be a successful plant breeder is believed to have expanded greatly (Coffman, 1998; Herdt, 1999; Frey, 2000). At the same time, serious financial constraints exist to the successful performance of this task. Furthermore, as practical near-market breeding for many major crops has passed or is passing into the private sector, there is increasingly less opportunity for breeders in training to acquire hands-on experience, which was previously gained in public sector universities.

The consensus is that the best solution to this problem is coordination of training efforts between the public and private sectors. Training of engineers is sometimes held up as an example. Economic justification for a public sector role in the training of plant breeders might be found in the public good component of human capital development. To the extent that plant breeding skills are not firm-specific, firms will not invest optimally in training, given the likelihood the scientist might take his or her skills to a rival firm. At the same time, private sector firms recognize the value of a steady supply of plant breeders with skills that may extend to molecular biology, and even some knowledge of general business theory and intellectual property. For example, a continued public role in the training of plant breeders is one of the recommendations of the American Seed Trade Association (ASTA) (1994) Basic Research Committee for corn and sorghum, two crops with the greatest concentration of private sector plant breeding.

Methodology Development

The ASTA Corn and Sorghum Basic Research Committee also made a recommendation that public programs continue to refine and test selection methodology. This would include developing and testing molecular-based systems (and, in all likelihood, comparing their efficiency with “traditional” selection methodology—see Moreau and others, 2000), and developing new methods of selection for pest resistance. This is echoed by a number of the recent authors cited in the introduction to this section. Despite private sector enthusiasm for some elements of genomics and proteomics, complete understanding of gene action, interaction, promotion, and silencing that will contribute to crop improvement is a long way off. Across all of the life sciences, there is a widely felt need for further advances and training in computational biology. Biology may, in fact, be moving away from a reductionist methodology to the study of entire biological systems, an approach that “promises stunning breadth of perspective. At the same time, it threatens to inundate scientists in a flood of data that will overwhelm their ability to interpret it” (Lander and Weinberg, 2000). New tools that will help make sense of these data seem likely to require substantial public sector investment in fundamental science.

This recommendation relates to the economic theory of knowledge, which has a public good component. To some extent, the public sector does appear to be moving in the direction of providing more fundamental research. In the United States, the Agricultural Research Service (ARS) of the Department of Agriculture may have increased its relative investment in so-called “basic” research (Klotz-Ingram and Day-Rubenstein, 1999). In the State Agricultural Experiment Stations, scientists who 40 years ago would have been working mainly in the field are today running labs (Coffman, 1998).

Germplasm Preservation and Development

The authors introduced above (Coffman, 1998; Duvick, 2000; and Frey, 2000) make particularly strong calls for increased public sector commitment to germplasm preservation and development. On a practical level, however, even stronger support comes from the private sector, from organizations such as ASTA. There are several related activities here: the collection and preservation of germplasm from crop species and their wild relatives, the incorporation of useful traits from this germplasm into material agronomically adapted to the target region, and perhaps the identification and development of germplasm with value-added traits.

Again, this is an area in which the private sector, at least, feels collaborative efforts would be particularly valuable. Social returns probably do diverge more from private returns in the germplasm maintenance and pre-breeding areas than they do for variety development. This may be because of differences between social and private discount rates and risk preferences. This argument appears to be less forceful, however, in the case of "value added" germplasm.

Minor Crops

Many plant breeding observers claim that public sector breeding should continue for minor crops, i.e., those with small markets or for which the seed market is too small to be served by existing private sector firms. Some even argue that existing resources should be diverted from major crops to minor crops (Coffman, 1998; Frey, 2000).

It is somewhat more difficult to support arguments for public breeding as applied to minor crops with economic reasoning. Theories of thin markets may indeed apply to specialty crops that may "grow well only in a small location, bringing benefits to consumers who may be distributed nationally and to local farm producers while limiting the size of the seed market to the firm" (Knudson, 1990). Furthermore, if there are substantial economies of scale in plant breeding, minor crop production might not be sufficient to justify a substantial breeding program. On the other hand, Herdt (1999) argues that "as the plant breeding activities of the big companies expand to fully meet the needs for the major crops there seems no obvious reasons why they would not turn to the minor crops." Also, as the extent grows to which research on one plant can address plant breeding problems in another plant, at least some of the plant breeding needs of minor crops may be addressed by research on major crops.

Other Related Issues

Several other arguments related to public sector contributions to plant breeding are sometimes raised. One public role that seems justified is the clear identification of problems and limitations of existing agricultural technology (Evenson, 1983). The private sector can play an important role in such identification, but a broader and more long-term view is important, and might be best maintained by the public sector.

Another argument sometimes made is that the public sector can "invent around" technological bottlenecks due to private ownership of intellectual property (Ruttan, 1982; Evenson, 1983). However, public sector institutions may want to guard against becoming too involved in near-market research at the expense of conducting more fundamental research that does not have immediate market applicability. On the one hand, to be able to "invent around" crucial technology bottlenecks, the public sector might need to be nimble and familiar with cutting-edge technology. On the other hand, antitrust policy—another policy solution—is in essence reactive, and does little to stimulate new research. It is also important to consider that rival private sector firms may also have strong incentives to invent around technological bottlenecks (Shoemaker and others, 2001).

The Public Sector Role in Defining Institutions and Intellectual Property

In contrast to their recommendations concerning plant breeding itself, observers considering the future of plant breeding are often more reticent in recommending specific changes in intellectual property regimes or other means such as specification and enforcement of royalty collection, for example. Intellectual property regimes affect private sector efforts, both in near-market variety development and in investment in more "basic" research such as genomics. The concern is that "the patenting of genes will result in only two or three companies having a major influence on the global food system" (Coffman, 1998).

To date, more specific recommendations on problems or potential changes in the intellectual property system as they relate to life sciences have come more often from lawyers (e.g. Barton, 2000) than from economists. Economists clearly have a role to play in making theoretical and empirical headway in answering questions related to industrial organization and intellectual property. Will the dominant form of private sector activity in plant breeding come from "life sciences" giants (Enríquez, 1998) or giants more specialized in agriculture (Wright, 2000)? Some initial attempts to address the issue theoretically have come from Rausser and colleagues (Rausser and others, 1999; Goodhue and others, 1999). Will large multinational firms supplying new plant varieties be more like the pharmaceutical industry, looking for blockbuster products (Cockburn and Henderson, 2000)? Or will such firms more closely resemble the semiconductor, computer, and software industries where blockbuster products dominate for a much shorter time period, and where a "cumulative innovation" model—in which innovations depend heavily on past innovations—may be particularly appropriate (Bessen and Maskin, 2000)?

Whatever the answers to these questions, society benefits when the public sector has "freedom to operate," when it maintains public access to research tools subject to intellectual property protection by the private sector, and when it engages in fruitful collaborative research. In its interaction with the private sector, public sector plant breeding benefits from constantly evaluating the degree to which it is performing research that is characterized by the "public good" model (Day-Rubenstein and Fuglie, 2000). The larger area of intellectual property in the life sciences is likely to be subject to accretion of precedent as well as formal revision. These revisions will be primarily directed to human health research. Agricultural science policymakers will likely benefit from participation in the debates.

Conclusions

Public sector plant breeding in industrialized nations has entered into increasingly turbulent times, with an uncertain future role. Budgets are stagnant or declining. In fact, some observers suggest that for the first time in decades, the rapid expansion of private sector plant breeding may also be reaching some limits, perhaps partially because of consumer resistance to genetically engineered crops (Pray, 2000).

Debates over the appropriate public sector role are not new, however, and some evidence suggests that the public sector is redefining its role in agricultural research. There is considerable consensus about future directions for public sector plant breeding, and many of the ideas appear to be supported by economic reasoning. Considerably more work needs to be done, however, to improve both theoretical and empirical models of the influence of institutions, such as the intellectual property regime, on both private sector plant breeding investment and the public sector's freedom to operate and to collaborate with the private sector. Public sector plant breeding will yield the largest social returns if it continues to focus on research directed at carefully identified problem areas and research with clear public good components.

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Appendix: Estimation of Plant Breeding Investments

Data on investment in disaggregated research areas such as plant breeding are hard to come by, even for the public sector. For a number of reasons, comparisons across countries and across time must be treated with great caution.

Most estimates follow one of two methodologies. In the first method, some effort is made to estimate total funds invested in plant breeding. Once these data are collected, the average monetary amount necessary to support a plant breeder and his or her research program over a year can be calculated if additional data are collected on numbers of plant breeders in the crop or crops under investigation. The second method is to begin by counting the number of plant breeders, then multiplying by the assumed annual investment in a single plant breeder. This amount might be determined by consensus within the plant breeding community, or be taken from a previous study. In general, the second method appears to lead to lower estimates of total plant breeding investment than the first.

Another methodological issue relating to the second method concerns who is to be counted as a plant breeder. First, are only "plant breeders" counted, or are other scientists in disciplines such as plant pathology, agronomy, physiology, and so on, whose research contributes to the plant breeding effort also included? Second, what educational levels are considered? In many studies (e.g. Kalton and Richardson, 1983; Kalton and others, 1989; Bohn, Byerlee, and Maredia 1999), all researchers with Bachelor of Science (B.Sc.) degrees or better are counted. In others (notably Frey, 1996), the definition is narrower, and seems to apply only to individuals who in some sense direct a breeding program.

In this report, we employ "first deflate/inflate, then convert" to change all amounts to 1996 U.S. dollars. Craig and others (1991) suggest that in many cases, particularly those involving developing countries, this approach would be preferred to a "first convert, then deflate/inflate" rule. Also, for some of the U.S. estimates, we have a research deflator that can be employed in comparison with the standard GDP deflator. This results in some interesting differences.