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Economic Incentives and Resource Allocation in U.S. Public and Private Plant Breeding

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ABSTRACT

Private investment in plant breeding has been increasing while public plant breeding has stagnated or declined. Moreover, research investment among crop commodities is uneven. Using a comprehensive survey of U.S. plant breeders from 1994, we use a simultaneous equations model to examine incentives and public-private tradeoffs in plant breeding research among 84 crop commodities. Allocation of private breeders among crops is strongly influenced by market size, hybrid seed technology, and ease of breeding improvement. In general, the allocation of public breeders does not appear to "crowd out" private breeders, but some competition may occur in applied breeding. Public breeding declines as private breeding increases on a commodity. Public breeding is also affected by market size, ease of breeding improvement, and political influence.

Key Words: *agricultural research policy, hybrid seed, plant breeders' rights, three stage least squares, tobit.*
JEL Classification: Q160, L330, O310, O320

The past few decades have witnessed a steady rise in private investment in agricultural research while public research resources have stagnated or declined (Fuglie; Alston, Pardey and Roseboom). This general trend has affected several areas of agricultural technology, including the breeding of new varieties of crops (Klotz, Fuglie and Pray). In a comprehensive survey of plant breeders conducted in 1994, Frey (1996) found that between 1990 and 1994 the number of plant breeders at all state agricultural experiment stations in the United States decreased by an average of 0.5 percent per year, while the number of plant breeders employed by private companies increased by 2.1 percent per year. By 1994, 68 percent of all plant breeders in the United States were employed in the private sector and only 32 percent at public institutions (Frey, 1996).

Within these overall trends, research resource allocation within agricultural research (i.e. among commodities) has been uneven. One concern about the growth of private research and decline of public research is that research on some potentially important crops may be neglected (the "orphan crop" problem). There is also a tendency for private plant breeding research to focus on hybrid seed technology. Frey (1996) found that more than one-third of all private breeders were working on (hybrid) field corn alone. This not only may limit the number of commodities addressed through private research, but also cause certain seed technologies—such as apomixis—to be underutilized.

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Another concern about the changing structure of agricultural research is the potential for duplication or competition between and among public and private researchers. Publicly bred varieties have competed with private varieties for market share in soybean (Huffman and Evenson) and cotton (Falck-Zepeda and Traxler). This could discourage private investment in agricultural research. The need for proprietary control over new technology among private breeders may also limit exchange of information and research material, leading to duplication of research efforts.

A further issue is that shifting the responsibility for crop improvement research from the public to the private sector may eventually lead to diminished productivity if basic research is neglected. In plant breeding, for example, it may take decades to introduce a new, exotic trait from a landrace or wild species into parent breeding material used to select commercial varieties (a process known as *germplasm enhancement*). Such work can significantly increase future returns from applied breeding, although it may not be profitable for a private firm to make such a long term and risky investment. If public resources are allocated to basic breeding research and crop germplasm enhancement, this could increase incentives for private investment in applied breeding. For example, Huffman and Evenson found that as private corn breeding expanded, public breeding research on corn shifted to more upstream research activities. Over the past several decades, private corn breeding has expanded more rapidly than for any other crop and continues to dominate private breeding investments.

In this paper we examine factors that influence incentives for the allocation of public and private plant breeding research among crops. In particular, we test the hypothesis that public and private research compete with one another. In the next section of the paper we present a conceptual model of the incentives for public and private research for crop improvement. We then discuss the specification and data of an econometric model to test the hypotheses. The fourth section presents empirical results and the final section conclusions and implications.

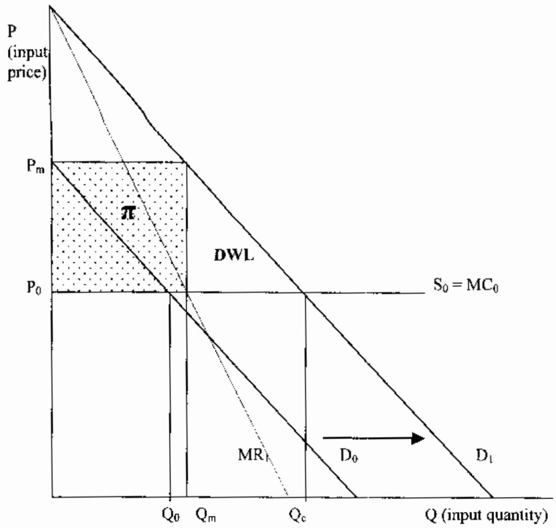

Figure 1. Economic benefits from plant breeding research

Conceptual Framework: Economic Determinants of Research

In our conceptual framework we focus on economic factors that may influence the allocation of resources within public and private plant breeding research. For private research, the profit incentive, or maximizing private returns to research, is assumed to be the primary objective. We assume that public research is motivated to maximize economic surplus, but with additional political constraints.

Figure 1 shows a stylized model of the welfare effects of introducing a new technology that is embodied in an input such as seed. In the figure, new technology shifts the demand for the input outward from D_0 and D_1. We assume the new technology is Hicksian-neutral so that it increases the marginal product of all inputs. Further, we assume that the marginal costs of manufacturing the input (MC_0) are constant so that the input supply curve is perfectly elastic. Finally, to simplify the diagram we assume that the diffusion of the new technology does not affect output price.[1] If prices

[1] If new technology increased output supply sufficiently to reduce output price, this would cause the input demand function in Figure 1 to shift inward. This would partly reduce the gains to producers and increase gains to final consumers. As the output price

are competitively determined, the equilibrium in the input market moves from (P_0, Q_0) to (P_0, Q_C). Given the assumption of no output price effects, the increase in economic welfare accrues to producers. Change in producer welfare is given by the area between the input demand curves and above the input supply curve S_0.

If the developer of a new technology has monopoly power over its price, the developer will charge above its marginal cost and earn a profit. The monopoly solution is to equate marginal cost with the marginal revenue curve (MR_1) and supply Q_m to receive a market price P_m. The monopolist is able to extract profit π, shown by the shaded region. In the short run the monopoly solution results in a dead-weight loss in economic welfare (triangle DWL in the figure). However, the monopoly profit also provides the economic incentive for private research. If public research is underfunded, an increase in private research can improve social welfare in the long run even in the presence of monopoly power over new technology (Dasgupta and Stiglitz; Sherer). In reality, a private company is unlikely to enjoy a pure monopoly over new technology due to competition from other innovating firms and the imperfect nature of intellectual property protection. Increased competition in the supply of new technology will reduce the monopoly power of any one firm and thereby reduce the private benefits from research.

One way that private plant breeders have been able to exercise market power is to focus on hybrid seed technology. With hybrid seed, farmers (or other seed companies) need to repurchase seed from the holder of the parent lines each year. They cannot reuse the progeny of hybrid seed because it is not reproduced with the same genetic characteristics or vigor as the original seed. Yield of hybrid seed rapidly falls if seed is saved from one season to the next. However, only a few crops can currently be grown commercially with hybrid seed. Hybrid seed technology is widely used for growing corn, sorghum, sunflower, and several vegetable crops.

Another way for seed companies to exercise market power is to obtain intellectual property protection over new plant varieties. Plant breeders' rights have been available for fruit crops and ornamental plants since 1930, for field crops since 1970, and for vegetable crops since 1980. In addition, coverage of utility patents was extended to include plants and plant parts in 1985 (Fuglie et al.). However, plant breeders' rights and plant patents have probably not been as effective a means as hybrid seed technology for protecting intellectual property in new varieties. Therefore, we expect private research to be heavily weighted toward crops produced from hybrid seed.

The economic incentive to invest in research is also influenced by technology opportunity. Commodities differ markedly in the relative ease or difficulty, for a given level of research effort, in making advances through research. To develop a new variety often takes several generations of selecting and backcrossing from the initial cross until final varietal selection and release. Some species of plants, such a trees, may take several years to reach yield-bearing maturity for evaluation by a breeder. Thus it can take a considerable period to select new varieties from a pool of crosses. For annuals, breeders have been able to decrease the time needed to breed and select a new variety by using "shuttle" breeding between colder and warmer climes so that more than one generation can be produced in a year. For a given level of research effort, species that take a longer time to breed will face a lower rate of return to research, *ceteris paribus*. Another possible source of technology opportunity could lie in the process of hybidization. If hybridization offers better prospects for genetic progress than the breeding of non-hybrid crops, a similar level of research investment would give a higher rate of yield growth in hybrid crops.[2]

change would affect D_1 and D_0 equally, it would not change the main conclusions for research resource allocation that we draw from the model.

[2] Kloppenburg, however, claims that if open-pollinated corn had received the same research intensity as hybrid corn, similar yield growth would have occurred in the former as in the latter. But we are unaware of

This model of technical change suggests that incentives for private research include 1) the size of the market, 2) the appropriability of the economic benefits from technical change (i.e., the degree of monopoly power), and 3) the expected advance in technology for a given level of research expenditure. The size of the market and the degree of appropriability will determine the size of the shaded region in Figure 1, or the benefits from research that are obtained by the supplier of the new technology. The cost of research will be a function of the relative ease or difficulty of developing and bringing to market the new technology. In our model we expect private firms to continue to invest in plant breeding research on a commodity until the marginal cost of research equals the expected marginal benefit the firm can capture, appropriately discounted for time and risk.

One view of public research is that it seeks to provide a public good. We define the "public good" from research as economic benefits that cannot be appropriated by an individual or firm. These benefits include the economic surplus of new technology that is adopted by a diverse population of agricultural producers, none of whom has an economic incentive to invest in research because of their small size. Public-goods research includes basic research to generate new scientific knowledge that is often generic and cannot be patented. It also includes applied research on technologies where patents, trade secrets, or other forms of intellectual property protection are insufficient to provide incentive for the private sector to invest adequately in research.

According to Ruttan, the decentralized nature of the public agricultural research system in the United States tended to foster competition within the system such that public researchers worked to promote the agricultural interests of farmers in their state. Another view of public research is that resource allocation is distorted from the maximization of economic surplus by political influence. Empirical research has found that lobbying efforts by farm commodity groups can influence the allocation of research resources in agriculture (Guttman; Rose-Ackerman and Evenson).

In recent years some public agricultural research institutions have obtained plant breeders' rights or patents for new varieties and sought to license these varieties in order to collect royalties (Knudson, Lower, and Jones). In this situation, the public breeder may be competing for the same profits that a private company may wish to earn from its varieties. Greater competition from the public sector would reduce market power over new seed technology of any one company, thereby reducing private returns from plant breeding. If, on the other hand, public research focused on "upstream" research that increased the scope for potential improvements through "downstream" varietal development, then this could increase the expected returns to applied plant breeder (Huffman and Evenson).

According to our model, public spending for research on an agricultural commodity is 1) positively influenced by the size of the market, 2) negatively influenced by the degree of private appropriability, and 3) positively influenced by the strength of the political lobby for a commodity. As in the case of private research, we can also expect the relative ease or difficulty of a particular research effort to affect the allocation of resources to that undertaking. While the economic model suggests that an increase in private research will lead to a decrease in public research, the effect of an increase in public research on private research is unclear (it could either serve as a complement or substitute). Our hypotheses regarding the influence of these variables on the allocation of public and private breeding resources are summarized in Table 1.

Econometric Specification and Data

The conceptual framework described above leads to the specification of the following simultaneous equations model:

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any rigorous attempt to examine this issue nor to disentangle the effects of stronger intellectual property protection and possibly greater potential for genetic improvement on the incentive to invest in breeding hybrid crops.

Table 1. Factors Affecting Public and Private Incentives For Agricultural Research

Parameter	Effect on Public Research	Effect on Private Research
Larger market	Increases	Increases
Stronger appropriability	Decreases	Increases
Less technological opportunity	Decreases	Decreases
Greater political influence	Increases	None
More public research	—	??
More private research	Decreases	—

$$\text{(1)} \quad Public = \alpha_1 + \beta_1 Private + \gamma_1 Value + \delta_1 Program + \lambda_1 Maturity + \epsilon_1$$

$$\text{(2)} \quad Private = \alpha_2 + \beta_2 Public + \gamma_2 Value + \delta_2(Value{*}Hybrid) + \lambda_2 Maturity + \epsilon_1$$

In this model the level of public research (variable name *Public,* measured by the number of scientist-years (SY) doing plant breeding at public institutions) is hypothesized to be a function of the level of private research (*Private,* also measured in SY), the value of crop production (*Value,* in billions of dollars received by farmers), whether the crop was covered by a government price support program prior to the 1996 Farm Act (*Program*), and whether a crop takes several years to reach maturity (*Maturity*). The amount of private plant breeding on a crop is modeled as a function of the amount of public breeding, the value of crop production, whether crop maturity is long, and whether the crop is grown from hybrid seed (*Hybrid*). *Hybrid* is modeled as a slope-dummy variable (*Value*Hybrid*): we expect that private-sector interest will be low in crops of little or no commercial value, whether produced from hybrid seed or not, but if greater market power allows a larger wedge between the marginal price of seed and the marginal cost of seed production, private interest will grow proportionally.

Private research is hypothesized to have a negative effect on public research, but the reverse effect cannot be hypothesized a priori by our model. The value of crop production is a proxy for the size of the social welfare gains from an improvement in production technology and is expected to be positively related to the level of public and private research. Crops with long duration until maturity are expected to receive less public and private research due to the increased research cost of making a technical improvement. Political influence, which is measured by whether a crop received government price support prior to the 1996 Farm Act, is hypothesized to positively influence public research in that crop. Whether the crop is produced from hybrid seed, a measure of market power, is hypothesized to positively affect private research investment.

Data on public and private breeding by crop are from a comprehensive survey of U.S. plant breeders conducted by Frey for 1994 (Frey, 1996). Frey obtained the number of full-time equivalent scientist-years (SY) allocated to plant breeding for each crop from 92 state and federal agricultural research institutions[3] and from 584 private companies and individuals. Of the private respondents, 329 reported SY data on plant breeding and 255 reported having no in-house plant breeding research. All major breeding companies participated in the survey. Frey (1996) estimated that the survey represented 100 percent of plant breeding SY at state and federal agricultural research institutions and 97.5 percent

[3] Public agricultural research institutions that responded to the survey included the Agricultural Research Service (USDA), 28 Plant Materials Centers (USDA), 50 state agricultural experiment stations, two universities not affiliated with a state agricultural experiment station, five agricultural experiment stations in U.S. territories, and six 1890s colleges (Frey, 1996).

Table 2. Distribution of Plant Breeders Among Basic Plant Breeding Research, Crop Germplasm Enhancement, and Cultivar Development

Units: Scientist-Years	*Plant Breeding Research*	*Germplasm Enhancement*	*Cultivar Development*	*Total*
ARS/USDA*	70	85	22	177
State agricultural experiment stations	159	153	217	529
Private sector	143	165	1191	1499
Total	372	403	1430	2205

* ARS/USDA: Agricultural Research Service, U.S. Department of Agriculture. The table does not include 36 breeders working at Plant Material Centers (PMC/USDA). Therefore, the table's total of 2205 SY is less than the total of 2241 SY reported in the text. Frey does not provide a breakdown by technology area of the research activity by plant breeders at the Plant Material Centers.

Source: Survey of plant breeders conducted by Frey (1996). Technology areas within plant breeding are defined in the survey as follows (quoted from Frey, 1996, p. 44). "*Plant breeding research*: Research on the genetics of plants and methodologies of plant breeding and biotechnology usually done to provide fundamental information useful for making plant breeding more efficient and productive. DO NOT include basic research on plant molecular biology. *Germplasm enhancement*: any activity that includes (a) gene transfer via sexual and asexual means from germplasm accessions and (b) increasing the frequencies of desirable genes in crop gene pools that will be used for developing parents or cultivars. *Cultivar development*: any activity of crossing, transforming, and/or selection (including marker-assisted selection) among plants which has the direct purpose of releasing a crop variety."

of the plant breeding SY in private industry. The measure of SY included "work done by a person who has responsibility for designing, planning, administering (managing), and conducting (a) plant breeding research, (b) germplasm enhancement, and (c) cultivar development, in one year." SY were broken down into these three categories for each commodity. The survey did not include technicians, clerical workers, or graduate students. Also, it did not include scientists working in basic research on plant molecular biology. Thus, some of the effort on new agricultural biotechnology was not captured by the survey.

From his survey Frey estimated that in 1994 there were 2241 SY in the United States working on plant breeding. Of these, 1499 were in the private sector, 529 at state agricultural experiment stations, and 213 at the U.S. Department of Agriculture (177 at the Agricultural Research Service and 36 at Plant Material Centers). Among the three technology areas, public breeders working at the federal level (ARS/USDA) emphasized mainly upstream activities: 48 percent were in germplasm enhancement, 40 percent were doing plant breeding research, and only 12 percent in cultivar development (Table 2). Breeders working at state agricultural experiment stations were fairly evenly distributed among basic and applied research activities. Among private breeders, more than 80 percent were doing applied research in cultivar development and only 11 percent were allocated to germplasm enhancement and 9 percent to basic breeding research. Despite the emphasis of private breeders on applied cultivar development, the aggregate investment by the private sector in upstream activities was nevertheless quite significant. Of the 372 public and private SY doing basic research on plant breeding, 143 were in the private sector. Of the 403 SY doing basic germplasm enhancement, 165 were employed at private firms.

In total, plant breeders worked on an astounding 219 species of food, industrial, and ornamental crops (out of a total of 250–300 crops grown commercially in the United States for these purposes). Of these 219 species, private breeders devoted time to 144 species, including 42 species not covered by public breeders (Frey, 2000). Table 3 shows crops to which the private sector allocated at least 20 SY. More than 500 SY employed by 91 companies were working on hybrid field corn and about 100 SY each on cotton and soybean. Many of the crops listed receiving the most private-sector emphasis are produced from hy-

Table 3. Crops for Which 20 or More Breeding Scientist-Years are Employed in the Private Sector

Crop	Cultivar Type	No. of SY	No. of Companies
Field corn	H	510	91
Cotton	PL	103	35
Soybean	PL	101	38
Tomato	½H/½PL	60	24
Wheat	PL	54	27
Alfalfa	S	41	12
Sorghum	H	41	19
Pepper	½H/½PL	38	27
Sunflower	H	31	14
Canola	PL	28	4
Sweet corn	H	27	12
Sugar beet	H	24	7
Rice	PL	22	8
Onion	½H/½PL	21	13
Muskmelon	H	21	15
Lettuce	PL	20	18

H = hybrid seed.
PL = pure line seed.
S = synthetic.
Source: Frey, 1996.

brid seed. Table 4 lists the crops with 15 or more breeders from the public sector. Wheat received more attention from public breeders than any other crop, with 77 SY working at 42 institutions. In general, public breeding is not as skewed toward any one commodity as private breeding is toward corn.

For this study we compiled data on the variables included in the model for 84 species of crops. These include all major crops and most minor fruit and vegetable crops. Not included in the model are ornamental crops. While Frey's data contain detailed estimates of plant breeding SY for ornamental species, we do not

Table 4. Crops for Which 15 or More Breeding Scientist-Years are Employed by State and Federal Agricultural Research Institutions

Crop	Cultivar Type	No. of SY	No. of Institutions
Wheat	PL	77	42
Soybean	PL	55	32
Potato	C	41	28
Field corn	H	35	32
Cotton	PL	31	20
Alfalfa	S	27	25
Tomato	½H/½PL	25	28
Rice	PL	20	15
Barley	PL	18	24
Peanut	PL	17	11
Bean	PL	15	14

H = hybrid seed.
PL = pure line seed.
S = synthetic.
C = clonal seed.
Source: Frey, 1996.

Table 5. Variables Used in Regression Model

Variable	Description	Mean	Stn. Dev.
Public	FTE breeders by crop employed by state and federal research institutions in 1984	7.420	13.176
Private	FTE breeders by crop employed in the private sector in 1994	15.526	57.844
Value	Value of crop production 1992–97 annual average (billion US$)	1.150	3.093
Maturity	1 if at least two years to crop maturity and 0 otherwise	0.369	0.485
Program	1 if a government program crop and 0 otherwise	0.143	0.352
Hybrid	1 if hybrid seed crop and 0 otherwise; 0.5 if crop species planted extensively with both hybrid and non-hybrid seed.	0.101	0.368

Source of data: Public and private full-time equivalent (FTE) for breeder scientist-years and information on hybrid seed utilization from Frey (1996). Value of crop production from National Agricultural Statistics Service. Data include 84 crop commodities (see Appendix Table for complete data set).

have complete data on other variables for these crops. Also, we do not have data on the size of the seed market for minor crops. As a proxy for seed sales we use the value of crop production (1992–1997 annual average) published by the National Agricultural Statistics Service. Information on which crops are grown from hybrid seed is from Frey (1996). Long maturation species include tree crops. The data used for the regression analysis are given in the Appendix Table.

Results

Definitions and descriptive statistics of variables in the regression model are reported in Table 5. There were an average of 23 plant breeders per crop, ranging from 0 for nine species to 545 SY working on field corn. The average value of annual production among the 84 crop species included in the model was $1150 million. This ranged from a high of $21,723 million for field corn to a low of $2.0 million for guavas. Seven crops are grown almost exclusively with hybrid seed and planted acreage of another three crops (tomatoes, bell peppers, and onions) is about evenly divided between hybrid and pureline seed (Frey, 1996). The rest are produced mostly from pureline seed or are clonal propagated. Thirty-seven percent of the species are classified as long maturity crops. These are either fruit or nut-bearing tree crops. Crops that had government price support programs include barley, sugarbeets, sugarcane, cotton, peanuts, oats, rice, wheat, tobacco, and field corn.

Tables 6 and 7 present three-stage least squares (3SLS) and tobit estimates of the model specified in equations 1 and 2. Although 3SLS treats the equations as a fully simultaneous system, estimates could be biased because the data are censored (i.e., for some observations, value of the dependent variable is truncated at zero). The tobit model corrects for possible biases from censored data but estimates each equation separately and not as a system.

In the 3SLS model, the variables explain 74 percent of the variation in the allocation of public-sector SY among crops and 97 percent of the variation in private SY allocation (although note that the 3SLS estimate of R^2 is not bounded between 0 and 1). While private research is more closely correlated with the economic variables than public research, these variables also influence the allocation of public research resources.

Coefficient estimates from the 3SLS and tobit models are similar. At the margin an increase in crop value of $1 billion is associated with an increase in 5.7 public breeders (5.4 in the tobit model). Political influence on the al-

Table 6. Factors Affecting Allocation of Public-Sector Breeders

	3SLS estimates	Tobit estimates
Constant	4.231**	3.410**
	(3.968)	(2.804)
Private	−0.194**	−0.174**
	(−7.022)	(−6.068)
Value	5.693**	5.412**
	(10.570)	(9.472)
Maturity	−3.727**	−3.995**
	(−2.318)	(−2.168)
Program	7.225**	8.039**
	(2.835)	(2.832)
R squared	0.736	—
Stn. Dev. Of residuals	6.732	7.478
Regression log likelihood (ln L)	−276.786	−254.037
Restricted log likelihood (ln L_0)	−335.246	−302.678
Likelihood ratio test ($\beta = 0$)	116.92**	97.282**
Likelihood ratio index ($1 - \ln L/\ln L_0$)	0.174	0.161
Observations	84	84

** = Significant at 5% level; * = significant at 10% level.

Table 7. Factors Affecting Allocation of Private-Sector Breeders

	3SLS estimates	Tobit estimates	Tobit estimates
Constant	3.355	2.925	2.681
	(1.159)	(1.356)	(1.278)
Public	0.339	0.0526	—
	(0.588)	(0.282)	
Public-basic	—	—	0.877**
			(1.928)
Public-applied	—	—	−1.406*
			(−1.866)
Value	4.958*	6.696**	6.620**
	(1.724)	(5.623)	(5.740)
Value*Hybrid	17.866**	16.640**	6.620**
	(8.569)	(15.222)	(13.520)
Maturity	−5.006*	−15.410**	−14.673**
	(−1.585)	(−4.211)	(−4.134)
R squared	0.968	—	—
Stn. Dev. Of residuals	10.284	12.470	12.068
Regression log likelihood (ln L)	−312.380	−230.122	−228.168
Restricted log likelihood (ln L_0)	−459.539	−334.363	−334.363
Likelihood ratio test ($\beta = 0$)	294.318**	208.452**	212.390**
Likelihood ratio index ($1 - \ln L/\ln L_0$)	0.320	0.312	0.318
Observations	84	84	84

** = significant at 5% level; * = significant at 10% level.

location of public research is also evident: program crops received an additional 7.2 SY of public breeders (8.0 in the tobit model) compared to non-program crops, other factors being equal.

In the private sector an additional $1 billion in crop value implied an increase in 5.0 private breeders for non-hybrid crops and 22.8 private breeders for hybrid crops. Estimates from the tobit model were slightly higher (6.7 SY for non-hybrids and 23.3 SY for hybrids for each additional $1 billion in crop value). While hybrid seed technology was not a prerequisite for private research (a large market will induce significant private research for non-hybrid crops), private research on hybrid crops was three to four times larger than research on non-hybrid crops of similar market value.

The significance of the hybrid seed variable suggests that either a) existing forms of intellectual property protection for other types of seed have not given private breeders the same incentive as hybrid seed for investing in research, or b) the potential for crop genetic improvement is greater for hybrid crops than non-hybrid crops for a similar level of research investment. At the time of Frey's survey, plant breeders' rights were available for all new varieties of all the crops included in the model except potatoes.[4] Despite the availability of plant breeder's rights for non-hybrid seed, private breeders clearly saw stronger economic incentives in breeding hybrid seed. This finding may imply that the market power associated with plant breeders' rights is still substantially below that afforded by hybrid seed technology.

Crops that take several years to mature—such as tree crops—received less public and private breeding resources. Because of the higher cost of achieving crop improvement on such crops, economic returns for a given level of plant breeding are reduced. Thus, average research intensity (research per dollar of crop value) on these crops is lower.

Finally, the model provides new evidence on the interaction between public and private research. Private investment in plant breeding led to a significant decrease in public plant breeding for that crop, which is consistent with our hypothesis that public research seeks to maximize the part of economic surplus from new technology that cannot be appropriated by private firms. Moreover, the net effect of an increase in private plant breeding is positive (from the 3SLS estimates, one additional private breeding SY decreased public breeding by 0.194 SY, for a net increase of 0.806 SY). Thus, the growth of private plant breeding over the past several decades has diminished public breeding research but increased breeding research investment overall. But this does not necessarily imply that research output increased, at least in the long run. If private research among competing companies is devoted to duplicative or highly applied work, the substitution of private for public breeders could actually lead to a decrease in effective research capacity.

We can use Frey's survey results to speculate on the effects of the growth of private breeding on the allocation of research resources among basic and applied breeding research. Let us assume the proportions among the types of breeding activities shown in Table 2 are maintained as the numbers of public and private breeders change. Further, let us group basic plant breeding research and germplasm enhancement together as basic research activities. Then an increase in one private breeder will increase private basic breeding by 0.205 SY and applied cultivar development by 0.795 SY. Two-thirds of the decrease in public breeding of 0.194 SY would be drawn from basic research activities and one-third from

[4] Potatoes fell through the cracks of plant breeders' rights legislation until very recently. The 1930 Plant Patent Act created a special category of patents for vegetatively reproduced plants but specifically excluded root and tuber crops. The 1970 Plant Variety Protection Act (PVPA) established plant breeders' rights for sexually reproduced crops but this did not include potatoes because they are grown from clonal seed. While utility patents were available for new plants and plant parts since 1985, this form of intellectual property right is not routinely used for new crop varieties because the "inventiveness" step is more rigorously compared with plant breeders' rights (Fuglie et al.). In 1996, the PVPA was finally amended to include potatoes.

applied breeding, resulting in a decline of 0.130 SY in public basic breeding and 0.064 SY in public applied breeding. The net effect is an increase in both basic and applied breeding, albeit heavily weighted to applied research (net increase of 0.075 SY in basic breeding and 0.731 SY in applied breeding, for aggregate net increase of 0.806 SY).

An increase in public SY had a positive though statistically insignificant effect on the level of private research. Thus, on the whole it appears that public breeding does not "crowd out" private research. However, it is possible that for some commodities public applied research may be competing with private research while for other commodities it may be complementing private research by focusing on upstream science and technology. In the former case an increase in public research would discourage private investment in breeding while in the latter case it could encourage it, such that the overall effect is indeterminate.

We estimated a tobit model in which public basic and applied breeders are treated as separate independent variables to see whether as public research moves upstream or downstream it may complement or compete with private research investment (Table 7). An increase in public basic research was correlated with a significantly increase in private research, while an increase in public applied research was correlated with a significant reduction in private breeding investment. A likelihood ratio test of whether the coefficients on public-basic and public-applied research are equal rejected this null hypothesis. However, since the tobit model is estimated as a single equation and not as a system, we cannot determine the direction of causation in these effects.

Potatoes may be the major field crop with *a priori* the most reason to suspect crowding out of private research by public research: 80 percent of total potato SY are in the public sector, and about half of public SY are devoted to applied cultivar development (Frey, 1996). Before 1990 private investment in potato breeding was very limited and usually occurred in partnerships with public institutions resulting in joint public-private varietal releases. Since 1990 most private breeding has focused on developing transgenic cultivars while public breeders have continued to focus on non-transgenic varietal development. However, without the public sector it is likely that private investment in conventional breeding would have been even less in this complex crop where yield potential, though naturally high relative to grain crops, is the same today as it was 100 years ago (Douches et al., Walker).

We were unable to examine the effects of basic and applied private research on public research because of the close correlation between these variables (the correlation coefficient between the number of private SY in basic and applied breeding was 0.98).

Conclusions and Implications

In this paper we have shown how a few economic variables explain most of the variation in public and private breeding effort among field crops and horticultural commodities in the United States. Private investment in crop breeding is closely correlated with the market value of the crop and whether the crop is produced with hybrid seed. Higher varietal development costs, such as occurs with tree crops, serve as a deterrent for research investment. These three factors explained 97 percent of the variation in private sector scientist-years allocated among 84 crop species, including all major field crops and most fruit and vegetable crops of economic significance in the United States. The allocation of public breeding resources was also correlated with economic variables, but somewhat less so than private research.

The results indicate the importance of intellectual property protection incentives for private breeding. Research intensity by the private sector (private breeders per dollar of crop value) was three times higher for crops produced from hybrid seed compared with crops grown from non-hybrid seed. Hybrid seed technology acts like a trade secret since it prevents others from multiplying the seed if they do not have access to the parental lines. Thus, by restricting access to the parent lines a seed company can exercise monopoly control over a new variety. It is important to note that all but one of the 84 crop species were also afforded plant breeders' rights at the time the data were collected. But this form of intellectual property protection appears to provide significantly less incentive for private research compared with hybrid seed technology. This result may also imply that the potential for genetic improvement is greater for hybrid crops than non-hybrid crops for a similar level of research investment. In any case, and if the U.S. experience is indicative, it would mean that the establishment of plant breeders' rights in developing countries is not going to be accompanied by a surge of investment in private research in non-hybrid crops. One is tempted to consider what would happen if hybrid seed technology were extended to other crops. According to our results, this would lead to a significant increase in private plant breeding research. Perhaps an important role for public research is to try to augment the number of species that can be economically hybridized.

In general, public breeding does not appear to "crowd out" private breeding, but there is some evidence that public applied breeding competes with private breeding. It also appears that an increase in private breeding on a commodity led to a small but statistically significant reduction in public research on that commodity. Nevertheless, the net effect of an increase in private research was positive: an increase in 1 private SY led to a net gain in 0.8 SY after subtracting the decline in public breeding. Moreover, even though private breeding is more oriented toward applied research than public breeding, there appears to be enough private investment in upstream research activities so that a shift to more private breeding raises research resources available to both basic and applied breeding. Nevertheless, in order to assure long-term productivity and efficiency in the U.S. plant breeding system, it is important to provide incentives for the private sector not only to invest in upstream research but also to put the results of this research into the public domain. In this way the system as a whole can continue to make the necessary incremental improvements to crop productivity. The disclosure requirements of patents and the research exemption of plant breeders' rights are examples of such incentives. Another is the research consortia model, which has been successful in pooling public and private resources for basic research and germplasm enhancement in corn (Knudson). It will also be necessary to maintain public investment in upstream research activities and, in the absence of stronger incentives for non-hybrid seed crops, in some applied breeding research as well.

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Appendix Table. Data Used in Regression Analysis

Crop	Crop Value (billion $)	Public Breeding (SY)	Private Breeding (SY)	Hybrid	Maturity	Program
Alfalfa	7.110	27.05	41.00	0	0	0
Almonds	0.941	0.60	0.50	0	1	0
Apples	1.540	4.20	2.00	0	1	0
Apricots	0.039	0.10	1.40	0	1	0
Artichoke	0.061	0.00	1.10	0	0	0
Asparagus	0.172	3.20	0.10	0	0	0
Avocados	0.235	0.50	0.00	0	1	0
Bananas	0.005	0.10	0.00	0	1	0
Barley	0.919	18.50	13.90	0	0	1
Beans (*Phaseolus*)	0.863	15.40	18.20	0	0	0
Beans, Lima	0.031	0.10	0.70	0	0	0
Beets	0.008	0.20	0.45	0	0	0
Blueberries	0.105	9.45	0.00	0	1	0
Broccoli	0.393	0.20	11.80	0	0	0
Brussel Sprouts	0.019	0.00	0.00	0	0	0
Cabbage	0.251	3.75	7.30	0	0	0
Caneberries	0.102	9.50	3.00	0	0	0
Carrots	0.461	2.40	11.90	0	0	0
Cauliflower	0.227	0.10	5.10	0	0	0
Celery	0.252	1.25	6.10	0	0	0
Cherries	0.250	0.50	1.20	0	1	0
Coffee	0.015	1.00	0.00	0	1	0
Corn, grain	21.723	35.30	509.75	1	0	1
Corn, sweet	0.603	5.75	27.00	1	0	0
Cotton	5.758	30.80	103.45	0	0	1
Cranberries	0.254	0.60	0.00	0	1	0
Cucumbers	0.309	5.95	8.30	0	0	0
Dates	0.021	1.70	0.00	0	1	0
Eggplant	0.019	1.30	0.30	0	0	0
Escarole/Endive	0.014	0.00	0.00	0	0	0
Figs	0.019	0.30	0.00	0	1	0
Flaxseed	0.013	1.30	0.00	0	0	0
Garlic	0.172	0.00	1.70	0	0	0
Ginger Root	0.006	0.00	0.00	0	0	0
Grapefruit	0.326	0.80	0.00	0	1	0
Grapes	2.214	8.55	2.40	0	1	0
Guavas	0.002	0.20	0.00	0	1	0
Hay, not alfalfa	4.474	44.00	10.20	0	0	0
Hazelnuts	0.026	0.00	0.00	0	1	0
Hops	0.129	2.20	0.50	0	0	0
Kiwifruit	0.016	0.30	0.00	0	1	0
Lemons	0.264	0.00	0.00	0	1	0
Lentils	0.029	0.50	0.00	0	0	0
Lettuce	1.521	4.35	20.05	0	0	0
Limes	0.007	0.00	0.00	0	1	0
Mushrooms	0.726	0.00	2.00	0	0	0
Mustard seed	0.003	0.50	0.30	0	0	0
Nectarines	0.092	1.35	3.80	0	1	0
Oats	0.309	12.80	4.90	0	0	1
Olives	0.068	0.00	0.00	0	1	0

Appendix Table. Continued

Crop	Crop Value (billion $)	Public Breeding (SY)	Private Breeding (SY)	Hybrid	Maturity	Program
Onions	0.684	4.95	21.40	0.5	0	0
Oranges	1.643	8.30	0.00	0	1	0
Papayas	0.016	1.70	0.00	0	1	0
Peaches	0.387	10.70	5.70	0	1	0
Peanuts	1.099	16.50	3.15	0	0	1
Pears	0.265	7.40	0.70	0	1	0
Peas (*Pisum*)	0.166	4.00	13.90	0	0	0
Pecans	0.221	2.40	0.00	0	1	0
Peppers, Bell	0.449	5.95	37.60	0.5	0	0
Pistachios	0.153	1.00	0.00	0	1	0
Plums & Prunes	0.274	4.80	3.10	0	1	0
Potatoes	2.602	40.65	8.90	0	0	0
Rice	1.446	20.10	21.90	0	0	1
Rye	0.030	0.90	0.10	0	0	0
Safflower	0.066	0.00	4.30	1	0	0
Sorghum, grain	1.501	14.30	40.80	1	0	1
Soybeans	14.544	54.60	101.35	0	0	1
Spinach	0.081	0.30	1.60	0	0	0
Strawberries	0.781	9.70	6.90	0	0	0
Sugarbeets	1.151	11.60	24.00	1	0	1
Sugarcane	0.878	7.40	1.00	0	0	1
Sunflower	0.398	3.16	31.45	1	0	0
Sweetpotatoes	0.184	13.05	0.10	0	0	0
Tangelos	0.018	0.00	0.00	0	1	0
Tangerines	0.102	0.00	0.00	0	1	0
Taro	0.003	0.20	0.00	0	0	0
Tobacco	2.841	14.10	4.70	0	0	1
Tomatoes	1.712	25.20	59.50	0.5	0	0
Walnuts	0.321	0.90	0.00	0	1	0
Watermelon	0.279	3.60	17.20	0	0	0
Wheat	8.580	76.45	53.95	0	0	1