10-2003

Aggregate Private R&D Investments in Agriculture: The Role of Incentives, Public Policies, and Institutions

Oscar Alfranca
University Politecnica de Catalunya

Wallace E. Huffman
Iowa State University, whuffman@iastate.edu

Aggregate Private R&D Investments in Agriculture: The Role of Incentives, Public Policies, and Institutions*

Oscar Alfranca
University Politecnica de Catalunya, Barcelona

Wallace E. Huffman
Iowa State University

Most observers have come to agree that Research and Development (R&D) is fundamental to the innovations that take place in advanced countries and that drive growth and development around the world. This is equally true for agricultural R&D, which has substantially increased the supply of food and fiber over time. Given the evident importance of agricultural R&D, we look at the forces that determine the amount of privately funded research in this vital sector using a sample of European countries. We construct indicators of private incentives, property rights, and publicly funded research in the various countries. Private research has grown with unusual speed in recent years and offers the prospect of advances in the quality of agricultural goods as well as reductions in their costs. Furthermore, considerable interest exists in knowing how changes in private and public research expenditures are related empirically; for example, are they complements or substitutes?[1] If they are substitutes, then additional private agricultural R&D expenditures may not result in larger total agricultural research expenditures.

The objective of this article is to present econometric evidence quantifying the effects of economic incentives, public policies, and institutions on national aggregate private agricultural R&D investments or expenditures. Previous studies have generally emphasized only one or at most two of these issues, but the primary hypothesis of this article is that all three are important and that interactions exist among them. Although the European Union (EU) is undergoing major economic integration, member countries continue to exhibit substantial differences in institutions, public policies, size, and relative importance of agriculture. Hence, these countries provide a good set of observations for testing our main hypothesis.[2] A model is formulated and fitted

0013-0079/2004/5201-0001$10.00

to annual data for nine EU countries, for the period 1984–95; we find strong impacts of incentives, public policies, and institutions on private aggregate agricultural R&D investment; we find interactions between public policies and institutions. Furthermore, for the EU countries in this study, the evidence is that public agricultural R&D crowds-out private agricultural R&D investments at low levels of private R&D, but at high levels of private R&D, they are complementary.

Private Agricultural R&D

First, we review the economics of private R&D investment decisions and selective empirical results, and second, we summarize the nature of private agricultural R&D investments in Western Europe.

General Issues

Private firms and individuals conduct research because they expect pecuniary rewards or payoffs. A number of conditions affect these decisions, and at the industry level, R&D expenditures are the results of aggregation over individual firm decisions. A useful discovery or innovation may enable reductions in the cost of producing an existing good, improve the quality of an existing good, or enable the development of a new good. The cost of discoveries is affected by the price of research inputs, the efficiency of the organization of research, the technological opportunities, the stock of available knowledge that can be drawn on, and the tax treatment of R&D expenditures.[3]

The returns to private R&D are determined by the potential size of the market for the discovery or aggregate demand, the ability of the discoverer to appropriate benefits, and the expected length of the useful economic life of a discovery. The size of the market for the discovery is affected by the market structure for existing products. For example, monopoly in the original product market reduces the demand for a discovery over competition in that market.[4] Each national market for goods and services is affected by regulatory policies and the existence of close substitutes. The openness of a country to trade is a major factor affecting the total size of the market for a discovery.

The ability of a discoverer to appropriate benefits from a discovery depends critically on the nature of the discovery, institutional mechanisms that exist for protecting intellectual property, and the general efficiency of public institutions. Once made, a discovery is either a pure public good or an impure public good. It is a pure public good when benefits are nonrival, that is, one user of the discovery does not affect the quantity or quality of knowledge available to other potential users, and nonexcludable, that is, the benefits from using the discovery cannot feasibly be excluded from those who want to use it, even though they pay nothing to the discoverer.[5] Furthermore, the use-value of the discovery is private information to the user, and he or she has no incentive to accurately reveal it. With these conditions, a discoverer cannot expect to appropriate (significant) benefits from other private users by charging fees for use.

A private discoverer, however, can use a pure public good discovery to produce and sell a product or to support an ongoing business, for example, to manufacture and market a durable good or to produce and market hybrid seeds. By attempting to keep the discovery secret and having a head start moving down the learning curve, a firm may be able to obtain some benefits from pure public good discoveries.[6] However, if the discovery is ever revealed publicly or can be reverse engineered, the pure public-good attributes of the discovery will come to play, and the discoverer will share benefits of the discovery with all other users.[7] These are reasons why private firms find research programs focused on discoveries that are of a pure public-good nature to be generally poor private investments, why large firms tend to view this research more favorably than small ones, and why private provision of these discoveries, although positive, is much less than the social optimum.

Economies of size enable large firms to respond to the high-income consumer by providing a stream of new products through the use of both science and communication.[8] R. W. Ward, who emphasizes the joint importance of "new products" and "images," contends that attracting the most technically and possibly the most artistically competent employees is relevant in very large food firms.[9] J. C. M. Van Trijp and J. E. B. M. Steenkamp observe that the R&D and marketing functions are linked in consumer-oriented new product design.[10] Moreover, the production of commercially successful items seems to require a broad multidimensional innovation approach. So, global size relates primarily to firm incentives.

When discoveries are impure public goods in the sense that they are excludable, the potential for discoverers to capture benefits from their discoveries increases. The legal institution of intellectual property rights (IPRs)—for example, patents, breeders' rights, copyrights, trade secrets, trademarks—is the main mechanism for accomplishing this. These property rights are created by nation-states and enforced by nation-states and international conventions or treaties. With patents, breeders' rights, and copyrights, the discoverer is given an exclusive right to control the use, including charging a fee for use, for a finite time period. This institution provides an added method by which discoverers can expect to obtain remuneration from others for the use of their discoveries.[11]

Western European countries harmonized their patent laws in 1977 and adopted a "first-to-file-for-a-patent" rule in deciding priority claims to patentable inventions. With this rule, patents are issued to the first person to file an application that can validly claim to have made an invention, and the patents last for 20 years from the date of application.[12] The first-to-file rule seems to provide less protection to discoverers than the first-to-invent rule applied by the U.S. Patent and Trademarks Office. Given a fixed length of term for a patent, the first-to-invent rule provides an incentive for firms who use discoveries to support a competitive edge in a product market to delay patent application until another firm has applied for a patent because the inventor can later prove that he or she was the first to discover. The first-to-file rule seems likely to lower transaction costs associated with litigation over who is the “first” relative to a first-to-invent rule.[13] Until the 1980s, intellectual property protection of biological materials had been limited primarily to secrecy. This changed first with the introduction of breeder rights, for example, plant variety protection certificates, in the 1970s, and then the extension of patents to biological materials (living organisms, plants, and nonhuman mammals) in the 1980s. The applications of recombinant DNA techniques have resulted in transgenic plants and animals being created, and the courts have ruled that these innovations have been large enough that they are not the products of nature and hence can be patented. The expected returns to private biotech research have been clouded, however, by environmental and health issues raised by antibiotech interest groups.[14]

If no institutional structure exists to easily enforce them, the granting of intellectual property rights to discoveries is of little value. For example, if the court system is very slow, legal fees are high, and court decisions are frequently reversed, an insecure institutional structure will reduce the expected private benefits of discovery relative to their full potential value. Failure to compensate for positive spillovers might be a negative incentive for private R&D investments. Hence, an effective legal system reduces uncompensated spillovers, which must occur for private incentives to direct efforts to private R&D.

Generally, insecure contractual and property rights discourage private investments by reducing the expected return and increasing the riskiness of investment.[15] Insecure private property rights frequently arise from weak and inefficient institutions, as reflected in bureaucratic delays in the provision of civil services, weak contract enforcement, and public takings of private property without fair compensation.[16]

In the United States, R. Levin et al. surveyed firms operating in 130 narrowly defined lines of business and found that patents were regarded as a highly effective means of appropriating returns primarily in drugs, organic chemicals, and pesticides.[17] Outside the pharmaceutical and chemical industries, firms reported that the advantages of having a head start and the “ability to move quickly down the learning curve” were more effective means of appropriating than patents. Biotechnology, however, was not covered in that survey. For process innovations, firms in most industries viewed secrecy as more effective than patents.[18]

Thus, aggregate expenditures for an industry are determined by complex interactions among participants.[19] The transfer (degree of publicness), the appropriability (IPRs and spillovers), and cooperation among affected firms (or noncooperative) affect aggregate investment.[20] Although highly structured theoretical models provide clear predictions, the empirical evidence has been quite mixed, and some of it is quite weak. For example, W. Cohen and R. Levin concluded that too much emphasis has been placed on the effects of industrial structure on private R&D investments and not enough on other issues.[21]

Spillover or borrowing effects reflect some of the new R&D research at the industry level. In relatively early work, J. Bernstein and M. I. Nadiri found significant production-cost-reducing and factor-intensity effects of a company's own R&D and interindustry R&D spill-ins.[22] J. D. Adams found that within- and between-industry R&D spill-ins operated with a long lag but were a significant factor in explaining industrial productivity.[23] R. E. Evenson and Y. Kislev, and also Evenson and D. Gollin, have shown transnational transfers of plant genetic material and crop varieties to be important to general varietal improvement, but borrowing is costly—knowledge does not spill-in costlessly.[24]

Agriculture in Europe

In the EU and Organization for Economic Cooperation and Development (OECD) countries, a large share of private agricultural R&D is invested in agricultural inputs—agricultural chemicals, plant breeding, farm machinery, and animal health—and food and kindred products but relatively little (less than 10%) in farm-level technologies.[25] In the EU, private agricultural R&D has been focused on agro-chemistry (folliculars, fertilizers, micronutrients, fungicides, insecticides, and soil disinfectants), plant breeding and varietal development, plant nutrition, plant growth regulators, plant parasitology, marine aquaculture, raw material production from cultured media (e.g., corn syrups, sugars), enzymatic conversion of starch to sugars, biotechnology in plants, combine and harvesting machine development, safety and ergonomics in farm machinery, and veterinary pharmaceuticals.

The focus of private agricultural R&D differs across Western European countries. In the United Kingdom, agricultural chemicals, machinery, and feeding stuffs have been important.[26] The Cambridge Plant Breeding Institute was transferred from the public sector to the private sector (Unilever) in 1987. Unilever then sold it to Monsanto in 1998. In the Netherlands, private research on horticultural crops is large. In France, private R&D—for example, in Vilmoria, the Cooperative Society for Research and Experimentation of the Eastern Pyrenees, the Technical Institute of the Sugar Beet Industry and the co-op Limagrain—is primarily focused on plant breeding, pesticides, and fertilizers. In Germany, private R&D is focused on pesticides and fertilizers, for example, companies like BASF, BAYER, Kali + Salz, and Hoechst; agricultural machinery, for example, Deutz and Mercedes; and animal feed and pharmaceuticals. In Sweden and Denmark, private research is on fertilizers, forestry, and communication systems.

Patent laws for the EU countries have been strengthened over the past 4 decades and are in general much stronger than in developing countries, but somewhat less than in the United States.[27] Among EU countries, Finland, Portugal, and Ireland have had relatively weak patent rights over the period 1960–90, and Sweden, Germany, and Denmark have significantly strengthened their patent rights over time (see table 1).

Cross-country comparisons of private and public agricultural R&D expenditures are made difficult by the fact that each country has its own definition

TABLE 1

National Indexes of Patent Rights, Western Europe: 1960–90

Country/Region	1960	1965	1970	1975	1980	1985	1990
Western Europe:							
Austria	3.38	3.38	3.48	3.48	3.81	3.81	4.24
Belgium	3.05	3.38	3.38	3.38	3.38	4.05	3.90
Denmark	2.33	2.66	2.80	2.80	3.62	3.76	3.90
Finland	1.99	1.99	2.14	2.14	2.95	2.95	2.95
France	2.76	3.10	3.24	3.24	3.90	3.90	3.90
Germany	2.33	2.66	3.09	3.09	3.86	3.71	3.71
Greece	2.46	2.46	2.46	2.46	2.46	2.46	2.32
Ireland	2.23	2.56	2.99	2.99	2.99	2.99	2.99
Italy	2.99	3.32	3.32	3.46	3.71	4.05	4.05
Netherlands	2.95	3.29	3.61	3.47	4.24	4.24	4.24
Norway	2.66	2.66	2.80	2.80	3.29	3.29	3.29
Portugal	1.98	1.98	1.98	1.98	1.98	1.98	1.98
Spain	2.95	3.29	3.29	3.29	3.29	3.29	3.62
Sweden	2.33	2.66	2.80	2.80	3.47	3.47	3.90
Switzerland	2.38	2.71	3.14	3.14	3.80	3.80	3.80
United Kingdom	2.70	3.04	3.04	3.04	3.57	3.57	3.57
Subgroup mean	2.60	2.82	2.97	2.97	3.39	3.46	3.52
United States	3.86	3.86	3.86	3.86	4.19	4.52	4.52
Mean: 111 countries	2.13	2.22	2.27	2.28	2.40	2.44	2.46

Source.—Adapted from J. C. Ginarte and W. G. Park, "Determinants of Patent Rights: A Cross-National Study," *Research Policy* 26 (1997): 283–301.

of what is included in private and public research, and the restructuring of public agricultural research in some of these countries over the past 2 decades has changed what is now included in public and private research.[28] For example, in the United Kingdom, some public agricultural research institutions have been sold to the private sector,[29] and in the Netherlands, research institutions of the Ministry of Agriculture, Nature Management, and Fisheries have been turned into a quasi-public institution (DLO). German data have special problems because of the fact that two separate countries existed before 1990, and pre-1990 data cover only West Germany.

Even with these deficiencies, it is useful to present some comparisons across EU countries. Table 2 presents information showing large differences in the share of private agricultural research expenditures in total public and private agricultural research expenditures of 14 EU countries for 1985, 1990, and 1995. The United Kingdom, Netherlands, and Sweden stand out for their large private sector shares, and Germany, Ireland, and Spain have unusually small shares. Furthermore, these data do not suggest a strong increase in the private R&D share over 1985–95. However, it is safe to conclude that private agricultural R&D has more of an input focus than public agricultural R&D.

The Econometric Model, Data, and Results

An econometric model of national aggregate annual private R&D investment is specified and fitted to panel data for nine EU countries (Austria, France,

TABLE 2

Private Agricultural R&D Expenditures as a Share of Total Public and Private Agricultural R&D Expenditures, EU-13, Selected Years (%)

Country	1985	1990	1995
Austria	41.2	34.9	36.9
Denmark	44.6	31.2	27.7
Finland	41.3	29.2	36.2
France	25.0	19.1	26.0
Germany	13.8	11.7	9.3
Greece	29.2	22.1	15.0
Ireland	16.6	25.6	12.8
Italy	23.9	24.4	25.9
Netherlands	59.6	59.2	47.9
Norway	34.2	46.6	38.4
Portugal	14.5	36.7	21.3
Spain	11.4	10.3	9.0
Sweden	47.1	42.2	43.2
United Kingdom	65.0	62.3	61.5

Sources.—OECD, *Statistical Compendium, Agricultural Statistics, Agriculture, Hunting and Forestry* (Paris: OECD, 2001), *Statistical Compendium, Industry, Science and Technology: Basic Science and Technology* (Paris: OECD, 2001), and (for GDP implicit price level) *Statistical Compendium, National Accounts* (Paris: OECD, 2001); Colin Thirtle, "Agricultural Research, Development and Extension Expenditures in the UK, 1947–1993," EPARD Discussion Paper no. 14 (University of Newcastle upon Tyne, Department of Agricultural Economics, 1989); and C. Thirtle, P. Palladino, and J. Piesse, "On the Organization of Agricultural Research in the United Kingdom, 1945–1994: A Quantitative Description and Appraisal of Recent Reforms," *Research Policy* 26 (1997): 557–76, for the United Kingdom.

Note.—EU = European Union.

Germany, Italy, Netherlands, Portugal, Spain, Sweden, and United Kingdom) over 1986–95. These countries account for a very large share of agricultural product in the EU: about 85.6%. Unavailability of private R&D expenditure time series data has been the main restriction to including more countries in the data set. Although the countries included in the panel collect and report R&D in line with the Frascati Manual, some specifications differ from the OECD standard. If definitions for the data are not identical, this makes meaningful comparisons more difficult, and it can be a source of measurement errors. Problems are most likely to arise with the definitions of the science and technology indicators and with methodological changes during the sample period (see appendix).

The Econometric Model

Definitions of variables as well as sample mean values, minimum and maximum values, and the standard deviations are presented in table 3.[30] Figure 1 displays the pattern of growth of (real) private agricultural R&D investments in each of the nine sample countries over 1984–95. These investments comprise the dependent variable to be explained by our econometric model.

The econometric model of aggregate gross real private R&D investment

TABLE 3

Definitions and Summary Statistics

Symbol	Definitions of Variables	Mean	Maximum	Minimum	SD
$\text{PrivateR\&DInv}_t$	Aggregate private investment in agricultural R&D: national annual aggregate private expenditures or gross investment on agricultural R&D* divided by the GDP implicit price level.†	3.59	5.09	1.96	.94
InterestRate_t	Real interest rate (%): the short-term interest rate on national government bonds (International Monetary Fund, Treasury-bill rate) less the annual rate of inflation on gross domestic product.†	5.17	17.36	−4.99	3.10
$\text{PrivateR\&DCap}_{t-1}$	Aggregate private agricultural R&D capital: the 1-year lagged value of the real national stock of private agricultural R&D.* Nominal R&D expenditures are deflated by the GDP implicit price level,† GDP then the stock is derived using the perpetual inventory method assuming a 12% depreciation rate.	5.34	6.98	3.21	.93
$\text{PrivR\&DSpillin}_{t-2}$	Index of the transnational private R&D spill-in potential: the commodity weighted stock of public agricultural R&D in other sample countries lagged 2 years.	7.57	8.20	6.27	.55
$\text{PublicR\&DCap}_{t-1}$	Aggregate public (Ministry of Agriculture and University) agricultural R&D capital lagged 1 year: nominal national public agricultural R&D expenditures* deflated by the GDP implicit price level,† then the stock is derived using the perpetual inventory method assuming a 12% depreciation rate.	6.63	8.58	4.41	1.01
AgOutput_{t-1}	Aggregate agricultural production lagged 1 year: the total value of final agricultural production‡ divided by the GDP implicit price level.†	8.80	10.00	.64	.64

CropShare$_{t-1}$	Crop share (%), lagged 1 year: value of crop production as a share of total value of final agricultural production.‡	44.39	41.14	28.88	10.71
PatentRights$_t$	An index obtained by summing 0 to 1 scores for each of five categories of patent law: extent of coverage, membership in international patent agreements, provision for loss of protection, enforcement mechanism, and duration of protection.§ Overall the index takes values 0–5 with large values indicating stronger patent rights.	3.59	4.24	1.98	.65
EfficientBureaucracy$_t$	Measures the speed and efficiency of the civil service, scored 0–4 with higher scores for greater efficiency.‖	2.33	2.40	1.50	.35
ContractEnforcement$_t$	Contract enforcement: measures the relative degree to which contractual agreements are honored and complications are presented by language and mentality difference, scored 0–4 with higher scores for greater enforcement.‖	2.87	3.20	1.80	.57
Openness$_t$	Economic openness: measures the extent of preferential treatment of nationals over foreigners in legal matters (and risk of expropriation for no compensation), scored 0–4 with higher scores indicating relatively more favorable treatment or less risk to foreign interests.‖	2.76	3.4	2.00	.39
D(*l*)	Country dummy variable taking a 1 if observation is country *l* (*l* = Austria, France, Germany, Italy, Netherlands, Portugal, Spain, Sweden, or United Kingdom) and 0 otherwise.				

* OECD, *Statistical Compendium, Industry, Science and Technology: Basic Science and Technology* (Paris: OECD, 2001).

† OECD, *Statistical Compendium, National Accounts*, GDP implicit price level (Paris: OECD, 2001).

‡ OECD, *Statistical Compendium: Agricultural Statistics; Agriculture, Hunting and Forestry* (Paris: OECD, 2001).

§ See J. C. Ginarte and W. G. Park, "Determinants of Patent Rights: A Cross-National Study," *Research Policy* 26 (1997): 283–301.

‖ S. Knack and P. Keefer, "Institutions and Economic Performance: Cross-Country Tests Using Alternative Institutional Measures," *Economics and Politics* 7 (1995): 207–27.

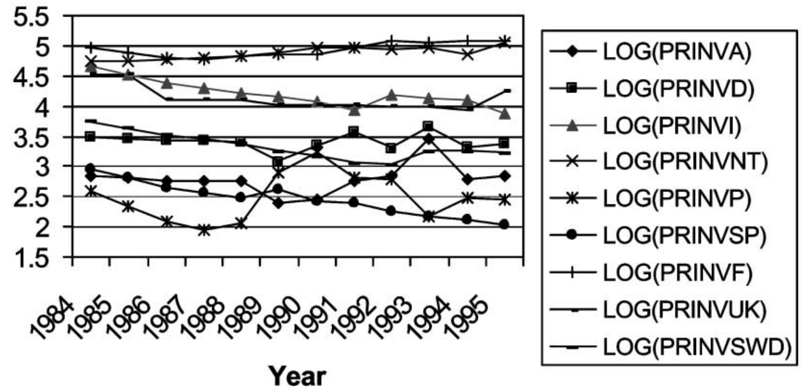

FIG. 1.—Private R&D investment in agriculture (in logs)

or expenditure is one that incorporates variables representing the effect of incentives, public policies, institutions, and a time trend. The incentives relate primarily to the size and composition of agricultural output. Each country has a set of institutions represented by country-specific indicators of patent rights, efficient bureaucracy, civil contract enforcement, and economic openness, which are hypothesized to affect the rate of private investment. Public policies such as public agricultural research investment decisions are expected to affect private R&D investment decisions. Transnational R&D capital is also expected to affect domestic private R&D investments.

The exact econometric specification of the private aggregate agricultural R&D investment equation is

$$
\begin{aligned}
\ln(\mathrm{PrivateR\&DInv}_{lt}) = {} & \\
& \sum_{l=1}^{9} D(l) + \beta_2 \mathrm{InterestRate}_{lt} + \beta_3 \ln(\mathrm{PrivateR\&DCap}_{lt-1}) \\
& + \beta_4 \ln(\mathrm{PrivR\&DSpillin}_{lt-2}) + \beta_5 \ln(\mathrm{PublicR\&DCap}_{lt-1}) \\
& + \beta_6 \ln(\mathrm{AgOutput}_{lt-1}) + \beta_7 \mathrm{CropShare}_{lt-1} + \beta_8 \mathrm{trend} \\
& + \beta_9 \mathrm{PatentRights}_{lt} + \beta_{10} \mathrm{EfficientBureaucracy}_{lt} \qquad (1) \\
& + \beta_{11} \mathrm{ContractEfficiency}_{lt} + \beta_{12} \mathrm{Openness}_{lt} \\
& + \beta_{13} (\ln \mathrm{PrivateR\&DCap}_{lt-1}) \times (\ln \mathrm{PublicR\&DCap}_{lt-1}) \\
& + \beta_{14} (\mathrm{ContractEnforcement}_{lt}) \times (\mathrm{EfficientBureaucracy}_{lt}) + \mu_{lt}, \\
& \mathrm{E}\mu_{lt} = 0,\ \mathrm{E}\mu_{lt}^2 = \sigma_l^2,\ \mathrm{E}\mu_{lt}\mu_{qt} = \sigma_{lq}^2,\ \nabla l,\ q,\ t,
\end{aligned}
$$

where μ_{lt} is a random disturbance term representing the effects of omitted variables that are peculiar to both a country (l) and time period (t). It has a zero mean and constant variance over time for any given country, but it differs across countries, and the disturbances are assumed to be contemporaneous correlated across countries. We assume that any unmeasured time-invariant country effects are uncorrelated with the time-varying regressors.[31] Homogeneity of degree zero is imposed on the R&D investment equation by deflating all nominal flow magnitudes by the GDP price deflator index.[32]

We now present and discuss hypotheses. We expect a higher private real interest rate or the opportunity cost of private investment funds to reduce the net present value of private R&D investments, other things equal, and to reduce the demand for private R&D investment, that is, $\beta_2 < 0$. Private R&D capital represents a stock of past discoveries that may be useful in future discoveries because they provide key building blocks to future discoveries, but the exhaustion of the innovative potential might be occurring faster than it is being restored, that is, "using up" some of the innovative potential.[33] Hence, the expected sign of β_3 is a priori uncertain. Private and public R&D capital seem likely to interact in affecting private agricultural R&D investment decisions, and they might be complements or substitutes:

$$\frac{\partial \ln(\text{PrivateR\&DInv}_{It})}{\partial \ln(\text{PrivateR\&DCap}_{It-1})} = \beta_3 + \beta_{13} \ln(\text{PublicR\&DCap}_{It-1}). \qquad (2)$$

If private research and public research capital are complements, then β_{13} will be positive, and if they are substitutes or if "crowding-out" of private by public investment occurs, then β_{13} will be negative. Thus, the expected net effect of the private R&D stock on current private R&D investment is a priori uncertain.

Private agricultural R&D investments in one country may affect investment decisions in other countries through transnational R&D transfers. These transfers are really of two types: (i) the size of the pool of generally accessible knowledge that is available from the outside for use by a particular country's scientists and (ii) the size of the borrowable stock of R&D from the outside, that is, knowledge relevant to the country's agriculture, or where the "technical distance is short."[34] For private R&D, transnational privately funded R&D is "closer" to the private R&D of a country than public R&D and should be a substitute. Second, transfers proxy the product market rivalry between firms in different countries.[35]

Evenson, and also D. K. N. Johnson and Evenson, present evidence of spill-ins for patented innovations across selected European countries.[36] These transfers are expected to be larger and more direct when the R&D is undertaken by large multinational companies, but even for R&D undertaken by domestic companies, some transnational externalities may occur. If transfer discoveries can be used directly, we expect $\beta_4 < 0$, or that transnational private R&D capital crowds-out private R&D investment. Alternatively, if domestic research must be undertaken to adapt new spill-in technology to local conditions, for example, costly borrowing, then we expect $\beta_4 > 0$.

In our model, we adopt a 2-year lag for the international transmission of agricultural knowledge. The main reason is the likely slower transmission of information and technology when it must cross national boundaries, for example, because of different languages, cultures, and so on. In our model, the regional stock of knowledge from borrowing is obtained by weighing R&D expenditures with the share of a country's output from wheat and milk production, which is a proxy for similarity of agricultural product mix.[37] The regional borrowable knowledge stock is formed by the general stock of borrowable knowledge less a country's own contribution.[38]

The marginal effect of public R&D capital on private agricultural R&D investment is:

$$\frac{\partial \ln(\text{PrivateR\&DInv}_{lt})}{\partial \ln(\text{PublicR\&DCap}_{lt-1})} = \beta_5 + \beta_{13} \ln(\text{PrivateR\&DCap}_{lt-1}). \qquad (3)$$

If public R&D is generally crowding-out private R&D, then the sign for equation (3) will be negative. We expect the main effect of public R&D capital in agriculture to be a substitute for private R&D, but if the interaction term with private R&D capital is positive, that is, $\beta_{13} > 0$, then at some level of private R&D capital, public R&D capital complements private R&D investment. A country having done more private R&D in the past then allows it to make better use of the public R&D capital.

The potential size of the national market for private agricultural innovations is proxied by the volume of agricultural production (AgOutput) and the crop share of final agricultural production (CropShare), both lagged 1 year. We expect the payoff to private agricultural R&D to be positively related to the size of local agriculture, or β_6, to be positive. Livestock-related sectors such as milk, swine, beef, and poultry are important to EU agriculture, as they account for 45% of agricultural output. The livestock sector, which has been highly protected from external competition, has been the focus of new technology development, for example, automation, artificial insemination, and new feeding systems for the local environment. Crop production has been heavily focused on supporting the livestock industry and on wine production. Hence, the expected sign of β_7 is negative.

Next, consider the effects of variables representing the effects of institutions. Stronger patent rights are expected to increase private R&D investments because private firms can expect to obtain a larger share of the social benefits from innovations resulting from their research and development, that is, $\beta_9 > 0$, but with a patent life of 20 years, we do not expect to preclude future related inventions that must build on past inventions. The speed and efficiency of civil services is expected to facilitate domestic private R&D investment. If obtaining needed permits and licenses involves slow and cumbersome processes, this will weight heavily against domestic private R&D

investment decisions. Furthermore, if efficient bureaucratic and contract enforcement are complementary, we expect β_{14} to be positive:

$$\frac{\partial \ln(\text{PrivateR\&DInv}_{lt})}{\partial(\text{EfficientBureaucracy}_{lt})} = \beta_{10} + \beta_{14}\text{ContractEnforcement}_{lt} \qquad (4)$$

and

$$\frac{\partial \ln(\text{PrivateR\&DInv}_{lt})}{\partial(\text{ContractEfficiency}_{lt})} = \beta_{11} + \beta_{14}\text{EfficientBureaucracy}_{lt}. \qquad (5)$$

Although the EU is a developed region, the extent of development and property rights differs. If the innovations needed by farmers must be highly tailored to local geoclimatic conditions, then strong rights for local compared with foreign firms would be important to private R&D investments, that is, this could lead to local protectionism and β_{12} being negative.

The country dummy variables [$D(l)$] in equation (1) are country-specific intercept terms or fixed effects, which accommodate cross-country differences in definitions of private R&D and differential R&D spill-in effects from EU countries not included in our sample. They also represent time-invariant but unspecified country-specific other factors, for example, agro-climatic conditions, major soil types, and proximity to other specific countries. We assume a constant relationship among the set of variables in our model and also that problems sometimes ascribable to random deviation of the characteristics of countries from their mean values are not important.[39] Besides, the econometric model is to be fitted to data over a relatively short time period, and random-effect estimates tend to be quite imprecise under these conditions.[40]

The Results

Equation (1) for each of the nine countries is stacked as a seemingly unrelated regression model, with coefficients on identical regressors being constrained to be the same across countries, except for the intercept, and fitted by the Zellner seemingly unrelated regression (SUR) estimation method with cross-country heteroscedasticity.[41] Thus, there are 90 observations obtained by pooling the 10 observations per country over the nine EU countries. The estimated coefficients of the aggregate private agricultural R&D investment equation and associated t-ratios are presented in table 4.[42]

Overall, the fitted model performs well. All coefficients are different from zero at the 5% significance level, and the hypothesis that the R&D investment equation has no explanatory power (i.e., all coefficients except for country fixed effects are zero) is rejected at the 1% significance level. Regression equation (1), table 4, has a large R^2 (0.97), indicating that a very large share—over 97%—of the variation of the log private agricultural R&D investments about its mean is explained by the regressors in the model.

Turning to particular effects, a higher real interest rate decreases private

TABLE 4

SEEMINGLY UNRELATED ESTIMATES OF INVESTMENT EQUATION FOR NATIONAL AGGREGATE PRIVATE AGRICULTURAL R&D: NINE EU COUNTRIES, 1984–95

	REGRESSION			
	Equation (1)		Equation (2)	
REGRESSORS*	Coefficient	*t* Value	Coefficient	*t* Value
Interest − $Rate_t$	−.017	−14.21	−.025	−14.97
ln ($PrivateR\&DCap_{t-1}$)	.456	6.26	.977	12.50
ln ($PrivR\&DSpillin_{t-2}$)	−.063	−2.05	−.139	−5.95
ln ($PublicR\&DCap_{t-1}$)	−.597	−6.59	−.384	−6.04
ln ($AgOutput_{t-1}$)	1.204	8.55	.658	9.55
$CropShare_{t-1}$	−.019	−9.75	−.0004	.80
$PatentRights_t$	.472	2.47		
$EfficientBureaucracy_t$	−2.592	−7.69		
$ContractEnforcement_t$	−.954	−3.40		
$Openness_t$	−.553	−12.90		
Trend	−.072	−10.90	−.059	−13.77
ln($PrivateR\&DCap_{t-1}$) × ln($PublicR\&DCap_{t-1}$)	.080	8.76	.016	1.49
$ContractEnforcement_t$ × $EfficientBureaucracy_t$	.959	7.84		
D(Austria)	−5.049	−4.02	−4.019	−5.87
D(France)	−5.850	−4.09	−4.550	−5.63
D(Germany)	−6.911	−5.29	−4.683	−5.90
D(Italy)	−5.757	−4.11	−4.874	−5.94
D(Netherlands)	−6.162	−4.49	−4.549	−5.94
D(Portugal)	6.629	7.19	1.350	3.57
D(Spain)	−5.562	−4.24	−4.969	−6.57
D(Sweden)	−4.520	−3.94	−3.537	−5.25
D(United Kingdom)	−6.739	−4.96	−4.898	−6.29
R^2 (adjusted)	.974		.969	
Durbin Watson	1.877		1.64	

NOTE.—EU = European Union.
* Each country has its own separate intercept, which is the coefficient of the country-specific dummy variable, i.e., there is no common intercept term.

R&D investment. The real opportunity cost of capital matters for private agricultural R&D investment. Public and private R&D capital are complementary in affecting private R&D investment, that is, the estimated value of β_{13} is positive, and the main effect of private R&D capital is also positive, so that the effect of private R&D capital on private R&D investment is strictly positive. The impact elasticity, evaluated at the sample mean of public agricultural research capital, is 0.985. Thus, having done more private R&D in the past allows a country to make better use of the past public R&D.

Additional public R&D capital has a negative direct and positive indirect effect on private R&D investment. At low levels of private R&D capital, for example, at or below the sample mean, the direct effect dominates, and additional public R&D capital substitutes for private R&D investment. Public R&D, however, turns into a complement provided that there is enough private R&D capital for firms to benefit, which occurs when private R&D capital is

1.25 times its sample mean value. Hence, additional public R&D capital sometimes decreases and at other times increases private R&D investment.[43] The implication is that a reduction in public R&D capital has a positive effect on aggregate private R&D investment, and it may be large enough to compensate for the loss of public expenditures. Hence, total (public and private) aggregated agricultural R&D investment may increase, and the private R&D share may rise dramatically.

We have striking results that transnational private R&D transfers appear to crowd-out privately funded R&D in the particular country that receives the transfers. First, transnational privately funded R&D is "closer" to the private R&D of a country than public R&D and should be a substitute. Second, spillovers proxy for product market rivalry between firms in different countries. Hence, private R&D does not have the same transnational effects that public R&D does.

The impact of additional agricultural output on private agricultural R&D investment is positive, and the impact elasticity is 1.20. Larger agricultural output leads to larger private R&D investment, but it is surprising that the impact elasticity is larger than one. The estimated coefficient for crop share of agricultural output is negative. Hence, output composition matters for private R&D investment decisions, and livestock production has more favorable effects on private R&D investments than does crop production.

Our results show that the quality of a country's institutions is an important factor in private agricultural R&D investment decisions. Consistent with expectations, when a country has stronger patent rights, private agricultural R&D investment increases significantly. For efficient bureaucracy and contract enforcement, the estimates of β_{10} and β_{11} are both negative, but the coefficient of the interaction term (β_{14}) is positive. When evaluated at the sample mean, the marginal effect of efficient bureaucracy and contract enforcement on private agricultural R&D investment is positive, 0.16 and 1.29, respectively—fewer bureaucratic delays and better contract enforcement provide a good political-economic climate for private agricultural R&D investment. The positive sign for β_{14} suggests that the contract enforcement and efficient bureaucracy are types of complements for affecting aggregate private R&D investment.

The effect of openness is negative. This result suggests a local political-economic climate that is favorable to domestic firms relative to foreign firms is most advantageous to local private agricultural R&D investment. Hence, it is consistent with agricultural technologies needing to be adapted to local economic conditions. Finally, the estimates of the country-specific fixed effects differ by a large magnitude, but we place little emphasis on the size of these parameters.

Although the empirical results for the institutional variables are quite strong, a joint test of the null hypothesis of "no effect of institutions"—that is, that $\beta_9 = \beta_{10} = \beta_{11} = \beta_{12} = \beta_{14} = 0$ in equation (1)—is performed. The sample value of the chi-squared statistic for the Wald test is 238, which is larger than the critical value (of 11.1) with 5 degrees of freedom at the 5%

significance level.[44] Furthermore, when these restrictions are imposed on the institutional variables (table 4, as regression eq. [2]), the size (and statistical significance) of the estimated coefficients for some of the remaining variables changes significantly. Hence, institutional variables do significantly affect domestic private agricultural R&D investments.

Conclusions

Research and development have been shown to be major forces behind the growth in agricultural output, especially agricultural productivity increases. Some studies have focused on modeling and explaining the public sector's willingness to invest in agricultural research in an environment where R&D produces impure public goods and positive interjurisdictional spill-ins are regional rather than widespread.[45] The current study, however, is one of the first to examine aggregate private agricultural R&D investment using a panel of developed countries and to identify separate effects of economic incentives, institutions, and public policies. Furthermore, it is the first study to provide estimates of the impacts of public agricultural research capital on domestic private agricultural R&D investment. The impact is in fact negative at and below the sample mean; that is, partial crowding-out occurs. Hence, if public agricultural R&D investments decreases, private agricultural research will increase by enough to offset the decline in public R&D investment. One possibility is that over the time period of the study, the EU countries have invested too heavily in applied research that is competitive with the private sector and not enough in basic-general and pretechnology sciences. Consistent with our findings, starting in the 1990s the national governments in some EU countries transferred or sold part of their agricultural research units to the private sector; for example, in both the United Kingdom and the Netherlands, the ministries of agriculture converted their agricultural research units into quasi-private institutions. Overall, public and private agricultural research in these nine EU countries has been complementary, holding trend factors constant. The study also finds a small negative transnational externality associated with private agricultural R&D investment in other EU countries, suggesting that private R&D discoveries are transmitted across country boundaries in a way that is competitive with or crowds-out local private R&D investments. Over time, this tendency is expected to grow as the EU becomes a single market.

Private sector R&D investment is shown to respond positively to the size of a country's agriculture, and the response elasticity is larger than one. Private agricultural R&D investments in the EU are negatively related to the relative importance of crop output in total agricultural production, other things equal. However, in the United States, the impression is that private R&D is more closely tied to crop than livestock production.[46]

The hypothesis that institutions do not matter was rejected. Stronger patent rights, better contract enforcement, efficient civil bureaucracy, and protectionism of local firms were shown to increase aggregate private agricultural

R&D investment unconditionally, other things equal. Furthermore, better contract enforcement and efficient civil bureaucracy appear to be complementary, which can be a large advantage for private R&D investments in some countries.

Over the period 1960–95, intellectual property rights in Western European countries have been strengthened. Given our results, this seems to have been one force for large private sector agricultural R&D investment. However, the finding of public agricultural R&D capital partially crowding-out private agricultural R&D investment suggests that national governments in the EU may not have adjusted fully to these changes. Restructuring public agricultural research so that it is complementary with private agricultural R&D investment would seem to be a good public policy for the future.

Appendix

Some particular measurement problems in the R&D data by country are outlined.

Austria. Expenditure data are based on the OECD statistical series: "Public Finding of R&D by Socio-Economic Objective: Agriculture, Forestry and Fisheries—Version 2." According to Phil Pardey and J. Roseboom, a complete breakdown of the advancement of knowledge item (including university funds) would certainly result in some increase in the agricultural research expenditure estimates.[47]

France. The National Centre for Scientific Research is included in the higher education sector, whereas in other countries such as Italy, this type of organization is classified in the government sector. Business enterprise R&D expenditure data by industry and by source of funds are only available for intra- plus extramural expenditure. This is the reason why the total by source of funds by industry is higher than the business enterprise R&D by industry.

Germany. OECD data for government R&D appropriations in Germany cover Western Germany only until 1990 and unified Germany after 1990. Through 1985, the technology balance of payments data for Germany cover transactions concerning patents, licenses, trademarks, models, and designs. After 1985, these data also cover technical services and industrial R&D. There are breaks between 1990 and 1991 as well as between 1991 and 1992 in total and socioeconomic objectives data.

Italy. Through 1990, the data represent the sum of intramural and extramural R&D expenditures, but after 1990, only the intramural R&D expenditure are included. The pre-1991 data for Italy are thus only partially comparable with those of other countries.

Netherlands. Netherlands has reorganized research in the Ministry of Agriculture and created a Knowledge Center associated with Wageningening Agricultural University. This shifts some R&D expenditures from the public to the university.

Portugal. Expenditure indicators are based on a classification of scientific disciplines rather than of the socioeconomic objective. According to Pardey and Roseboom, consistency in institutional coverage between observations is difficult to verify, especially for the earlier years.[48]

Spain. Data are underestimated between 10% and 15% per year because R&D personnel data for higher education only include researchers but not other staff. In October 1986, Spain joined the European patent convention. As a result, the number of patent applications for 1986 is not comparable with later series.

Sweden. Data for R&D performed by the government and private nonprofit institutions are underestimated because social sciences and humanities are excluded. The methodology for measuring government R&D appropriations has been subject to annual changes since 1991, so that a comparison of the data from 1990 to 1994 would appear to be of limited value only.

United Kingdom. Between 1985 and 1986 some government agencies were reclassified to the business enterprise sector. This caused a break in series for the data covering the performance and financing of government expenditure in R&D.

Notes

* An earlier draft was completed while Alfranca was a visiting scholar at Iowa State University in 1999. See also O. Alfranca and W. Huffman, "Impact of Institutions and Public Research on Private Agricultural Research," *Agricultural Economics* 25 (2001): 191–98. Helpful comments have been obtained from Robert Evenson, Carl Pray, Hans Roseboom, participants in a session at the 2000 International Association of Agricultural Economists Meeting, Berlin, and two anonymous reviewers. Financial support was provided by the Comision Interministerial de Ciencia y Tecnologia (CICYT) of the Spanish government, Project SEC96-2300; Comissio Interdepartamental de Recerca i Innovacio Tecnologica (CIRIT) of the Catalan government, Project SGR97-333; and the Iowa Agriculture and Home Economics Experiment Station, Project 1003.

1. See Paul A. David, Bronwyn H. Hall, and Andrew A. Toole, "Is Public R&D a Complement or Substitute for Private R&D? A Review of the Econometric Evidence," *Research Policy* 29 (2000): 497–529; Keith O. Fuglie, "Trends in Agricultural Research Expenditures in the United States," in *Public-Private Collaboration in Agricultural Research,* ed. Keith O. Fuglie and David E. Schimmelpfennig (Ames: Iowa State University Press, 2000), pp. 9–24.

2. In European countries subject to the Common Agricultural Policy, which had high intervention prices and external protection, large surpluses of some agricultural commodities, e.g., milk and cereals, accumulated. These surpluses created skepticism by taxpayers in these countries about public agricultural research to increase agricultural productivity.

3. Also, see Carl Pray and Keith Fuglie, "The Private Sector and International Technology Transfer in Agriculture," in Fuglie and Schimmelpfennig, eds., pp. 269–300, for another discussion of policies and incentives for private agricultural research and technology transfer.

4. See Kenneth Arrow, "Economic Welfare and the Allocation of Resources for Inventions," in *The Rate and Direction of Inventive Activity,* ed. Richard R. Nelson (Princeton, N.J.: Princeton University Press, 1962); F. Dasgupta and J. Stiglitz, "Industrial Activity and the Nature of Innovative Activity," *Economic Journal* 90 (1980): 266–93; J. Reinganum, "The Timing of Innovation: Research, Development, and Diffusion," in *Handbook of Industrial Organization,* ed. R. Schmalensee and R. Willig, 2 vols. (Amsterdam: North Holland, 1989), 1:850–908.

5. See Richard Cornes and T. Sandler, *The Theory of Externalities, Public Goods and Club Goods* (New York: Cambridge University Press, 1996).

6. See W. Cohen and R. Levin, "Empirical Studies of Innovation and Market Structure," in Schmalensee and Willig, eds., 2:1059–1108; R. Levin, K. Klevorick, R. Nelson, and G. Winter, "Appropriating the Returns from Industrial R&D," *Brookings Papers on Economic Activity* 3 (1987): 783–820.

7. Furthermore, the state of technology also affects the ability to reverse engineer discoveries, e.g., with modern DNA analysis the genetic composition of hybrid corn varieties no longer remains a trade secret.

8. See Oscar Alfranca, R. Rama, and N. Von Tunzelmann, “Competitive Behaviour, Design and Technical Innovation in Food and Beverage Multinationals,” *International Journal of Technology Management* (2003), in press.

9. R. W. Ward, “Advertising and Promotions,” in *Agrofood Marketing*, ed. D. I. Padberg, C. Ritson, and L. M. Albisu (Oxon, U.K.: CIHEAM-Cab International, 1997).

10. Hans C. M. Van Trijp and Jan Benedict E. M. Steenkamp, “Consumer-Oriented New Product Development: Principles and Practice,” in *Innovation of Food Marketing Systems: Product Quality and Consumer Acceptance*, ed. Wim M. F. Jongen and Matthew T. G. Meulenberg (Wageningen, the Netherlands: Wageningen, 1998), pp. 37–66.

11. Subsidiaries are also a mechanism for transferring and marketing innovation.

12. A patent, however, must be renewed by paying an annual fee after the second or third year.

13. Also, under a first-to-file rule, the lag time between discovery and public disclosure is shorter, which facilitates public accumulation of knowledge.

14. See G. Gaskill, M. W. Bauer, J. Durant, and N. Allum, “Worlds Apart? The Reception of Genetically Modified Foods in Europe and the U.S.,” *Science* 285 (1999): 384–87; W. E. Huffman and A. Tegene, “Public Acceptance of and Benefits from Agricultural Biotechnology: A Key Role for Verifiable Information,” in *Market Development for Genetically Modified Foods*, ed. V. Santanillo, R. E. Evenson, and D. Zilberman (Wallingford, U.K.: CABI, 2001), pp. 179–90.

15. See Douglas North, *Institutions, Institutional Change and Economic Performance* (Cambridge: Cambridge University Press, 1980); M. Olsen, *The Rise and Decline of Nations* (New Haven, Conn.: Yale University Press, 1982); S. Knack and P. Keefer, “Institutions and Economic Performance: Cross-Country Tests Using Alternative Institutional Measures,” *Economics and Politics* 7 (1995): 207–27; P. Mauro, “Corruption and Growth,” *Quarterly Journal of Economics* 110 (1995): 681–712.

16. For example, Knack and Keefer show using data for a set of about 100 countries that the rate of average gross private investment over 1974–89 was increased significantly when a country had lower business environment risk, i.e., more secure and efficient property rights.

17. Levin et al. (n. 6 above).

18. Also, see P. A. Geroski, “Markets for Technology: Knowledge, Innovation and Appropriability,” in *Handbook of the Economics of Innovation and Technological Change*, ed. Paul Stoneman (Oxford: Blackwell, 1995), pp. 90–131.

19. J. A. Schumpeter (*Capitalism, Socialism and Democracy* [New York: Harper, 1950]) is given credit for stimulating modern interest in the effect of industrial structure on innovation.

20. Reinganum (n. 4 above); Dasgupta and Stiglitz (n. 4 above).

21. Cohen and Levin (n. 6 above).

22. J. Bernstein and M. I. Nadiri, “Inter-industry R&D Spillovers: Rates of Return and Production in High-Tech Industries,” *American Economic Review* 78 (1988): 429–34.

23. James D. Adams, “Fundamental Stocks of Knowledge and Productivity Growth,” *Journal of Political Economy* 98 (1990): 673–702.

24. Robert E. Evenson and Y. Kislev, “Research and Productivity in Wheat and Maize,” *Journal of Political Economy* 81 (1973): 1309–29; Robert E. Evenson and Douglas Gollin, “Assessing the Impact of the Green Revolution, 1960 to 2000,” *Science* 300 (May 2, 2003): 758–62.

25. C. Klotz, K. Fuglie, and C. Pray, “Private-Sector Agricultural Research Expenditures in the United States, 1960–1992,” ERS Staff Paper no. 9525 (U.S. Department of Agriculture, Washington, D.C., October 1995); Julian Alston, Phillip Pardey, and Vincent Smith, “Financing Agricultural R&D in Rich Countries: What’s Happening and Why?” in Fuglie and Schimmelpfennig, eds. (n. 3 above), pp. 25–54.

26. See Colin Thirtle, P. Palladino, and J. Piesse, "On the Organization of Agricultural Research in the United Kingdom, 1945–1994: A Quantitative Description and Appraisal of Recent Reforms," *Research Policy* 26 (1997): 557–76; C. T. Whittemore, "Structures and Processes Required for Research, Higher Education and Technology Transfer in the Agricultural Sciences: A Policy Appraisal," *Agricultural Economics* 19 (1998): 269–82; Johannes Roseboom, "Technological Innovation in Agriculture: The Contribution of Agricultural Input Industries" (paper presented at the Twenty-Fourth International Conference of Agricultural Economists, the Hague, 2000). Available from ISNAR at http://www.isnar.cgiar.org/.

27. J. C. Ginarte and W. G. Park ("Determinants of Patent Rights: A Cross-National Study," *Research Policy* 26 [1997]: 283–301) produced a national patent rights index for over 100 countries by combining scores on five separate components of patent law: (i) extent of coverage, (ii) membership in international patent agreements, (iii) provision for loss of protection, (iv) enforcement mechanisms, and (v) duration of protection. Each separate component is assigned a value between 0 and 1, and a country's patent rights index is then the summation over the five component scores.

28. See Wallace E. Huffman and R. E. Just, "The Organization of Agricultural Research in Western Developed Countries," *Agricultural Economics* 21 (August 1999): 1–18.

29. Thirtle et al.

30. Our empirical measure of R&D capital, which needs a data-lean methodology, draws heavily on the methodological approach suggested by Zvi Griliches, "Issues in Assessing the Contribution of Research and Development to Productivity Growth," *Bell Journal of Economics* 10 (1979): 92–116, "Market Value, R&D and Patents," in *R&D, Patents and Productivity*, ed. Z. Griliches (Chicago: University of Chicago Press, 1984), and *R&D and Productivity: The Econometric Evidence* (Chicago: University of Chicago Press, 1998).

31. See Jeffrey M. Wooldridge, *Econometric Analysis of Cross Section and Panel Data* (Cambridge, Mass.: MIT Press, 2002).

32. See OECD, *Technology and Industrial Performance: Technology Diffusion, Productivity, Employment and Skills, and International Competitiveness* (Paris: OECD, 1996).

33. Wallace E. Huffman and R. E. Evenson, *Science for Agriculture: A Long-Term Perspective* (Ames: Iowa State University Press, 1993).

34. Evenson and Kislev (n. 24 above).

35. See Zvi Griliches, "The Search for Spillovers," *Scandinavian Journal of Economics* 94, suppl. (1992): S29–S47.

36. See Robert E. Evenson, "Inventions Intended for Use in Agriculture and Related Industries: International Comparisons," *American Journal of Agricultural Economics* 73 (1991): 887–91; Daniel K. N. Johnson and R. E. Evenson, "R&D Spillovers to Agriculture: Measurement and Application," *Contemporary Economic Policy* 17 (1999): 432–56; Robert E. Evenson, "Agricultural Technology Spillovers," in Fuglie and Schimmelpfennig, eds. (n. 3 above), pp. 219–44.

37. In the EU, wheat is the most important grain crop grown, and milk is the most important livestock product; see U.S. Department of Agriculture, *Agricultural Statistics, 2001* (Washington, D.C.: U.S. Government Printing Office, 2001). See also Adam Jaffe, "Technological Opportunity and Spillovers of R&D: Evidence from Firms' Patents, Profits, and Market Value," *American Economic Review* 76 (1986): 984–1001; and Evenson and Kislev for similar methodology.

38. See J. Khanna, W. E. Huffman, and T. Sandler, "Agricultural Research Expenditures in the United States: A Public Goods Perspective," *Review of Economics and Statistics* 76 (May 1994): 267–77; Todd Sandler, "Global and Regional Public Goods: A Prognosis for Collective Action," *Fiscal Studies* 19 (1998): 221–47.

39. See Marc Nerlove, *Essays on Panel Data Econometrics* (New York: Cambridge University Press, 2002).

40. Wooldridge.

41. See William H. Greene, *Econometric Analysis*, 5th ed. (Upper Saddle River, N.J.: Prentice-Hall, 2003). The estimated equation is similar to the model of corporate investment by Yehuda Grunfeld, "The Determinants of Corporate Investment," in *The Demand for Durable Goods*, ed. A. C. Harberger (Chicago: University of Chicago Press, 1960), pp. 211–66.

42. Extensive construction of interaction terms between the institutional and policy variables is not possible because of the modest number of observations.

43. By confining our attention to public-private substitution in agriculture R&D, we could be missing complementarities with publicly funded R&D in scientific fields such as fundamental biology or biomedical research. Unfortunately, no data are available to incorporate this information into the model (at the moment), and the use of proxies, e.g., general R&D expenditure in medicine, present weak econometric results in the model.

44. Greene.

45. See, e.g., Khanna et al.

46. Huffman and Evenson (n. 33 above).

47. Phil Pardey and Johannes Roseboom, *A Global Database on National Agricultural Research Systems*, ISNAR Agricultural Research Indicator Series (the Hague: ISNAR, 1989).

48. Ibid.