

**New Insights on the Organization of
Agricultural Research: Theory and Evidence
for Western Developed Countries**

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*Abstract***New Insights on the Organization of Agricultural Research:
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by Wallace E. Huffman

Public and private R&D are important sources of advances in knowledge leading to new technologies for and products from agriculture in western developed countries. Over the past fifteen years, a significant reduction in the rate of growth of public funding for agricultural research in western developed countries has occurred relative to the preceding decade. The future, however, holds unexplored options for the organization of public agricultural research. Advances in the theory of impure public goods can be applied to create new financing jurisdictions and funding sources for public agricultural research. Advances in principal-agent theory can be applied to the unique characteristics of the R&D production process, i.e., output is highly uncertain and administrators cannot effectively monitor scientists' effort, to design incentive compatible contracts that significantly improve scientists' attention to effort and quality of research payoffs. Some implications for alternative funding mechanisms are developed. The paper concludes with several new insights about the likely organization of agricultural research in western developed countries for the 21st century.

Key words: agriculture, research, organization, finance, developed countries, impure public goods, principal-agent models, twenty-first century.

New Insights on the Organization of Research: Theory and Evidence for Western Developed Countries

by

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It is now well accepted that institutionalized research, rather than research by farmers, is a important source of discoveries leading to new technologies that facilitate the modernization of agriculture and total factor productivity increases. In most western developed countries, the research is financed and conducted by both public and private institutions. Research, however, is a very different activity to foster, promote, and finance in ways that bring forth the full creativity and effort of scientists/researchers. We are only beginning to try to uncover the secrets to good organization.

The objective of this paper is to summarize recent developments and emerging trends in the organization of agricultural research, discuss new insights on financing agricultural research, and examine efficient incentives for scientists and R&D in general. The final section of the paper will develop some implications for the organization of agricultural research in the 21st century. The paper draws heavily from my research in Huffman and Just (1999a,b; 1998), Huffman (1999), and Just and Huffman.

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Recent Developments and Emerging Trends

Some important recent developments and emerging trends in the organization of agricultural R&D in western developed countries are identified and discussed briefly.

Development 1: The rate of growth of public agricultural research expenditures has been reduced significantly. During 1971-1981, the annual (compound) average growth rate of real agricultural research expenditures for these 18 western developed countries was a relatively large 2.9 percent, 3.2 percent for the Western European countries and 2.6 percent for the North American countries (table 1). For all of the countries except Germany, the growth rate was positive. During 1981-1993, the growth rate for public agricultural research expenditures, however, was significantly lower by about 1 percentage point — 1.9 percent for all 18 countries, 2.2 percent for the Western European countries, and 1.9 percent for the North American countries. During this latter period, three countries (Belgium, Greece, and Ireland) had negative growth in agricultural research expenditure, the U.K. had no net growth, and Canada had an average growth rate of only 0.26 percent. Over the two combined periods, Germany has almost no net growth in public agricultural research expenditures.

Development 2: Traditional national (or central) government funding sources for agricultural research are reducing systematic funding, including formula or program funding, and increasing emphasis on centrally controlled competitive grant programs.

This new direction is especially apparent in the United Kingdom and less in the United States and Germany. During 1972-1982, most of the U.K. public agricultural research funds were

allocated noncompetitively by the Ministry of Agriculture, Food, and Fisheries on a program basis (Thirtle, et al 1997). The latest major redirection of U.K. public agricultural research started in 1982. As a result, some applied research institutions were sold to the private sector. The national government cut ear-marked or program funding for institutes and laboratories that were engaged in “near market” and “agricultural productivity enhancing” research and increased funding for the Higher Education Institutes (HEI) and the Biotechnology and Biological Science Research Institute (BBSRI). The latter two institutes primarily operate competitive grants programs in “basic science” and in “public interest” research focused on food safety and environmental issues. Scientists from a broad set of institutions are eligible to bid on HEI and BBSRI projects. In 1993/94, competitive grant funds for agricultural research increased to 20 percent of public funds allocated to agricultural research (but 80 percent continue to be allocated as program funds or block grants to agricultural research institutions). See Thirtle et al 1997.

In the U.S., the composition of the “regular federal” funding (i.e., Cooperative States Research Service, CSRS, or Cooperative States Research, Education, and Extension Service, ESREES) and mechanism for allocating federal funds to the state agricultural experiment station system (and other cooperating state institutions) have changed. In 1887, when the SAES system was first covered by the new passed Hatch Act, approximately 82 percent of SAES funding from the national government came from regular federal funds. This share trended downward to 65 percent in 1900, 22 percent in 1960, and 14 percent in 1990 but were larger in 1996 (15 percent) (Huffman and Just 1991a). The share of regular federal funds distributed by competitive grants to SAES was 0 in 1980, 8.6 percent in 1990, and 16.6 percent in 1996

(Huffman and Evenson 1993, Huffman and Just 1999a). Hence, “regular federal” funds for agricultural research are being allocated increasingly by competitive grants and less by formula or block grants to state.

Historically a legislated formula for allocating federal appropriations to the SAES system has been central to national government funding of public agricultural research (Huffman and Evenson 1993, pp. 21-23; Alston and Pardey 1996, Ch. 2; Fuglie et. al. 1996). Initially every state received an equal sized national government appropriation, but over the period 1935-55, the formula was modified to also depend on a state’s share of total U.S. farm population and total U.S. rural people. After strong encouragement from the National Research Council, the USDA initiated a Competitive Grants Programs in 1977. Its funding increased substantially beginning with the National Research Initiative (NRI) in 1986. The NRI competition is open to all public and private researchers.

Development 3: Public agricultural research scientists are being encouraged to pursue nontraditional sources of funding such as outside departments (ministers) of agriculture in national governments, private corporations, producer (commodity or cooperative) groups. The trend is strongest in the United Kingdom, the U.S., France, the Netherlands, and Canada. In the United Kingdom, the recent redirection of agricultural research funds away from the Ministry of Agriculture, Food, and Fisheries to the Higher Education Institutes and establishment of new statutory bodies (commodity groups) to fund agricultural research represents a new emphasis on nontraditional agricultural research funding (Smith 1996; Thirtle, et. al. 1997). In 1993/94, the HEI funds represented 15 percent of expenditures on U.K. public agricultural research, which was considerably larger than the 5.5 percent share in 1987/88.

In the U.S. at both the state and federal level, nontraditional sources of resources and technology transfer have been developed recently. Over the past two decades, SAES scientists in the U.S. have turned increasingly to “non-regular federal” and private sector sources. In 1960, the share of SAES system funding coming from nontraditional federal government sources was 5.7 percent, and it has grown--12 percent in 1970 (1980, 1990), and 15 percent in 1996 (see Huffman and Just 1999a). These funds were distributed by the USDA in contracts and cooperative agreements and by the National Institutes of Health, the U.S. Agency for International Development, the National Science Foundation, the U.S. Department of Health and Human Services, the Public Health Service, and other agencies primarily by competitive grants.

During the past decade, U.S. federal laboratories have greatly increased the amount of collaborative research with the private sector. The 1986 Technology Transfer Act established a mechanism, a CRADA, through which federal and non-federal researchers could collaborate (Fuglie et al. 1996, p. 55). This legislation permits federal laboratory to enter into CRADA's with universities, private companies, non-federal government entities, and others. The principle objective of a CRADA, however, is to link the pretechnology research capacity of federal laboratories with the commercial research and marketing expertise of the private sector. The cooperating institution receives the rights of first refusal to any joint discovery and may be given exclusive access to data from a joint project (Fuglie et. al. 1996, p.56). CRADA activity has increased rapidly after 1987, but the private sector CRADA resources are less than 1 percent of the budget of the Agricultural Research Service of the USDA (Huffman and Just 1999b).

In France, the growth of systematic/program funding for research in national institutes has not been fast enough to cover the cost of experimentation. Scientists are now encouraged to undertake cooperative or joint venture projects with public (regional governmental) and private sector partners. In the Netherlands, there has been a large increase in the number of public-private partnerships for agricultural research, including the private sector investing significantly in resources of the public institutions. In Italy, funding of public agricultural research by the National Research Council, Ministry of Industry and Trade, and Ministry of Research and Universities represent nontraditional sources (Huffman and Just 1999b).

In Canada, since the early 1980s, commodity, producer, processor, and trade associations have been collecting funds for financing agricultural research. These groups include the Canadian Horticultural Council, the Canola Council of Canada, the Brewing and Malting Barley Research Institute, and the Canadian and Western Grains Councils (Guitard 1985). However, a new agricultural research policy was established in 1994, the Matching Investment Initiative (MII). Under this program, the federal government matches up to dollar-for-dollar the private sector's contributions to joint research ventures. The MII was implemented by the federal government to offset declines in federal funding for agricultural research. Also, new funds for public research are coming from commodity check-off programs for wheat, barley, and beef.

Although there is clearly increased emphasis on obtaining private sector funding for public agricultural research institutions, the share of the total funds that these institutions research from the private sector is small. Among the western developed countries, the U.S. receives the largest share of private sector funding of public agricultural research, 7.5 percent in

1960, 9.2 percent in 1980, and 14.3 percent in 1996 (Huffman and Just 1999a,b). Private sector funding of research in public institutions raises a number of political-economic issues that do not appear in private sector funding of its own activities.

Development 4: Public universities are increasingly entering into and contemplating exclusive joint ventures with a particular large agro-chemical company. The University of California-Berkeley has entered into an unusual partnership on R&D and other institutions, e.g., University of Missouri, are evaluating alternatives. Novartis has agreed to provide \$25 million for funding over 5 years of research projects largely in the Department of Plant and Microbial Biology, University of California-Berkeley, and to pay possibly \$25 million for renovations of laboratories for the above department. The research funds for projects are to be channeled through a faculty controlled committee that will evaluate research proposals. Novartis is apparently needing a new source of discoveries in the plant science area beyond its own scientists or that it can easily acquire through mergers or purchase in the IPR market. It will get exclusive rights to develop the most promising scientific discoveries for a fixed period of time after the discovery.

The College of Natural Resources at Berkeley apparently saw no state government support for renovating its laboratories in Plant and Microbial Biology in the near future but felt that obsolete laboratories could undermine their otherwise high quality research program. The Novartis-Berkeley partnership raises serious issues about conversion of use of public facilities and scientists to private gain for one particular company. It may, however, be a useful model for a university research program that has lost its public funding base for new or renovated laboratories and possibly for salaries and current expense funds.

New Financing Prospects

The emphasis is on financing discoveries that are impure public goods, i.e., ones that have both public and private good dimensions (Huffman and Just 1999b; Huffman 1999).

New Jurisdictions and Clubs

The theory of public goods is central to our understanding of the economics of financing and organizing agricultural research. Some agricultural research produces pure public goods, meaning that innovations are nonrival (being indivisible) and nonexcludable (being costly to selective withholding). For example, the scientific discovery by James Watson and Francis Crick in 1953 of the structure of DNA and suggestion of how it replicates created a pure (multinational) public good. Once their findings were published, access to the knowledge was unlimited. Because the discovery was of the nature of an abstract concept and not embodied in a particular product, material, or process it was not patentable. Given the discovery that a gene was a specific sequence of bases (proteins) in DNA, other scientists were then able to envision the growth and functioning of organisms as programmed by functional base sequences. Much agricultural research, however, produces impure public goods which are partially excludable. Access to benefits of research may have a geographical dimension, (e.g., local, regional, national, or international), usefulness may be limited to particular plant or animal species, or strong intellectual property rights, e.g., patents, trade secrets, breeders' rights, may be politically, economically, and legally feasible giving owners sole right to control or license an innovation's use for a fixed period. For example, the U.S. patent system now gives an inventor the right to control the use of his/her discovery for 20 years.

Some examples illustrate partial excludability of benefits for scientific innovations. First, consider the public applied agricultural research at Kansas State University that led to a new hard red winter wheat variety in 1995 that was uniquely adapted to Kansas growing conditions and widely adopted by Kansas farmers in 1996 and 1997. Because the wheat variety is self-pollinated, farmers can save their own seed for replanting the following year. This use of so-called “bin-run” seed greatly reduces private sector interest in wheat varietal development.¹ Benefits of the research spilled across state boundaries in the sense that the new variety also replaced some acreage of older hard red winter wheat varieties in the surrounding states of Oklahoma, Colorado, and Nebraska, but in other states, the new variety was either not good enough to dislodge older varieties or hard red winter wheat is not grown.

Second, the discovery of the structure of DNA enabled later discoveries, some of which were patentable and generated large licensing revenue and new companies. That is, an intellectual property right system can be used to make excludability economically feasible and to convert discoveries into impure public goods that are marketable. For example, the discovery by Cohen and Boyer in 1973 of the basic technique for recombinant DNA, the splicing of genes possibly from different species, was both a discovery of a method and a product. The Cohen-Boyer patent on the basic technique of gene-splicing was awarded in 1980 to Stanford University and the University of California and launched the new field of genetic engineering (Office of Technology Assessment 1989). Boyer then became a cofounder of the private company Genentech about 1980 in an effort to exploit commercial possibilities of genetic engineering.²

Third, Monsanto discovered and patented a Roundup Ready technology for soybeans in 1995. A U.S. patent limits the use of this technology for 20 years, and Monsanto charges a technology fee of \$5 per acre (initially) for the use of Roundup Ready technology embedded in soybean varieties. The technology changes weed management from several applications of several active ingredients per year to a single application of one broad-spectrum herbicide. The average reduction in weed control cost, including the added cost of the technology fee, has been about \$10 per acre (Carlson, Marra, and Hubbell 1997). Roundup Ready soybeans allow farmers to plant in narrow rows or drill seeds, which reduces soil erosion over wide-row planting and crowds out some weeds. Farmers, however, must forego saving and using their own soybean seed from Roundup Ready varieties. Monsanto has found it profitable to price Roundup Ready technology to achieve widespread adoption by soybean producers, and this allows farmers and consumers of soybean products to share in the benefits of the new technology. Over the long term scientist will be able to innovate around Monsanto's patent and the life of the patent is limited. Hence, the benefits from the Roundup Ready technology for soybeans is only partially appropriable to Monsanto or partially excludable.

Because of limited potential appropriability of discoveries that are of a pure public good nature, e.g., the discovery of the structure of DNA, the private sector will grossly underfund this type of research relative to the social optimum or not finance it at all (Huffman and Just 1999a; Cornes and Sandler 1996). Hence, the public sector can be expected to play a major role in financing fundamental discoveries that are of a pure public good nature. More applied and product/design or process/method oriented discoveries that the fundamental discoveries enable have higher expected appropriability through patenting, and the private sector can be expected

to finance a major share of them, e.g., the development of bt cotton and corn, Round Up Ready Soybeans, bGH or bSt for dairy cows. Advances in technology, however, sometimes lead to advances in science to resolve unanticipated outcomes.

Positive externalities or spillovers are common with research and other public goods, and they frequently are a source of socially inefficient decisions on optimal provision. When a public good, say a scientific innovation, provides benefits outside the political jurisdiction that finances/provides it, and no compensation is paid by outsiders, positive externalities in the form of spillovers occur. Spillovers occur when the “economic jurisdiction” or impact area is larger than the political boundaries or the financing jurisdiction. For agricultural research (and other public goods), it is important to distinguish between “political or deciding” and “economic or benefitting” jurisdictions (Cornes and Sandler 1996; Olson 1969, 1986). Serious social inefficiency arises in the form of underinvestment either when an economic jurisdiction is broader than the political jurisdiction (as above) in both examples or when the economic jurisdiction is a small subpart of a larger political jurisdiction and provision of research funds, e.g., is by collective action (Olson 1969, 1986), i.e., a local public good.

Some scientific discoveries have beneficiaries that are not defined geographically, and Olson (1986) suggests calling them the “clientele” and Cornes and Sandler (1996) suggest calling them a “club.” With public agricultural research funded by collective action, scattered research clientele (or club members) increases greatly the cost of organizing to finance agricultural research, and as the number of members in the clientele group or club grows, the free- or easy-rider problem generally causes the group to lose its power and to become political

ineffective (Olson 1965; Cornes and Sandler 1996). For these clientele groups to be politically effective, they must solve the free-rider problem.

One effective means of solving this problem is to obtain federal legislation requiring participation of target-group members. In the United States, the 1985 farm bill permitted agricultural commodity groups to hold a referendum for coverage by mandatory commodity check-off programs to finance commodity promotion and agricultural research. A commodity group is then designated to manage the check-off funds, e.g, the National Pork Council, the National Corn Growers Association, National Soybean Association, National Cattlemen's Association. In Canada and the United Kingdom, national legislation has also enabled producer commodity councils to fund research and other activities (Huffman and Just 1998; Guitard 1985; Smith 1996; Thirtle et. al 1997).

Private interest group financing of public agricultural research is socially efficient if (1) all of the beneficiaries of the research are included in the "group" and (2) the private financing does not adversely affect (i.e., crowd out) the amount of public resources allocated to other socially worthwhile agricultural research. Unfortunately, one or both of these conditions are seldom met. First, the (potential) beneficiaries of agricultural research are generally much larger than any particular commodity group (or corporation). Notably over the long-run, a large share of the benefits of public agricultural research goes to consumers (see Alston and Pardey 1996, Ch. 5). In contrast to the broad distributional benefits associated with public research, a large share (but not all) of the benefits of private sector agricultural research goes to the companies financing and conducting the research (Huffman and Evenson 1993). Second, research as a production process has a large amount of *ex ante* uncertainty and public

institutions that are under financial distress frequently look favorably on almost any outside source of funding. Thus, a private group is frequently able to contract with a public research institute to undertake a project for less than the expected cost which creates joint public-private financing. Hence, public funds that would otherwise have gone to other public agricultural research projects having greater public goods content are redirected by the joint venture.

From a public interest perspective, the key issue is the size of the social payoff for the joint public-private venture versus purely publicly financed projects which are foregone by the redirection of public resources to the joint venture project. If the social opportunity cost is low, then the redirection is socially good, but if the opportunity cost is high, society is worse off by these joint public-private ventures than if no private funding of public agricultural research occurred. See Ulrick, Furtan, and Schmitz (1986) for adverse effects of private funding of barley research, and Huffman and Just (1994) for adverse effects of federal grant, contract and cooperative agreement funding of public agricultural research on state agricultural total factor productivity. The displacement of public goods research by private or quasi-private goods research can be a significant “crowding out” effect that can undermine the willingness of taxpayers to support public goods research.

Stronger IPRS and Private Incentives

The relative importance of private agricultural R&D differs across western developed countries. When the private sector undertakes a larger role in the production of scientific innovations, the demands on the public sector are reduced and the nature of the social need changes. The private sector’s share is relatively large (> 50 percent) in the United Kingdom, the Netherlands, United States, Germany, and France but small (< 30 percent) in Portugal, Greece,

Ireland, and Canada (Pardey, Roseboom, and Craig; Alston, Pardey, and Smith 1998).

Both governmental policies and market forces greatly affect the incentives for private sector investment in agricultural R&D.

Public policies have several different types of effects. First, government farm commodity and agricultural trade policies affect the market prices for final commodities and inputs, the price elasticities of aggregate supply of agricultural output and demand for agricultural inputs. Hence, they affect the expected profitability of farmers' adopting new technologies and the derived demand for them. Second, environmental, resource, public health, and food safety policies change the cost structure of firms and (or) influence consumer demand for final products. Third, public investments in general and pretechnology research produce new innovations, and some of them provide good commercial opportunities for private sector development and marketing. Fourth, national (and international) laws provide the mechanisms for definition, enforcement, and transfer of IPRs (Evenson 1984).

IPRs include patents, breeders' rights, copyrights, trademarks, and trade secrets. The patent, which provides protection for embodied inventions, is the key IPR for private sector innovation in agriculture of western developed countries. A holder of a patent on an invention in a particular country is given the right by the granting country to exclude others from the unauthorized use, sale, or manufacture of the invention for a finite period, generally 20 years. These rights, however, apply only within the boundaries of the granting country, and only through international patent right exchange agreements do they have power in other countries.

The Patent applicant must disclose or remove from secrecy the essential features of the invention so as to "enable" others to make or use the invention (Huffman and Evenson 1993,

Ch. 5). Disclosure has two main purposes. In return for granting a limited monopoly position to the inventor for 20 years, the nature of the invention is revealed which facilitates accumulation of the stock of knowledge and exchanges among innovators and scientists, and second, a country establishes strong incentives for private sector finance and conduct of R&D. Patent laws generally exempt abstract or non-embodied ideas and concepts from protection. Thus, for an invention embodied in a product, process, or biological materials, the holder of a patent can use or license its use. This gives the owner the right to an income stream from the commercialization of inventions or from licensing it to others. However, if a country has ineffective procedures for protecting patent rights, the size of the potential income stream from inventions is greatly reduced and might be zero.

The strength of IPRS is associated with both the IPR laws and the quality or technology of enforcement. Patent right laws for the 18 western developed countries of this study have been strengthened over the past two decades, and this has increased the economic incentives for private R&D. The strength of patents across the 18 countries can be compared using a patent rights index developed by Ginarte and Park (1997). The overall index is derived from five separate indexes for: (1) extent of coverage, (2) membership in international patent agreements, (3) provisions for loss of protection, (4) enforcement mechanisms, and (5) duration of protection. For example, loss of protection means 'working' requirements, compulsory licensing, and revocation of patents. Duration is the share of 20 years that a granting country gives protection. Each of the five components was given a value between 0 and 1 by the authors for each country and year, and a country's patent-rights index is the summation over these values, taking values between 0 and 5.

The values of the patent rights index, 1960-1990, for western developed countries are summarized. First, the mean patent rights index value for the 18 western developed countries is significantly higher than the average value for a set of 111 high, middle, and low income countries, being 22 percent higher in 1960 and 36 percent higher in 1990. Second, the patent rights index for the western developed countries has increased rapidly since 1975. The mean of the index increased slowly during 1960-1975 (an average rate of 0.7 percent per year) and more rapidly during 1975-1990 (an annual average of 1.1 percent per year). Third, the U.S., Austria, the Netherlands, and Italy stand out because of their high patent-rights index values (over 1975-1990), and Portugal, Greece, and Ireland stand out because of their usually low values. Fourth, although most of the western developed countries have strengthened their patents rights over 1960-1990, the index values for Canada and Portugal are unchanged and the index value for Greece actually declined from 1985 to 1990.

Two technological advances have effectively strengthened IPR laws associated with biological material. First, DNA analysis permits a scientist to identify with great precision the genetic composition of new organisms. In essence, DNA finger printing has made proving that protected material has been pirated much easier. The patent examiners have, however, created some new problems by giving overlapping patents on biological materials (Lesser, Horstkotte-Wassler, Lile, and Byerlee 1999).

Second, scientific discovery by the USDA-ARS and Delta and Pine Land Company of the *terminator gene*, or “Varietal Crop Protection System” may greatly change the economics of plant-breeding for non-hybrid crops. The terminator gene renders seeds sterile. This significantly alters one of the two primary functions of a plant’s DNA, i.e., eliminates the ability

of the plant to reproduce itself. It means that farmer's cannot save their own seed and effectively plant them. This gene has no direct beneficial effects on crop yields, which is different from hybrid technology, where plants also cannot effectively reproduce themselves. The terminator gene is now owned by Monsanto and has the potential to be used to increase the private returns to innovators for a discovery but to reduce the social benefits of the discovery because many of the positive externalities are eliminated. Hence, further strengthening of intellectual property right to encourage greater private R&D is not without controversy.

Setting Efficient Incentives for Research

Because of significant changes in the R&D environment over the past two decades, scientists and research administrators find themselves struggling with new issues and employing new territory. Important features of the R&D production process add up to a difficult environment in which to set efficient incentives for scientists' effort and quality of output.

Key Attributes of Research

First, the R&D payoff is best described as the "best" of scientists' outputs, rather than their total output. Second, the research production process is subject to a large amount of *ex ante* uncertainty. No target discovery may occur, a poor discovery may occur, or a great discovery might occur. Furthermore, unanticipated discoveries frequently occur. Hence, payoff or value of a research project is unknown at the outset of the project and output/quality is noncontractable. Third, asymmetric information exists on scientists' efforts (and ability). The scientist has much better information about how he allocates his effort and on his research ability than the research administrators. Hence, it is generally economically impossible for a research

administrator to monitor the effort of scientists. Furthermore, given *ex ante* uncertainty in the research production function, it is impossible for a research administrator to accurately infer effort (or ability) from observed output/quality. Hence, a moral hazard arises in contracting on scientists' effort because the administrator cannot verify that a scientists' effort has met any agreed upon contract terms. Fourth, administrators are less risk adverse than administrators because they manage a much larger portfolio of projects. Each scientist has at most one or two projects per period, but a research administrator may have 30 to several hundred scientists working. With different attitudes toward risk between administrators and scientists, potential inefficiencies arise when scientists are expected to bear a larger share of research risk.

Modeling Research Incentives with Uncertain Payoffs

Before assessing implications of recent trends in agricultural research, we sketch the basic model (Huffman and Just 1998). First, the research administrator is assumed to observe the research payoff at the end of a project, to compensate scientists' for their effort, possibly with a compensation package including a fixed salary and a performance incentive, and to be risk neutral about R&D payoffs.³ For the purpose of this paper, a research project is an attempt to develop a particular innovation or an annual contract to conduct research in a particular area. The administrator's objective is to maximize expected R&D payoff net of scientists' compensation.

Second, scientists are assumed to obtain utility from income, disutility from effort or work, to be risk averse, and to have a reservation utility. More specifically, each scientist (denoted by the subscript i) is assumed to have a quadratic cost of effort, $c_i(e_i) = k_i e_i^2 / 2$ (which generates a positive-sloped effort schedule with respect to compensation) where e_i is effort, to

have constant absolute risk aversion N_i , to have a fixed certainty-equivalent reservation utility (μ_i), and to choose effort on research to maximize individual expected utility subject to attaining at least the reservation utility.

Third, each scientist is assumed to work alone (to avoid team or easy-rider problems) and to undertake one project that produces exactly one indivisible unit of output, but with random quality depending on his effort. Hence, the research output is one-dimensional. For notational simplicity, the non-stochastic component of the production process is assumed identical across scientists — an assumption that is easily relaxed later — so the quality index can be simply defined as effort plus random components. To examine the implications of random quality, we let

$$(1) \quad y_i = e_i + \epsilon_i + \eta$$

where y_i is quality of research produced by scientist i , ϵ_i is a scientist-specific random component with zero mean and variance F_i^2 , and η is a random component affecting all scientists with zero mean and variance F_η^2 . The scientist-specific random term may represent the effects of individual ability, creativity and efficiency of mental processes. The common shock might represent unanticipated problems associated with the particular innovation toward which all the scientists' efforts are directed, or it could represent unanticipated exogenous advances in the public stock of knowledge during the research project. Assuming that ϵ_i and η are uncorrelated, the variance of research output is the summation of the two variances, $F_i^2 + F_\eta^2$ (note that if the two are correlated, a suitable redefinition can make them uncorrelated).

The effort level, e_i , is the source of asymmetric information. It is unobservable to the research administrator but treated as known to the scientist. Research quality, y_i , is assumed to

be observable to both the administrator and scientist but only at the end of the research project. We permit more than one scientist to work independently on identical research projects, but only the highest quality output contributes to the administrator's R&D payoff. This might arise through the publication process where an editor publishes the "best" paper on a topic given that it adds significantly to the state of knowledge, or farmers use only the crop variety or animal breed that has the "best" anticipated performance.

Optimal Compensation of Research Scientists

We derive the optimal compensation scheme, given the attributes of research, the scientist, and administrator. To convey some basic results about optimal compensation and the associated R&D payoff, consider contracting between a research administrator (or funding agency) and one scientist. According to principal-agent theory, when contracting is repeated many times and the agent has discretion in actions including the level and timing of effort, the structure of the optimal pay scheme is linear in the observed principal's payoff (Holmstrom and Milgrom; Levitt). Hence, we consider Pay Scheme I consisting of two parts: (i) a guaranteed payment, w_i , that is independent of the observed R&D payoff, and (ii) an incentive payment that amounts to a positive share, β_i , of the observed R&D payoff,

$$(2) \quad w_i = w_i + \beta_i y_i.$$

A larger β_i implies a "higher powered" incentive scheme. Substituting equation (1) into (2), the structure of this pay scheme is seen to be linear in the scientist's effort,

$$(3) \quad w_i(e_i) = w_i + \beta_i e_i + \beta_i \bar{y}_i + \beta_i \epsilon_i^*.$$

Equation (3) depicts how *ex ante* uncertainty in the research production process is transmitted into *ex ante* wage uncertainty for the scientist. From equation (3), the expected wage

conditional on effort is $E(w_i) = \mu_i + \beta_i e_i$ and the wage variance is $v(w_i) = \beta_i^2 T_i^2$. Where the scientist's utility is $U_i(e_i) / U_i^*[w_i(e_i) - c_i(e_i)]$, the scientist's expected utility maximization problem is

$$\text{Max}_{e_i} E[U_i(e_i)] = \mu_i + \beta_i e_i - .5k_i e_i^2 - .5N_i \beta_i^2 T_i^2$$

for which first-order conditions imply the optimal effort choice, $e_i^* = \beta_i/k_i$.⁴

With one scientist, the optimal compensation scheme for the administrator is obtained by choosing μ_i and β_i to maximize the administrator's expected R&D payoff net of scientist's compensation subject to (i) the scientist allocating effort to maximize his expected utility and (ii) the resulting certainty-equivalent utility being at least as large as the scientist's certainty-equivalent reservation utility μ_i ,

$$(4) \quad \text{Max}_{\mu_i, \beta_i} E[e_i^* - w_i(e_i^*)] = e_i^* - \mu_i - \beta_i e_i^* \quad \text{s.t.} \quad E[U_i(e_i)] \geq \mu_i.$$

Note that conditioning the administrator's problem insures that the scientist will be offered a compensation package that he will accept. In our model, it is unproductive for the administrator to offer a compensation scheme that the scientist will reject because the administrator's expected payoff is zero when the scientist rejects his compensation package, i.e., $e = 0$. Kuhn-Tucker conditions (or direct examination) reveal a boundary solution, $E[U_i(e_i)] = \mu_i$, implying

$$(5) \quad \mu_i^* = \mu_i - .5(\beta_i^*)^2/k_i + .5N_i(\beta_i^*)^2 T_i^2.$$

Substituting (5) into (4) and maximizing with respect to β_i , or substituting (5) into the corresponding first-order condition for β_i , reveals the optimal scientist performance incentive,

$$(6) \quad \beta_i^* = \frac{1}{1 + N_i k_i T_i^2},$$

which, when substituted into (5), gives the optimal guaranteed payment,

$$w_i^* = \mu_i + \frac{N_i k_i T_i^2}{2k_i(1 + N_i k_i T_i^2)}.$$

With this optimal pay scheme, some notable results follow: First, the administrator compensates the scientist for effort and provides partial insurance against income risk from *ex ante* income uncertainty. With asymmetric information, the administrator does not provide full insurance because it would create a moral hazard problem for the administrator — the scientist would be fully insured against income risk and, thus, tend to shirk on effort.

Second, the guaranteed component of pay is positively related to the scientist's reservation utility μ_i , but the reservation utility has no impact on the incentive component of pay.

Third, as the riskiness of the research process increases, i.e., T_i^2 increases, the importance of the incentive component of pay relative to the guaranteed component decreases. The optimal pay guarantee is increasing (decreasing) in riskiness of the research process if $N_i k_i T_i^2 < (>) 3$. Thus, high risk, high risk aversion and/or high opportunity cost of time is sufficient to cause the guaranteed payment to increase in research risk. If research is infinitely risky ($T_i^2 \rightarrow \infty$), then $w_i^* = \mu_i$, and the optimal pay scheme is a guaranteed or fixed wage equal to the certainty-equivalent reservation utility (and $w_i^* = \mu_i$).

Fourth, when scientists differ in their reservation utility, degree of risk aversion, opportunity cost of effort, or riskiness of research output, the *optimal pay scheme differs across scientist*. The incentive-performance factor is higher for a scientist with less risk aversion, lower opportunity cost of effort, and lower scientist-specific research risk. The guaranteed component of the wage is higher for scientists who have a larger reservation utility (e.g., higher salary

offers elsewhere). The guaranteed component is also higher (lower) for a scientist with higher risk aversion if $N_i k_i T_i^2 < (>) 3$, and for a scientist with higher opportunity cost of effort if $N_i k_i T_i^2 < (>) 1.78$.

To examine these implications further, note that the expected R&D payoff for the research administrator after paying wages is

$$(7) \quad A_1 = (1 - \beta_i) e_i^c + \beta_i \left(\frac{1}{2k_i(1 - N_i k_i T_i^2)} \right) \mu_i,$$

and the expected wage of the scientist is

$$(8) \quad E(w_i) = \beta_i \left(\frac{1}{2k_i(1 - N_i k_i T_i^2)} \right) \mu_i.$$

These expressions reveal, not surprisingly, that a research administrator is better off contracting with a scientist that has low research risk, low risk aversion, and low opportunity cost of effort. Also, the scientist who has these characteristics fares better in terms of expected compensation.

Perhaps, the result that scientists with low opportunity cost and low risk earn greater compensation is surprising, but it is explained by the fact that more is traded away for purposes of risk avoidance by those with high opportunity cost and high risk aversion. Among the pool of talent represented by scientists, at least two of these three attributes (research risk, risk aversion, and opportunity cost) are likely negatively correlated, which adds to the research administrator's dilemma of choosing scientists. The implications for research institutions where changes in employment are infrequent (research institutions with permanent employees and universities with tenure systems) is that hiring decisions are crucial and potentially the most crucial element of successful and efficient R&D administration.

In this model, an increase in *ex ante* R&D payoff uncertainty, say due to an increase in the variance of the common shock F_{*}^2 , causes the scientist to allocate less effort to the research project which reduces the expected quality of research and the expected R&D payoff. Because of asymmetric information regarding effort and incomplete insurance against the scientist's income risk, the scientist's expected compensation is also reduced. Furthermore, the expected R&D payoff net of scientist's compensation is reduced. Thus, in this model where an optimal compensation policy is in place and the research administrator employs only one scientist per research project (i.e., there are no duplicate projects), it is never optimal for the administrator to take actions that will increase *ex ante* uncertainty for scientists unless they lead to counter veiling effects on research quality.

Some Implications for Funding Mechanisms

The attributes of different funding mechanisms, e.g., block grants, "outside" peer review competitive grants, are different in ways that affect effort and research quality. One research policy change where the scientist could perceive increased risk is where formula funding is replaced by competitive grant funding. For example, this change might increase the risk that a scientist will receive adequate funding to carry out or complete planned research. An increase in perceived risk would lead a scientist to allocate less effort to research, which in turn lowers expected quality and expected net R&D payoff from research. Thus, any switch from formula funding to competitive grant funding should be verified to have a sufficiently positive effect on project quality, for example by weeding out frivolous projects or channeling funds to higher quality scientists (accounting for imperfect correlation between quality of project proposals and ultimate research discovery quality), to offset the effect of increased risk perceived by scientists.

Furthermore, based on the summary of evidence presented by Knetsch (1999), the additional compensation required by scientists to bear this added risk may be much larger than research administrators' anticipate.

Although peer-reviewed competitive grant programs have been growing in popularity in Western developed countries, they also have important imperfections and deficiencies as a research contract. The problems are associated with *ex ante* uncertainty of the research production process and asymmetric information on scientists' effort and ability. For example, a research proposal has little direct value in the R&D payoff of a project, but a peer-reviewed grant system places the quality incentive on the research proposal rather than the actual discovery. The research output is observed only after the award is given and its quality is imperfectly correlated with the proposal quality.

Additional problems arise from the heavy externalities that extramural competitive grants programs impose on scientists and their institutions. The externalities are because of a system in which the external funding agencies do not explicitly finance all of scientists' time. If scientists receive no compensation for proposal writing or are compensated only for successful proposals, the incentive is to write proposals for work that has already been completed or to write proposals that appear attractive but commit little. The resources required for unsuccessful proposals must be covered by the scientists' institutions possibly at high opportunity costs in terms of teaching time or reduced research output from other research projects. The proposal evaluation and ranking process also consume scientists' time that is not compensated by granting agencies.

Finally, because of their small numbers, the standards of reviewers and review panels are more narrow, conservative, and/or possibly short-sighted than the broad scientific community on acceptable research methods and potentially attainable discoveries. Thus, the “peer panels” tend to impose homogeneity of approaches (which reduces the diversity of sampling) or to require preliminary research evidence (which retards the research process). A socially desirable national research funding mechanism for basic and pretechnology science should not unload the riskiness of scientific discovery onto institutions or individuals that have high risk premiums. Many of these issues are addressed in a recent General Accounting Office report (U.S. GAO). These are problems that could potentially be mitigated in the federal peer-reviewed competitive grant programs.

With the switch from block and institution grants for agricultural research toward competitive grants, given the current structure of competitive grants, scientists are being expected to bear a much larger share of the production risk. Because scientists are more risk adverse than research administrators, this represents socially inefficient risk bearing. Scientists can reasonably be expected to be compensated well for bearing this added risk, otherwise their research effort and quality of research will be reduced significantly. It seems unlikely that this is the outcome that was anticipated when the recent trend toward competitive grant funding of agricultural research was initiated.

Concluding Observations

The twentieth century has been one of amazing science-based technological progress. Both public and private financing have been important for paying for scientists’ efforts. The organization of research, including its incentives seem important to the direction of efforts of

scientists, the quality of discoveries, and the composition and impacts of discoveries on agricultural productivity and on social welfare. Based on earlier considerations presented in the paper, some implications for the organization of agricultural research in the 21st century are presented.

The national agricultural R&D systems of “large countries” that have developed as a system of shared public and private finance and performance of agricultural research and the public component is decentralized between the nation and state/provincial governments, e.g., the United States and Germany, are best positioned for meeting the R&D needs of their residents in the 21st century. These systems are better positioned for financing and conducting agricultural research to meet the changing demand for local or impure public goods than the national financed, administered, and conducted systems, e.g., France. The decentralized systems are large enough to obtain many of the benefits from basic or pretechnology research. Small countries must strive to improve their access to new technological innovations by forming new political alliances with other countries, being open to international technology transfers, and to imports of technically enhanced goods directly.

New political jurisdictions will be formed for the purpose of financing agricultural research producing impure public goods benefitting primarily the jurisdiction. This will become an important new funding source for public research institutions. These jurisdictions will include new alliances across countries and subregions within large countries. Small countries will look actively for potential alliances with other, especially larger countries, that they can join. They are too small to capture significant benefits from pretechnology and general science research supporting agriculture. Furthermore, they will increasingly see that it is to their long term

advantage to open markets so that they can benefit from the technical advances made in other countries. Within large countries, a mosaic of overlapping political jurisdictions may develop; they have worked well for the provision of many other local public goods and services, e.g., education, water control districts.

Intellectual property rights will be further strengthened to increase the share of total agricultural research, e.g., in biotechnology and new information systems, that is financed and conducted in the private sector. Drawing upon the information revealed in the recently published patent rights index for western developed countries, the potential exists for further strengthening the patent rights. This will make it possible for the private sector to provide more of its own research needs, and we believe that this is the best direction for the private sector to channel resources for research.

Private sector financing of public agricultural research will not grow in importance as a funding source for public institutions in western developed countries. During the 21st century, it will become clear that joint public-private sector financing of joint-ventures research venture may look like good opportunities, but they actually come at high social cost due to crowding out other socially preferred projects. The private interests of companies and commodity groups are seldom well aligned with the social good or public interest and few companies and clubs are willing to make unrestricted research grants to public research institutions or scientists as Revlon has supported cancer research over the past decade at UCLA Medical School. This creates a major conflict with the interests of taxpayers that provide a majority of the support of most public agricultural research institutions. Furthermore, because we see no evidence that public agricultural research funds are allocated so as to equalize expected marginal returns, joint

public-private ventures come at a high opportunity cost when they redirect public funds to areas that have a lower social rates of return, or crowd out other socially worthwhile projects.

As the stock of knowledge continue to grow and intellectual property rights to scientific discoveries are strengthened, the division of labor between research undertaken by the public and private sector will continue to shift. The private sector will find it profitable to undertake an increasing share of the applied research. The public sector should and will allocate an increasing share of its research efforts to discoveries in basic and pretechnology sciences. Some areas of applied research, however, remain privately unprofitable but socially worthwhile, e.g., research on environmental and natural resource quality, food safety and human nutrition, agricultural policy, and genetic improvement of minor crops. Thus, there continues to be a need for selective applied research by the public sector in socially worthwhile areas.

Major changes are expected during the 21st century in the management of agricultural research, the philosophy of funding institutions, and mechanisms for distributing funds. Scientists employed by research institutions will increasingly receive incentive compensation based on the quality of their research or value of the research payoff. Administrators will increasingly implement a partial incentive contract with scientists that involves both an optimal compensation guarantee and an optimal performance incentive. The performance incentive should be defined by the characteristics that matter in valuing the R&D payoff to the employing institution. More basically, what matters in valuing the R&D payoff will most likely be rooted in the values of the political jurisdiction or clientele financing the institution (or research).

Quality-based incentive contracting will become a relative popular mechanism for allocation funds from newly established political jurisdictions that finance research to research

performing institutions and scientists. Principal-agent theory and incentive contracting for research implies that optimal contracts have a quality-based (and not a cost-based) incentive. Contracts for research where quality of output is of upmost importance should not include cost incentives. Given that scientists' effort is not contractible and output is uncertain, an incentive to cut cost unduly cuts scientists' effort and quality of the output and the value of the research payoff. Furthermore, contracts will be increasingly defined in terms of broad performance attributes that reflect the value of the research payoffs to the funding institutions or financing jurisdiction rather than specifications of a particular innovation. This added breadth can be expected to reduce riskiness of projects to scientists and induce increased research effort.

Traditionally structured peer-review competitive granting systems will lose their glamor during the 21st century as the imperfections and inefficiencies in this type of research contract become more widely known. Although peer-reviewed competitive grant programs are popular with the U.S. National Science Foundation and National Institutes of Health and research financing institutions elsewhere, they have important imperfections and deficiencies as a research contract. The problems are associated with *ex ante* uncertainty of the research production process and asymmetric information on scientists' effort and ability. The research output is observed only after the award is given and its quality is imperfectly correlated with the proposal quality. Additional problems arise from the heavy externalities that national competitive grants programs impose on scientists and their institutions when they do not pay the full cost of research. The externalities arise because the national funding agencies do not explicitly finance all of scientists' time and effort for research. The resources required for unsuccessful proposals must be covered by the scientists' institutions possibly at high opportunity costs in terms of

teaching time, reduced research output from other research funds or unpaid time. The proposal evaluation and ranking process also consume scientists' time that is not compensated by external granting agencies.

The purpose of research proposals will be re-evaluated, and the proposal process will be modified. Short research proposals (e.g., a few pages in length) covering reasonably long periods of time (e.g., 3 - 5 years) serve sufficiently to permit administrators to monitor, review, and manage — if the more crucial steps are taken to implement optimal incentives based on attributes of value to the institution. Research proposals should state the objectives sufficiently to allow the administrator to verify that anticipated payoffs fit the criteria that are used in valuing the R&D payoff of the institution. Under the new management of agricultural research, scientists' effort and time for reviewing and evaluating will be allocated exclusively to assessing the quality of research output, e.g., reviewing manuscripts for publication and evaluating research payoffs, and not to research proposals.

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Table 1. Expenditures on Public Agricultural Research and Rate of Growth (constant 1993 ppp): Western Developed Countries, 1971, 1981, 1993

Countries/Region	Level (\$ mil)			Rate of growth (%)	
	1971	1981	1993	1971-81	1981-93
Western Europe					
Austria	19.7	23.0	27.5	1.55	1.49
Belgium	31.4	47.2	36.2	4.08	-2.21
Denmark	35.2	38.3	59.6	0.84	3.69
Finland	23.2	39.1	64.2	5.22	4.13
France	298.0	410.0	503.5	3.19	1.71
Germany ¹	308.6	299.8	332.8	-0.29	0.87
Greece	23.7	49.0	31.5	7.26	-3.68
Ireland	29.7	33.9	27.9	1.32	-1.62
Italy	68.3	188.2	360.6	10.14	5.42
Netherlands	134.7	202.1	226.7	4.06	0.96
Norway	32.8	58.0	105.3	5.70	4.97
Portugal	28.3	29.4	59.4	0.38	5.86
Spain	51.0	98.6	214.2	6.59	6.47
Sweden	57.7	81.1	138.3	3.40	4.45
Swiss	34.4	36.6	50.2	0.62	2.63
United Kingdom	274.5	371.0	370.8	3.01	-0.00
Subtotal	1,451.2	2,005.3	2,608.7	3.23	2.19
North America					
Canada	354.7	452.3	466.4	2.43	0.26
United States	1,235.6	1,620.4	2,054.3	2.71	1.98
Subtotal	1,590.3	2,072.7	2,520.7	2.65	1.63
Total 18 countries	3,041.5	4,078.0	5,129.4	2.93	1.91

¹Only for (West) Germany

Source: Huffman and Just 1999b.

Endnotes

1. The new terminator gene recently developed jointly by USDA-ARS and Delta and Pine Land Company, and now owned by Monsanto, could change the economics of bin-run seed because it disrupts the ability of a seed to reproduce itself. This could increase the expected private return to wheat varietal development, which has been an area that the private sector had largely dropped.
2. This is an example of the sometimes suggested linear and uni-directional relationship from advances in science to advances in technology. Although this may be a good representation for some of the advances in biotechnology, it does not hold generally. I return to this issue later in the paper.
3. The risk neutral preference for administrators can be justified by thinking of them as managing a large portfolio of projects. The assumption of risk neutrality can be modified but at significant cost in additional complexity of the presentation but not change the basic conceptual conclusions, provided the scientists are more risk averse than the administrators.
4. We chose for our agent's (scientist's) utility function, the one that has attracted the most attention in the principal-agent literature.