ESSAYS ON AGRICULTURAL RESEARCH INVESTMENT

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ESSAYS ON AGRICULTURAL RESEARCH INVESTMENT

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ABSTRACT

This dissertation addresses three questions regarding investments in agricultural research and development (R&D): why, how much, and why not more? The economics literature sees profit as the principal incentive to investing in agricultural R&D. However, this profit motive is constrained by many factors, which makes it quite complicated to detect a direct link between R&D investment and impact. Conceptually, this link could be captured by an *R&D opportunity curve*, which links the investment in a portfolio of R&D projects with (expected) rates of return to individual R&D projects.

While such a link between R&D investment and impact is usually assumed to be implicit, this dissertation attempts to make this link explicit and estimate the shape and position of the agricultural R&D opportunity curve for different sets of countries (developed versus developing) and for different time periods (early 1960s versus early 1980s). This is done by bringing together information on investment levels in agricultural R&D (the *how much* question) with information obtained from a large number of different studies on rates of return to agricultural R&D.

The question of "How much is invested in agricultural R&D?" is addressed in a series of four chapters that have been published previously as articles. They show that in both developed and developing countries, the *growth* in investment in public agricultural R&D has slowed down steadily during the past 30 years. Nevertheless, between 1961 and 1991 public agricultural research investments in developed countries increased in real terms (i.e., net of inflation) by a factor of 2.7 and in developing countries, by a factor of 5.3. Despite this growth, however, there has not been a notable decline in the average rate of return to investments in agricultural R&D. This finding can only be reconciled by assuming that the R&D opportunity curve is not constant but shifts (and in this case positively) through time.

The estimated shape and position of the R&D opportunity curves provides a good starting point for assessing the widely shared perception that there is underinvestment in agricultural R&D. An important finding of this dissertation is that in relative terms, developing countries not only have a considerably more limited portfolio of profitable agricultural R&D projects to choose from than developed countries, but their capacity to select, finance, and implement those opportunities is also substantially weaker. Hence, underinvestment in agricultural R&D tends to be more critical in developing than in developed countries.

ACKNOWLEDGEMENTS

I have wanted to write this dissertation for more than ten years, but finding the (right) time turned out to be difficult in combination with a full-time job. In the meantime, however, the material to draw upon accumulated steadily. By basing my dissertation on published articles, the idea was that it could be done quite quickly. Only a solid theoretical introduction and a concluding chapter that would pull the various articles together were needed. The truth is, however, that I got somewhat carried away. By selecting underinvestment in agricultural R&D as the unifying theme for my conclusions, this section (Part III) expanded substantially. The end result is something of a hybrid between a traditional dissertation and one that is based on published articles.

The four articles included in this dissertation (chapters 3–6) were written with Julian Alston, Jock Anderson, Nienke Beintema, Barbara Craig, Phil Pardey, and Hans Rutten. I thank them sincerely for their collaboration and their contribution to this dissertation. Thanks also go to the publishers of *World Development* and *Agricultural Economics*, who allowed me to reprint the four articles.

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Last, but not least, I want to thank Cees and my family and friends for understanding and accepting that I had to spend less time with them than I should have during the past few years.

Han Roseboom
February 2002

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ABBREVIATIONS

AgGDP	Agricultural Gross Domestic Product
ARI	Agricultural Research Intensity
ASTI	Agricultural Science and Technology Indicators
CGIAR or CG	Consultative Group on International Agricultural Research
DLO	Agricultural Research Department
DST	Directorate of Science and Technology
DSKT	Directorate of Science and Knowledge Transfer
ERR	Expected Rate of Return
FTE	Full-Time Equivalent
FVS	Faculty of Veterinary Sciences
GDP	Gross Domestic Product
GM	Genetically Modified
IFPRI	International Food Policy Research Institute
ISNAR	International Service for National Agricultural Research
KCW	Knowledge Center Wageningen
MOA	Ministry of Agriculture
NARO	National Agricultural Research Organization
NARS	National Agricultural Research System
NRLO	National Council of Agricultural Research
NSI	National System of Innovation
OECD	Organization for Economic Cooperation and Development
PPP	Purchasing Power Parity
R&D	Research and Development
ROR	Rate of Return
S&T	Science and Technology
TFP	Total Factor Productivity
TNO	Netherlands Organization for Applied Research
WAU	Wageningen Agricultural University

> "For man by the Fall fell at the same time from his state of innocence and from his dominion over created things. Both these losses can even in this life be partially repaired; the former by religion and faith and the latter by arts and sciences."
>
> *Sir Francis Bacon (1561–1626)*[1]

1. Introduction

Innovation is a step into the unknown, into the unpredictable. In contrast to production, innovation has long been considered a unique activity or event that does not repeat itself or which follows a certain predictable pattern. Hence, it could not be captured in mathematical equations or economic models. So, while acknowledging its importance, economists have long treated innovation as an exogenous factor, as manna from heaven. Why and how it occurred remained unknown and unexplained, or in Rosenberg's words, "economists have long treated technological phenomena as events transpiring inside a black box" (Rosenberg 1982, p.1).

Nevertheless, as reflected by the steep increase in innovations during the past century, innovation itself has become a matter of routine activity – governments and private companies nowadays invest large sums in research and development (R&D) and related innovative activities. With the rise of innovation as a routine activity, it has become possible to start detecting the economic processes and forces that advance it. And so, since the 1960s, economists have made considerable progress in opening up the "innovation" black box, although a great deal remains unexplored. This dissertation is a part of this tradition and attempts to make a contribution to a better understanding of the economic processes that shape agricultural innovation around the world. In addition, given massive rural poverty and food insecurity in large parts of the world, it is critical to understand whether and how agricultural innovation can make a difference. Merely investing more in agricultural R&D is too simple an answer – there is a limit to what agricultural R&D can do.

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[1] Sir Francis Bacon's work marked a turning point in Western thinking about the contribution of science to economic welfare. Before Bacon, the generally accepted viewpoint was that attempts to improve conditions on earth were pointless because these conditions were the result of Adam and Eve's original sin in Paradise. Salvation was only possible in the afterlife. In the *New Atlantis,* Bacon called this way of thinking into question and, instead, suggested that organized and effectively applied science could undo the Biblical Fall (at least partially) and improve the condition of mankind (Martin and Nightingale 2000).

This dissertation focuses on the most visible part of innovation in the economy, namely that of R&D undertaken by research organizations, universities, and the R&D branches of commercial enterprises. These specialized agencies by no means capture the whole innovation process, nor are they the only source of innovation. Farmers, for example, have through daily trial and error improved their farming practices for thousands of years and did not stop doing that after the introduction of formal agricultural research around the turn of the last century. On the contrary, today's farmers are testing and adapting new farming practices more intensively than ever before. Nevertheless, when trying to make comparisons across countries and over time, investments in agricultural R&D can be considered a reasonable proxy for the relative intensity of innovation taking place in agriculture.

This dissertation addresses the following three sets of questions:

(1) Why do we invest in agricultural R&D? What, according to economic theory, drives investment in agricultural R&D, and what are the constraints?
(2) How much do we invest in agricultural R&D? How have investment patterns changed through time? And, how do regions and countries at different stages of economic development differ in terms of the intensity of their agricultural R&D?
(3) Why, despite an impressive track record, have we not invested more in agricultural R&D? How much more could we have invested? And, are optimal levels of investment in agricultural R&D the same for all countries at all times?

Part I of this dissertation (chapter 2) deals with the first set of questions. It describes and discusses the basic concepts and ideas that have shaped the theoretical framework of this dissertation and focuses on the question of what drives the innovation process and what holds it back. Chapter 2 starts with a summary and discussion of the neoclassical perspective on technical change (induced innovation and endogenous growth), followed by alternative views from other economic and non-economic approaches.

Part II of this dissertation (chapters 3-6) deals with the second set of questions, which are more of an empirical nature and which are addressed in a series of four previously published articles. They report on the ongoing surveys undertaken by the Agricultural Science and Technology Indicators (ASTI) project – a project that is implemented jointly by the International Food Policy Research Institute (IFPRI) and the International Service for National Agricultural Research (ISNAR). Chapters 3 and 4 report on developments in the global capacity for agricultural R&D and document the differences between regions and countries at different stages of economic development.

Chapter 5 focuses specifically on the agricultural R&D capacity of sub-Saharan Africa. It reports how African countries in the aftermath of their independence have struggled with building their own agricultural R&D capacity. Despite some good progress in capacity building during the 1970s and 1980s, in more recent years, the thin demonstrable pay-off of agricultural R&D at the macro level and the deplorable state of most government finances has pushed many agricultural research organizations in Africa into a negative downward spiral of funding cuts and poor performance.

Chapter 6 is a case study on the financing of agricultural R&D in the Netherlands – one of the most productive agricultural producers in the world. It gives a detailed overview of the changes that have taken place in the financing of agricultural R&D between 1970 and 1995, as well as the underlying changes in the institutional setting and policies.

Part III deals with the third set of questions. The impact of agricultural R&D, in developing as well as developed countries, has generally been quite impressive as documented by numerous rate-of-return studies (Alston *et al*. 2000; Evenson 2001). Hence, most leading agricultural economists argue that there is substantial underinvestment in public agricultural R&D (Ruttan 1980; Pinstrup-Andersen 2001). However, there are two apparent weaknesses in this underinvestment argument: (1) it is not the rate of return on the average R&D project that matters, but the rate of return on the marginal R&D project, and (2) the evidence on rates of return itself may possibly be biased.

Since rates of return play such an important role in determining underinvestment in agricultural R&D, chapter 7 reviews the most commonly used rate-of-return methodologies and identifies their limitations and possible biases. Chapter 8 structures the underinvestment hypothesis more explicitly by introducing a simple model that captures the underinvestment argument in strict economic terms. It provides the basis for a new interpretation of rate-of-return results and, in particular, their distribution. Rates of return on agricultural R&D projects collected by Alston *et al.* (2000) provide the empirical underpinning of the model. Once the gap in agricultural R&D investment is defined more precisely, it is possible to explore more effectively how the gap can be explained. Some of the possible explanations are methodological, while others point to issues such as incomplete information, poor priority setting, tax burden, budget rigidity, and political bias in the selection of R&D projects. The latter explanation is taken a step further, using the model to test the effect of introducing a positive bias towards agricultural R&D projects that specifically target poor farmers.

Chapter 9 draws the principal conclusions and highlights the importance of both *human* and *social* capital in agricultural innovation. It argues that social capital plays a major role in creating the right environment in which R&D investment can prosper and in which the promise of a better future can be realized. Economic underdevelopment not only means that there is a smaller portfolio of profitable R&D projects to choose from, but the ability to identify and exploit these opportunities is also more limited. In other words, the R&D underinvestment gap is greater for developing countries than for developed countries.

Part I: A Theoretical Perspective on Innovation

For a long time, economists have treated technology as an external factor that comes as manna from heaven. Solow (1957), in his classic article on "Technical Change and the Aggregate Production Function," showed that a great deal of the growth in output went unexplained by measuring just the growth in (capital and labor) input use. He labeled this unexplained residual as "technical change," covering both *technological* and (although less explicitly) *institutional* innovations. Until that time, economists had emphasized the importance of capital accumulation in explaining economic growth, but now they had stumbled upon a factor that seemed to be far more important than the increased use of capital.[1]

Solow's (1957) article opened up a major research agenda for the economics profession on how to integrate the processes of technological and institutional innovation into economic theory and, hence, reduce the unexplained residual. There is no question that considerable progress has been made during the past 40 years, but with few exceptions, economists have focused on technological rather than institutional innovation as the ultimate mainspring of growth. However, as North (1990) has argued:

> . . . the growth of productivity that has occurred since the rise of the West is as much attributable to the development of institutions that have allowed us to reduce *transaction costs*, and thereby to exploit more fully the potential gains from exchange, as it is to our increased control over nature.

Olson (1996) takes an even more radical position and argues that institutions are a more critical factor in explaining differences in income per capita than access to technology, capital, or natural resources, or differences in the quality of marketable human capital. However, because it is difficult to measure transaction costs, economists have tended to assume institutions as given and shy away from institutional innovation (North and Wallis 1994).

The chapter that follows summarizes the ideas and concepts about technological and institutional innovation that form the basis for this dissertation.

---

[1] By modeling technology as embodied in machinery and plants, Solow (1962) tried to provide a partial explanation that has become known as the "vintage capital theory."

2. Innovation theories

This chapter describes and discusses the ideas and concepts that have structured or influenced my thinking about technological innovation and which form the basis for this dissertation. The unifying theme of this theoretical overview is to understand why we invest in (agricultural) R&D. What are the economic incentives to do so? And what are the constraints that research investors may meet on their way?

To understand the neoclassical perspective on innovation, section 2.1 discusses how economists have modeled technical change as a shift in the *production function*. A basic assumption made in this dissertation – and by most economists – is that investments in (agricultural) R&D can enhance and speed up this shift. The *induced innovation theory* tries to make this link explicit, at least theoretically, and provides a framework for tackling questions concerning the rate and direction of technical change (section 2.2).

The *endogenous growth theory* (section 2.3) also builds on the production function. While rather abstract in nature, the theory has been highly influential in shaping recent thinking about how knowledge and the creation of new knowledge and technology may explain differences in economic prosperity.

The production function, the induced innovation theory, and the endogenous growth theory are all rooted in the neoclassical tradition. Section 2.4 discusses three of the more prominent extensions or critiques of the standard neoclassical tradition coming from *game theory, institutional economics*, and *evolutionary economics*. Of these three approaches, evolutionary economics has distanced itself most significantly from the neoclassic tradition.

The standard neoclassical approach remains very abstract about the innovation process itself and treats technology as a black box, which is not very satisfactory, to say the least. Section 2.5 provides a selective summary of ideas and concepts derived from the science and technology (S&T) literature that shed more light on the innovation process itself. Many of these ideas and concepts come from historians, political and social scientists, as well as economists who are prepared to operate outside the neoclassical straightjacket. Their ideas provide important clues on how innovation processes work and could be enhanced. Section 2.6 summarizes the principal conclusions.

2.1 *The production function and technical change*

The production function constitutes the centerpiece in the neoclassical perspective on technological innovation. It is a device by which economists try to capture complex input-output relationships and distill from them information on how such relationships repeat themselves over and over again. First proposed by Wicksteed in 1894, a production function summarizes the conversion process of various inputs X into a final output Y as follows:

$$Y = f(X_1, X_2, \ldots, X_m) \qquad [2.1]$$

Important assumptions usually made regarding the production function are constant returns to scale (when all inputs increase by x%, output will also increase by x%) and diminishing marginal productivity (when one input increases and the rest are kept constant, additional output will gradually decline). At the macro level, inputs are usually reduced to the standard production factors – labor (L) and capital (K) – so that the production function can be written as:

$$Y = f(L, K) \qquad [2.2]$$

The production function provides economists with a powerful tool to empirically investigate production processes. Initially, a *fixed* production function was assumed. Hicks (1932) and Schumpeter (1934), however, introduced the idea that the *production function* is not necessarily fixed but may shift over time so that the same inputs produce more output (or the same output is produced with fewer inputs). They attributed such a shift to *technical change*. It was not until the 1950s, however, that this idea became part of mainstream neoclassical economics through work on total factor productivity by economists like Abramowitz (1956), Fabricant (1959), Kendrick (1961), Mills (1952), Schmookler (1952), and Solow (1957).

In his seminal article on "Technical Change and the Aggregate Production Function," Solow (1957) calculated that gross output per man-hour doubled over the period 1909-1949 in the USA, with 1/8 of this increase attributable to increased use of capital and 7/8 to technical change. Until that time, economists had emphasized the importance of capital accumulation in explaining productivity growth, but now they had identified a factor that seemed to be far more important than the increased use of capital. The real – measurable – importance of technical change in the economy became clear for the first time.[2] It forced economists to start thinking more seriously about the factors that shape technical change.

By dividing both sides of equation 2.2 by Y and assuming constant returns to scale, the production function takes the form of a unit isoquant:

$$Y^* = f(K/Y, L/Y) \qquad [2.3]$$

[2] How to distinguish a shift along the production function from a shift of the production function itself has been a major source of debate in the literature. See Thirtle and Ruttan (1987) for an overview.

where Y^* represents a unit volume of output (e.g., a ton of wheat). In this case, technical change expresses itself as an inward movement of the production isoquant (see figure 2.1). As we will see in the next section, the induced innovation theory uses this particular representation of the production function.

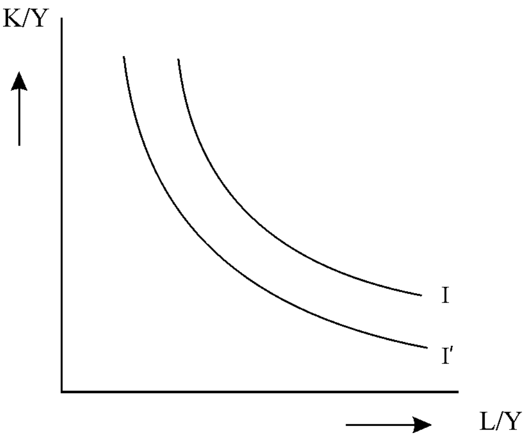

Figure 2.1: *Technical change as a shift of the production isoquant*

2.2 *The induced innovation theory*

During the 1930s, a time of massive unemployment, many economists and policymakers were worried about the impact of technical change on employment. Hicks (1932), in his *Theory of Wages,* argued that there is no inherent labor-saving bias (i.e., a reduction of labor input relative to capital input) in technological innovation. Rather, he said, rising wages could be expected to induce entrepreneurs to seek labor-saving innovations in order to offset rising labor costs. More generally, he argued that:

> A change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind – directed to economizing the use of a factor which has become relatively expensive. (Hicks 1932)

Hicks labeled this process *induced innovation*, but he did not specify the mechanism by which it would occur. It was only in the 1960s, when economists started to search for ways to explain technical change, that Hicks' induced innovation hypothesis attracted renewed attention and more complete induced innovation models were developed.[3] Ahmad (1966) made a key contribution to the induced innovation theory by introducing the concept of an *innovation possibility curve.* He defined this curve as the envelope of all potential production processes an entrepreneur might develop, given the current state of

[3] See Binswanger and Ruttan (1978) for an overview of induced innovation models developed by Ahmad (1966), Kennedy (1966), Fellner (1971), Nelson and Winter (1973), and Radner (1975).

knowledge, with *a given amount of R&D expenditure*. Each production process in the set is characterized by an isoquant with a relatively low elasticity of substitution (figure 2.2).

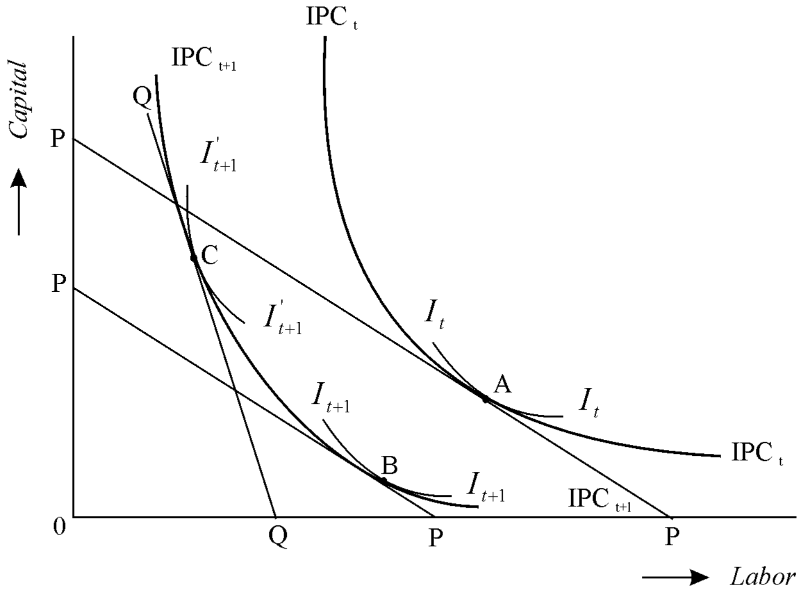

Figure 2.2 *Ahmad's induced innovation model*

An isoquant I in figure 2.2 represents the technically efficient combinations of factor inputs that produce a fixed amount of output. Constant economies of scale are assumed. The factor price ratio, represented by a line *PP*, defines the economically efficient combination among the technically efficient combinations. So the economically efficient combination in period t is point *A* on isoquant I_t, which is part of a larger *innovation possibility curve* IPC_t. The innovation possibility curve in period $t+1$ is defined by all possible production processes (represented by I_{t+1}, I'_{t+1}, etc.) that could be developed with a given research budget. It is assumed here that the IPC shifts neutrally and I_{t+1} is not dependent on I_t. If the factor price ratio remains the same, the technically and economically optimal combination in the next period would be point *B* on isoquant I_{t+1}. However, if the factor price ratio changes, as represented by line *QQ*, point *C* on isoquant I'_{t+1} would be the optimal point to choose.

Atkinson and Stiglitz (1969) challenged the idea that with technical change the whole production function shifts, or for that matter, the whole innovation possibility curve. They argued that it is more likely that improvements in production techniques would cluster (i.e., I_{t+1} depends upon I_t) around those that are already in use, rather than embracing all other theoretically available factor combinations. In this case, instead of the whole curve shifting inwards, it is more likely that the curve will develop bumps, as it were, leading to higher levels of productivity over a relatively narrow range of combinations of capital to labor that are close to the existing range of technologies in use. The implications of this refinement are that technical change may not necessarily lead to a widening choice in the range of available technologies and that any bias in technical progress is unlikely to be random. It may very well strengthen existing bias, e.g., capital-intensive technologies are more likely to lead to further improvements in such technologies.

In the induced innovation theory, two aspects of technical change stand out: its *direction* and its *rate*. Of these two, direction has received considerably more attention in the literature than rate. However, the two are closely linked because technical change is assumed to move in the direction that is most profitable, given relative factor scarcities, and hence yields the highest rate of technical change for a given R&D investment. The next two sections discuss the two dimensions of technical change in more detail.

2.2.1 *The direction of technical change*

Perhaps the most successful application of the induced innovation theory has been the one made by Hayami and Ruttan (1971, 1985) to agriculture.[4] They introduced their own version of the innovation possibility curve, namely that of the *metaproduction function,* which they describe as follows (Hayami and Ruttan 1985, p.134–135).[5]

> The metaproduction function can be regarded as the envelope of commonly conceived neoclassical production functions. In the *short run*, in which sub-stitution among inputs is circumscribed by the rigidity of existing capital and equipment, production relationships can best be described by an activity with relatively fixed factor-factor and factor-product ratios. In the *long run*, in which constraints exercised by existing capital disappear and are replaced by the fund of available technical knowledge, including all alternative feasible factor-factor and factor-product combinations, production relationships can be adequately described by the neoclassical production function. In the *secular period* of production, in which the constraints given by the available fund of technical knowledge are further relaxed to admit all potentially discoverable possibilities, production relationships can be described by a metaproduction function which describes all conceivable technical alternatives that might be discovered.

The Hayami-Ruttan version of the induced innovation theory centers on the two primary production factors in agriculture: land and labor. The paths of agricultural innovation in Japan and the USA since the late 19th century provide a very convincing illustration of how differences in relative factor scarcities induce technological innovation in different directions. Labor-scarce US agriculture focused predominantly on agricultural mechaniz-ation (i.e., labor-saving technologies), while land-scarce Japanese agriculture emphasized biological and chemical innovations (i.e., land-saving technologies).

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[4] See also Binswanger and Ruttan (1978), Thirtle and Ruttan (1987), and Ruttan (2000).

[5] Hayami and Ruttan see their metaproduction function merely as an operational definition of the innovation possibility curve in the sense that it can be measured empirically from observable data (Hayami and Ruttan 1985).

Figure 2.3, adapted from Binswanger (1978b), illustrates how, at the level of the firm (or farm), technical change can lead to changes in factor proportions as argued by Hicks. Technical change is defined here as the proportional decrease in unit costs of production achievable by an innovation when both the old and the new techniques operate at their optimal input combination and when factor prices are held constant.

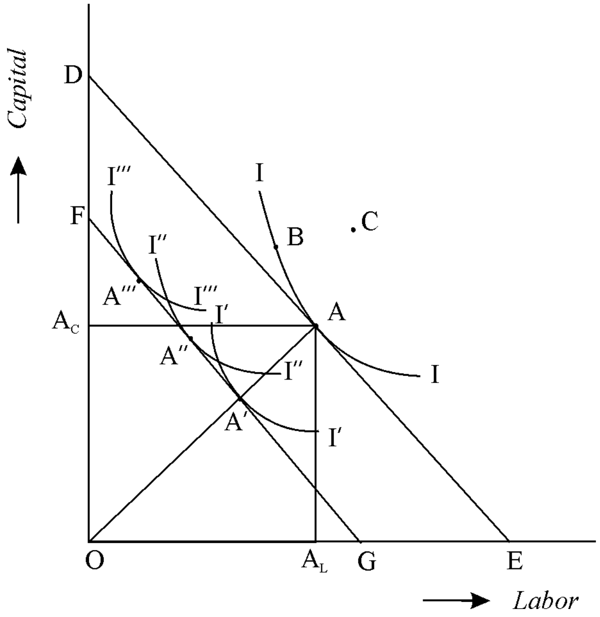

Figure 2.3: *Rates and biases of technical change*

Let *I* and *I′* be, respectively, the unit isoquants before and after the technical change. The slope of the line *DE* is the ratio of the factor prices – labor and capital (or land in the case of agriculture). A firm (or farm) that produces output at point *C* is technically inefficient. If it moves from *C* to *B,* it becomes technically efficient. However, at *B* the firm still makes an allocation error because moving to point A, which is the economically efficient point, can reduce costs further.

Any inward movement of the isoquant reflects a technical change. When the isoquant moves from *I* to *I′*, costs (not including the costs of research and adoption) are reduced by the amount of *GE*, in terms of labor, or *FD*, in terms of capital. The relative savings in resources due to technical change is *GE/OE* and *FD/OD*. Note that the three new technologies – *I′*, *I″*, and *I‴* – are identical in terms of relative resources saved. What differentiates them is the factor-saving bias of the technical change. While all factor combinations on the line *OA* are Hicks-neutral (having no change in factor proportions), all possible factor combinations in the triangle *OAD* are labor-saving (relative to the original technology, *A*) and those in the triangle *OAE* are capital-saving. All factor combinations within the quadrant $OA_l\,AA_c$ save on both factor inputs relative to *A*. The labels *labor-saving* and *capital-saving* refer to the factor input that is saved most.

So far little has been said about the level of investment in R&D required to achieve the new technology: it is either kept constant (Ahmad) or not specified (Binswanger).

2.2.2 *The rate of technical change*

The induced innovation is largely silent on the rate of technical change,[6] as it fails to specify a link between R&D investment and technical change. However, any discussion on the rate of technical change is based on the assumption that a relationship between R&D investment and technical change exists. Without some regularity between innovative input and impact, there is little for the policymaker or the company strategist to relate to. Metcalfe (1995) captures this relationship in an *innovation possibility frontier* (see figure 2.4). The innovation possibility frontier relates the reduction in unit production cost achieved in a given time period to investment in R&D.

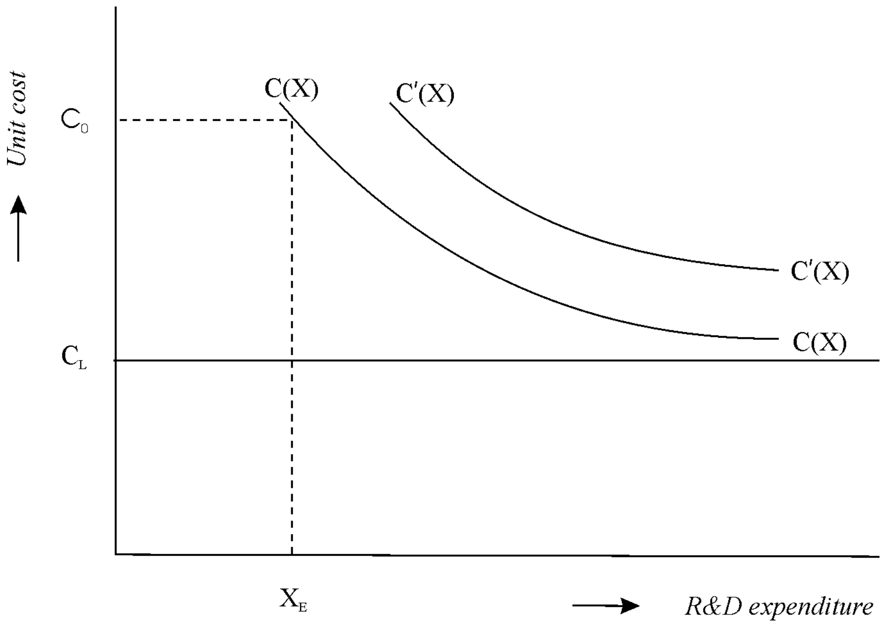

Figure 2.4: *The innovation possibility frontier*

C_0 in figure 2.4 is the current cost level and C_L is the best improvement that can be achieved given the current state of the art. X_E is the minimum research investment needed before any improvement in technology is achieved. Shortening the time period (i.e., trying to achieve the cost reductions earlier in time) shifts the innovation possibility frontier upwards.

[6] Ben-Zion and Ruttan (1978) make an attempt at determining the rate of technical change but do not get further than asserting that technical change is higher in periods of rising demand than in periods of falling demand.

An implicit assumption often made regarding the innovation possibility curve as well as the innovation possibility frontier is that increases in productivity are permanent. Without any further R&D investment, productivity will stay the same. However, and this is particularly true for biological technologies, increases in productivity may not be permanent and may erode over time as new diseases emerge. As Adusei and Norton (1990) demonstrated, a substantial part of agricultural R&D investment can be labeled as *maintenance* research, i.e., research that is needed just to keep the production function at its current position or the unit cost of production at its current level.[7] Therefore, the right way to compare R&D investment opportunities is against a scenario of what would happen if one did not invest in R&D.

Strictly within the neoclassical theory, the optimal level of R&D investment by a firm (or for that matter, by a government research agency) is determined by the point where marginal research costs equal marginal research benefits.[8] Adopting the model of the firm as an optimizing innovator developed by Nordhaus (1969) and Metcalfe (1995), five different factors that define the appropriate scale of R&D investment can be identified:

(1) The initial scale of the market and its expected growth rate: the greater both of these are, the greater the optimal amount spent on R&D. This reflects the idea that the exploitation of innovations is subject to increasing returns.
(2) The capability of the firm to appropriate R&D benefits: the better this capability is (either through market power or legal protection), the more the firm will be prepared to invest in R&D.
(3) The marginal productivity of R&D, as determined by the firm's command of the design configuration and its ability to organize and manage the innovation process. The greater the marginal productivity, the greater the optimal research spending.
(4) The cost of capital invested in the R&D program that is taken to be equal to the rate of discount in computing the present value factor: the greater this rate of discount, the smaller the optimal amount spent on R&D.
(5) The time horizon over which the firm assesses the present value of profits from innovation: the larger this is, the greater the incentive to invest in R&D.

Jointly, these factors determine the profitability of a firm investing in R&D. It may well turn out, however, that an investment in R&D is not profitable at all because, either singly or jointly, research is not productive enough, the market is too small, the discount rate too high, or the possibility of appropriating the R&D benefits too small.

A limitation of Metcalfe's model (and that of many other innovation models) is that it does not consider risk and uncertainty. The story would still hold true if the firm is assumed to be risk-neutral and if probabilities of outcomes could be calculated and all the

[7] According to Adusei and Norton (1990), the USA devotes roughly one-third of total agricultural production research to maintenance. Given the greater incidence of crop diseases in the tropics, the share of maintenance research in tropical areas is probably even higher.
[8] See Nordhaus (1969), Binswanger (1978), and Metcalfe (1995).

variables reinterpreted as mathematical expectations. Without these conditions, there is a much more complicated story to tell, in which risky prospects have to be translated into certainty equivalents via an expected utility function, or explicit attention has to be given to the variance as well as the expected values of outcomes.[9] In an expected utility framework, less will be spent on R&D the greater the risk of project "failure," the greater the loss associated with failure, the smaller the gain associated with success, and the greater the degree of risk aversion. While for many routine activities, risks can be insured, for innovation activities this is quite unlikely (and in practice, uncommon) because of the information asymmetries associated with innovation that cause moral hazards and adverse selection problems.

Major complications emerge when one tries to link the outcomes of Metcalfe's micro-economic model on the rate of technical change with more aggregated ones at industry or sector level.[10] In particular, four complicating factors stand out, namely: (a) appropriability of research benefits, (b) technology diffusion, (c) research duplication, and (d) market structure and competition. Metcalfe's model assumes that the innovating firm can prevent others from using the new process or technology. Remove this assumption and there is a far more complicated story to tell. Technology can spill over to other firms, creating (social) benefits that cannot be appropriated by the innovating firm. This leads to a major gap between private and social incentives to invest in R&D.[11]

Metcalfe's model also assumes that the diffusion of technology within and between firms is immediate. But, even within a firm, the uptake of new process technology takes time because capital goods have to be replaced and new skills learned. Also, the controlled diffusion of technology to other firms by means of patents and joint ventures is complicated and far from immediate. The uncontrolled diffusion of technology is even more complicated.[12]

In Metcalfe's model, duplication of R&D is not an issue. At the level of industry, however, this is a source of major concern, which is closely related to the issue of market structure and competition. One of the older debates in the S&T literature relates to Schumpeter's (1942) argument that a large firm operating in a concentrated market is more innovative, so there is a trade-off between perfect competition and innovative activity. While competition is considered an important positive force in innovation processes, it, at the same time, places constraints on the appropriability of R&D benefits (intellectual property rights and trade secrecy can only counterbalance this to some extent). This not only reduces the amount an individual firm will invest in R&D, but also leads to more duplication of the R&D effort. The Schumpeterian hypothesis about firm

[9] Anderson (1991) provides an overview of the role of risk and uncertainty in agricultural research. See also Freeman and Soete (1999) for a discussion of risk and uncertainty related to innovation in private industry.
[10] Binswanger (1978b) noted similar complications but focused mainly on the direction of technical change.
[11] By using trade secrecy or patents, private firms can try to stop or slow down the free spillover of technology and appropriate a larger part of the research benefits, which in turn, affects their incentive to invest in R&D.
[12] Geroski (2000) provides an excellent overview of such diffusion issues.

size, market concentration, and innovative activity has been tested extensively in the literature, but this has not yielded a final verdict on the issue (Cohen 1995). Nevertheless, two tentative conclusions seem to transpire from the literature: (a) there are no economies of scale with respect to firm size in the invention process (on the contrary, small firms seem to be more creative) and (b) a market structure that is neither fully competitive nor monopolistic creates the best incentives for innovation.

In a highly fragmented and competitive industry or sector with weak technology property rights, the private incentives to invest in R&D are also weak. Moreover, the chance of duplicating the research effort is high. This leads to a situation in which the market produces a level of innovative activity that is substantially below what a "socially managed industry" would produce and at a higher unit cost (Arrow 1962; Dasgupta and Stiglitz 1980). Agriculture is a classic example of a sector that fits this description. Government intervention may overcome this situation by (a) strengthening technology property rights, (b) facilitating joint research efforts between firms in the same industry, or (c) providing public R&D.

While Metcalfe's model of the firm as an optimizing innovator provides some important elements for understanding differences in innovation rates among firms, the model largely fails to capture the interaction between firms in a market or industry and how this may affect innovation incentives. At the other end of the spectrum, macroeconomic growth theory (see next section) completely abstracts from industries and markets and focuses on aggregate economic growth. What is missing is a consistent model concerning the rate of technical change at the sector or industry level, which links R&D input to impact. In chapter 8, an attempt will be made to fill this void.

Nevertheless, what Metcalfe's model makes explicit is that an investment in (agricultural) R&D is made on the basis of expected profitability. Despite the difficulty in directly observing the link between R&D investment and impact (an investment in infrastructure, for example, has a far clearer cause and effect), it is the profit motive that steers the allocation of resources towards R&D investment. And, it is relative factor scarcities that signal in which direction innovation has the highest payoff.

2.3 *Endogenous growth theory*

Understanding long-run economic growth is one of the more challenging theoretical issues in economics. The bottom line of the standard neoclassical economic growth models is that in the long run, the economy will grow as fast as its population – the growth rate of which is exogenous to the model. The effects of institutional and technological innovation on the rate of economic growth are seen as transient. Once they have been fully incorporated, the economic growth rate will return back to the population growth rate and to income-per-capita growth of around zero. During the past century, however, the world has experienced population growth in combination with growth in income per capita that has been unprecedented. Solow (1956, 1957) and Swan (1956) amended this inconsistency between theory and fact in the 1950s by adding a technology term to the model. As Barro and Sala-i-Martin (1995) show, the implication of this fix is that the steady-state growth rate of the economy is equal to that of the rates of population and technology growth combined. Both, however, are *exogenous* to the economic growth model – not a very satisfying solution. It was only in the 1980s that economists again paid serious attention to the inadequacy of the neoclassical economic growth theory. In particular, Romer (1986) and Lucas (1988) initiated a new boom in research on economic growth models, which replaced the exogenously driven explanations of long-term economic growth by a new type of growth model in which the key determinants of growth are *endogenous* to the model (Barro and Sala-i-Martin 1995).

What is perhaps most characteristic of these endogenous growth models is that they break out of the neoclassical straightjacket of diminishing returns across all inputs. In particular, the models emphasize increasing returns to knowledge (since using knowledge does not necessarily exclude others from using it, i.e., knowledge is considered nonrivalrous) as an important feature of long-term economic growth. This was built into the models by assuming that knowledge is a capital good with an *increasing marginal product* – an idea that was borrowed from Arrow's (1962) paper on learning by doing.[13] Initially, the accumulation of knowledge (or the learning by doing) was, itself, still exogenous to the model, but more recent versions of the endogenous growth model also try to capture the deliberate creation of knowledge through R&D by profit-maximizing agents (Romer 1990; Grossman and Helpman 1991; Aghion-Howitt 1992). A simple version of these R&D-based models of economic growth, modeled after the production function, can be summarized in the following two equations:

$$Y = K^{1-\alpha}\left(AL_Y\right)^{\alpha} \qquad [2.4]$$

and

$$\dot{A}/A = \delta L_A \qquad [2.5]$$

where Y is output, A is knowledge, and K is capital. Labor is used either to produce (L_Y) or to search for new knowledge (L_A). Equation 2.4 is a standard Cobb-Douglas production function, and equation 2.5 typifies the R&D equation in the R&D-based endogenous

[13] Four broad categories of learning and knowledge accumulation that shape up innovation processes can be identified: (1) learning as joint product with other activities involving the production and use of technology (Arrow's [1962] learning by doing), (2) learning as a result of using a product, which feeds back into product design and development (Rosenberg's [1982] learning by using), (3) learning as a result of interaction with other organizations (Lundvall's [1992] learning by interacting), and (4) learning as a result of a formal internal discovery process, typically organized around a directed R&D program. All four learning processes usually operate jointly, although their relative importance varies across firms, industries, and economies as well as over time. While each of them has its own characteristics and set of incentives, what they have in common is that knowledge resides in people. In the knowledge economy, the focus has shifted from physical to human capital.

growth models (Jones 1995). Here, the growth in knowledge ($\dot{A}/A$) is equal to the number of people attempting to discover new ideas (L_A) multiplied by the rate at which R&D generates new ideas (δ). Holding the latter constant, the model predicts that an increase in the level of resources devoted to R&D should increase the growth rate of the economy. Jones (1995) argues that this "scale-effect" prediction is grossly inconsistent with the facts: despite an eightfold increase in the R&D labor force in the five principal developed countries over the past 50 years, average growth rates have remained fairly stable.[14] Nevertheless, the great contribution of the endogenous growth pioneers is that they shifted the focus of the neoclassic economic growth theory from physical to human capital.

2.3.1 *A semi-endogenous, R&D-based growth model*

Jones (1995) proposes an alternative specification of the R&D equation in which an addition to the stock of knowledge ($\dot{A}$) depends on the number of people conducting R&D multiplied by the rate at which R&D generates new ideas:

$$\dot{A} = \delta L_A \qquad [2.6]$$

Rather than assuming that the rate at which new ideas are being discovered (δ) is constant, Jones suggests that this may be a function of the amount of accumulated knowledge in the economy and parameterizes the arrival rate ($\tilde{\delta}$) as follows:

$$\tilde{\delta} = \delta A^{\varphi} \qquad [2.7]$$

Two opposite forces determine φ. On the one hand, the amount of accumulated knowledge may contribute to the production of new knowledge today through positive spillovers – past inventions make the researchers who follow more productive. On the other hand, the more knowledge that has been accumulated, the more difficult it will be to create new knowledge (assuming that there is an end to what can be known).[15] Basically, these two opposite forces have strong parallels with Machlup's (1962) ideas about agenda-enhancing and agenda-reducing R&D. In that sense, R&D can reduce as well as replenish the pool of attainable knowledge.

A further refinement introduced by Jones is the consideration of duplication in R&D, which reduces the total number of innovations produced by L_A units of labor. Therefore, it is not L_A that belongs in the R&D equation but L_A^{λ}, $0 < \lambda \leq 1$. Incorporating this change into equations 2.6 and 2.7 yields the R&D equation:

[14] Also, an alternative specification, which relates the growth of knowledge to the share of labor devoted to R&D rather than the quantity, is inconsistent with the facts (Jones 1995).
[15] Romer (1998) argues that "It's not the opportunities in nature that are scarce. It's the human talent to pursue the many opportunities we face."

$$\dot{A} = \delta L_A^{\lambda} A^{\varphi} \qquad [2.8]$$

When φ=1 and λ=1, the above equation reduces to the R&D equation assumed in the models of Romer, Grossman-Helpman, and Aghion-Howitt (see equation 2.5). What stands out clearly here is the arbitrariness of their assumption that $\varphi = 1$. One might make a plausible case for increasing returns to R&D so that $\varphi > 0$, but $\varphi = 1$ represents a completely arbitrary degree of increasing returns. By assuming that $0 < \varphi < 1$, Jones (1995) shows that his model can produce a balanced growth path that is consistent with an increasing R&D labor force.

By rewriting equation 2.8 in terms of the growth of knowledge, Jones (1995) shows that a constant growth rate of knowledge (which one assumes by definition along the balanced growth path) can be consistent with an increasing number of scientists, provided that L_A^{λ} and $A^{1-\varphi}$ grow at the same rate, a restriction that will naturally tie down the growth rate of knowledge:

$$\dot{A}/A = \delta L_A^{\lambda} / A^{1-\varphi} \qquad [2.9]$$

In addition, by differentiating both sides of equation 2.9, Jones (1995) solves the balanced growth-rate path of knowledge explicitly, which also pins down all the other interesting growth rates in his model:

$$g_A = g_y = g_c = g_k = \lambda n/1\text{-}\varphi \qquad [2.10]$$

where n is the growth rate of the labor force and g_y, g_c, and g_k are the growth rates, respectively, of output per worker, per capita consumption, and the capital-labor ratio. Equation 2.10 indicates that long-run per capita growth is ultimately tied to the growth rate of the labor force and the parameters φ and λ, which determine external returns (as well as returns to scale) in the R&D sector. Therefore, we are back to where the standard neoclassical model started, namely that the growth rate depends ultimately on the growth rate of the labor force (and thus of population), an exogenous variable. But, as Jones (1995) argues, growth in his model is endogenous in the sense that it derives from the pursuit of new technologies by rational, profit-maximizing agents.

Using an extended version of his model, Jones (2000) attributes roughly 30% of the post-1950 growth of the US economy to the rise in educational attainment, 50% to the rise in research intensity (i.e., the share of the labor force working in R&D), and only 10%–15% to the steady-state growth rate of the economy. The latter is (along the lines of equation 2.10) driven by the worldwide discovery of new ideas, which in turn is tied to world population growth. The US capital-output ratio declined slightly during the second half of the twentieth century and, in Jones' growth-accounting framework, it had no positive impact on the growth of labor productivity during this period. Jones argues that the US economy has been far from its steady-state growth rate for a long time and that much of the post-1950 growth has been driven by transition dynamics. However, educational levels cannot expand forever, nor can R&D intensity. Once their growth rates slow down or disappear, the per capita growth rate will return to its substantially lower, but still positive, steady-state rate.

An important parallel can be found in the dramatic increase in physical capital and the corresponding rise in the capital-output ratio that drove much of the nineteenth century growth in the US. However, once the transition to a capital-intensive economy was made, the contribution of capital to further per capita growth came to an end. But growth rates did not decline because other factors, such as educational attainment and research intensity, took over. This leaves us with the question, "When will the transition to a knowledge-intensive economy come to an end?" One can only speculate that this moment is still far away as the "research intensity is less than one percent of the labor force, so that the upper bound imposed by nature does not seem likely to bind in near future" (Jones 2000, p.31).

2.3.2 *Absolute and conditional convergence*

What transpires from these rather abstract economic growth models is that economies will converge to the same income per capita in the very long run.[16] Countries may at times forge ahead, as the now developed countries did in their transition to a capital-intensive economy between, say, 1800 and 1950 and as they continue to do in their current transition to a knowledge-intensive economy. Where does this leave the developing countries? Certainly, catching up is difficult when the target is moving fast. But as Japan, Hong Kong, Singapore, South Korea, and Taiwan have shown, it can be done. Which raises the question, "What has held other developing countries back from following at the same or an even faster rate?"

One suggestion made in the economic growth literature is that one should distinguish between *absolute* and *conditional* convergence of economies. In the case of absolute convergence, the hypothesis is that poor economies can unconditionally catch up with rich countries (implicitly assuming that the steady state for all countries is the same), while in the case of conditional convergence, the hypothesis is that each country has its own steady state, towards which it will converge.[17] Sampling a wide range of variables that may proxy for differences in steady-state positions (such as education, life expectancy, and political stability), Barro and Sala-i-Martin (1995) show that their inclusion makes a major difference across a sample of 127 countries. When these additional variables are held constant, the relation between per capita growth rate and the initial level of income per capita becomes significantly negative, as predicted by the neoclassical growth theory. The conditions that define the steady state of each economy

[16] Dosi *et al.* (1994) provides an alternative, "evolutionary " model of long-term development, which allows initially identical countries to differentiate over time. In their model, the random luck of early success in innovation reinforces later innovative advances.

[17] Cho and Graham (1996) stress that such convergence may happen from below as well as from above. Moreover, they come up with a surprising finding: that poor rather than rich countries operate above their steady state.

may be considered fixed in the short to medium term, but in the long run, they may change, making the steady state itself a moving target.

Hall and Jones (1998) take a different perspective. They demonstrate that differences in physical capital and educational attainment only partially explain the differences in output per worker across countries. The unexplained residual stands out as a far more relevant factor in explaining these differences. They then go on to explain this large variation in productivity across countries by differences in the *social infrastructure,* which they define as those institutions and government policies that provide the incentives for individuals and firms in an economy. So rather than differentiating by steady-state determinants, as done by Barro and Sala-i-Martin, Hall and Jones turn to the ideas of institutional economists like North (1973, 1990) and Olson (1982, 1996) to explain what holds countries back from catching up. They argue that differences in social infrastructure (the parameters of which largely overlap with the steady-state determinants) across countries cause large differences in capital accumulation, educational attainment, and productivity and, therefore, large differences in income across countries. Hence, unleashing the potential and unconditional convergence of poor countries requires, above all, good institutions and government policies, or to quote Olson (1996, p. 19):

> . . . the large differences in per capita income across countries cannot be explained by differences in access to the world's stock of productive knowledge or to its capital markets, by differences in the ratio of population to land or natural resources, or by differences in the quality of marketable human capital or personal culture. Albeit at a high level of aggregation, this eliminates each of the factors of production as possible explanations of most of the international differences in per capita income. The only remaining plausible explanation is that the great differences in the wealth of nations are mainly due to differences in the quality of their institutions and economic policies.

2.3.3 *The unexplained residual*

By including human capital and the creation of new knowledge in its growth model, the endogenous growth theory has made progress in reducing the unexplained residual and in improving our understanding of the economic growth process. Still, an uncomfortably large residual remains unexplained. The emerging consensus in the literature is that the missing factor in the present economic growth models is that of the social dimension of economic activity – the way economic actors interact and organize themselves. Abramowitz (1986), for example, stresses the importance of *social capability*; Hall and Jones (1998), that of *social infrastructure*; Dasgupta and Serageldin (2000), that of *social capital*; and Nelson and Sampat (2001), that of *social technology* to explain differences in economic growth and productivity. The four concepts overlap to a large extent and all four have incorporated institutional concepts and ideas. However, measurement of the various "social" concepts stands out as particularly problematic and is often left unresolved. Grootaert's (1998) paper on social capital explicitly addresses the issue of measurement and lists more than 50 different indicators that have been used in one way or another to measure social capital. However, there is no consensus yet on the definition of social capital or how to measure it.

Putting the right combination of natural, physical, human, and social capital to work is what differentiates rich countries from poor ones. Also, in agriculture these four factors probably explain to a large extent observed differences in productivity. Each factor constitutes a potential bottleneck in achieving higher agricultural productivity and provides insight into a part of the productivity puzzle, but never the complete picture.

In a rather abstract and aggregate way, endogenous growth theory tries to establish a link between the human effort to innovate and economic growth – between R&D investment and impact. By attributing increasing returns to knowledge, the endogenous growth theory provides a very positive outlook on the future and on what human ingenuity can do. It also provides an explanation of why economic growth in developed economies has not slowed down and why many of the doom scenarios of pollution and depletion of resources have had little predictive value. Human inventiveness has been capable of overcoming many of the predicted constraints on further economic growth by significantly reducing pollution and by cutting spillage of scarce resources. Nevertheless, not all countries seem to exploit knowledge as a source of economic growth with equal success. What holds these countries back is not so much the lack of human capital, but the lack of social capital that is needed to create the right environment for innovation to prosper.

2.4 *Beyond neoclassical theory*

One of the more serious critiques of the neoclassical innovation theory is that its microeconomic foundation, based on the theory of the firm as profit maximizer, is dismally weak (Dasgupta and Stiglitz 1980). It is possible to give a full account of the neoclassical innovation model without once mentioning the term *entrepreneur* or the inherently risky nature of R&D investment decisions. The relative factor scarcities are the magnets by which the neoclassical innovation process is pulled, but its internal mechanism – the learning, search, and formal R&D processes – remains a black box. Nelson and Winter (1982) propose a notably different, *evolutionary economics,* approach to technical change, which will be discussed in section 2.4.1.

The *new institutional economics* offers more of an extension than a critique of the neoclassical (innovation) theory. It argues that institutional innovation, by reducing *transaction costs*, may be as important in explaining productivity growth as technological innovation (North 1990). Olson (1996) takes an even more radical position and argues that institutions are a more critical factor in explaining differences in productivity than access to technology, capital, or natural resources – or differences in the quality of "marketable" human capital.

Yet another extension to the neoclassical theory comes from *game theory*. It argues that firms do not make innovation decisions in isolation but try to anticipate what their competitors may do. So, rather than seeing firms as just stand-alone profit maximizers (the standard neoclassical assumption), game theory argues that firms' innovation decisions are also influenced by strategic considerations vis-à-vis other competitors. According to game theory, strategic considerations can both speed up and slow down investments in R&D.

2.4.1 *Evolutionary economics*

Nelson and Winter (1982) provide a notable alternative to the standard neoclassical approach to technical change in their seminal book, *An Evolutionary Theory of Economic Change*. They argue that neoclassical economics has such difficulty accommodating technical change into its theory because of two principal assumptions on which it has been built: (1) the *maximizing behavior* of economic agents and (2) *equilibrium*. Orthodox microeconomics assumes that firms seek to *maximize* profits (or any other objective) with given assets and technology and with *full* knowledge of the market and possible opportunities. There is no room for *bounded rationality* or *uncertainty* in describing technical change, which leads to a lack of descriptive realism in the characterization of firm behavior. In addition, technical change is a dynamic process and creates disequilibria and therefore does not fit well with a comparatively static equilibrium. Although neoclassical economic theory is flexible enough to accommodate some of these criticisms in its models, Nelson and Winter propose a more radical break with neoclassical orthodoxy and propose an *evolutionary* approach to technical change.

This evolutionary approach is built on three basic concepts. The first is that of *organizational routines*. At any time, organizations have built into them a set of ways of doing things and ways of determining what to do, which can typically be expressed in terms of identifiable rules of thumb. They reflect the bounded rationality that shapes their day-to-day decision-making. These routines are of course geared towards profit making, but not necessarily towards profit maximization, as assumed by neoclassical theory. The second concept is that of *search routines*, which encompass all those organizational activities that are associated with the evaluation of current routines and which may lead to their modification, to more drastic change, or to their replacement. These activities are themselves partly routine and predictable, but they also have an unpredictable, stochastic character. However, whatever new routines emerge, they are largely bounded by the current routines in use. Moreover, imperfect understanding and imperfect, path-dependent learning entails persistent *heterogeneity* among organizations, even when they face identical information and identical notional opportunities.[18] The third concept is that of the *selection environment* of an organization, which is the ensemble of considerations (including profit) that affects well-being and, hence, the extent to which an organization expands or contracts. To use the evolutionary metaphor more explicitly: routines are the genes of the organization, and search generates mutations in these routines, which will survive or not depending on how well they fit the environment (Nelson and Winter 1982).

[18] In contrast, neoclassical economics assumes that all firms have full knowledge of all potential opportunities and hence they all behave in the same way.

These concepts form the basis for various evolutionary *simulation* models, which, as Nelson and Winter claim, can explain the observed macro-economic facts as well as the neoclassical equilibrium models. A major critique of those simulation models, however, is that they lack the mathematical rigor and transparency of orthodox equilibrium models and tend to be rather unstable (Krugman 1996).[19]

Dosi (1997) argues that the evolutionary economic theory can easily accommodate induced innovation arguments. Adopting an evolutionary perspective, inducement can work in four ways:

(1) Changes in relative prices and in demand or supply conditions may well affect the search heuristics of a firm.
(2) Such changes may also influence the relative allocation of search efforts to different technologies or products.
(3) These first two mechanisms of "inducement" rest on the ways changing market conditions influence incentives and, in turn, the way these incentives affect behavioral patterns – either in terms of search heuristics or allocation rules.[20] However, changing relative prices can easily "induce" changes in the directions of technical change (even holding the search behavior of firms constant) via the selection of the stochastic outcomes of the search itself.
(4) Even when one assumes the extreme case that economic agents are totally inertial in their production routines, market selection will favor those firms that use the "better" techniques (conditional on prevailing prices) via their differential ability to invest in production capacity.

The identified mechanisms operate without any reference to production functions or innovation possibility curves, but together they make a good case for induced innovation. Dosi (1997) argues that the evolutionary version of induced innovation is considerably more convincing than the neoclassical one, which only considers mechanisms one and two.

A weakness of both the neoclassical and evolutionary induced innovation theory is that they focus on existing firms and their behavior. They say very little about new firms entering the market. However, as Schumpeter has argued, most (and in particular the most radical) new technologies and products come with new firms and new plants. The evolutionary approach is even more restrictive than the neoclassical one in the sense that it restricts the set of technological opportunities that a firm may explore to those that are close to the current set. Today's production routines define those of tomorrow, just as

[19] "Evolutionary theorists, even though they have a framework that fundamentally tells them that you cannot safely assume maximization-and-equilibrium, make use of maximization and equilibrium as *modeling devices* – as useful fictions about the world that allow them to cut through the complexities. And evolutionists have found these fictions so useful that they dominate analysis in evolution almost as completely as the same fictions dominate economic theory" (Krugman 1996).

[20] In the biological evolution theory, mutations are completely random, while in the socioeconomic version, economic actors may steer innovations in anticipation of a changing selection environment.

mutations in species take place only very gradually. The introduction of new species or species coming from another habitat is not considered. However, for the developing countries, this is probably a more relevant way of looking at the introduction of new technologies, as they usually come with new (and often foreign) firms.

Nevertheless, selection mechanism three still holds. When the newcomer does not face any local competition, any production routine will fit so long as it is competitive with imports. Transport costs, import levies, undervalued exchange rates, etc., may all help to create a relatively large space of possible (and not always state-of-the-art) input-output combinations. When there is local competition, new or imported production routines have to be more efficient than the existing local ones. However, imported production routines can be radically more efficient than the local production routines[21] and therefore relatively insensitive to the local factor price ratio. Moreover, new firms that are linked to multinational companies often have access to cheaper capital and knowledge and hence face a different relative factor price ratio than local companies.

Perhaps the evolutionary approach helps us most clearly to understand when induced innovation can be expected: namely, in those instances where production routines can only be changed gradually and where the entrance of newcomers into the market with vastly superior technology is unlikely. Industry does not fit this description very well; agriculture, however, does. This is probably also why induced innovation in the general S&T literature is not more than a footnote, while in agricultural economics, it plays such a prominent role.

Land-labor ratios in agriculture change slowly, with small gradual steps. The supply and division of land binds the adoption of new technology to a relatively narrow path, which changes only slowly but steadily through time. Unlike capital, land cannot be moved around. Moreover, improvements in production techniques and economies of scale in industrial production are more erratic than in agriculture. Agricultural production routines that depend more on capital than on land, such as intensive poultry production, clearly fit less well with the induced innovation perspective. The declining importance of land and labor as inputs in modern agriculture also makes the induced innovation perspective less relevant.

Although evolutionary economics radically breaks with two important assumptions made by neoclassical economics (maximizing behavior and general equilibrium), it subsumes rather than displaces the induced innovation arguments. In some ways, it makes an even stronger case for induced innovation by providing it with a considerably more realistic description of the microeconomic processes taking place than does the neoclassical description, which is based on the theory of the firm. Empirically, however, the evolutionary description provides very little to explain differences in rates of technical change. Evolutionary theory is particularly useful in so far as the process of reaching the optimum is of interest rather than the optimum itself (Gomulka 1990).

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[21] Economies of scale often play a critical role in cost reduction.

2.4.2 *New institutional economics*

Economists are usually aware of the importance of institutions but find it hard to deal with them and therefore tend to keep them outside their models.[22] New institutional economics tries to give institutions their proper place in explaining economic phenomena by looking upon institutions as *the rules of the game* and their manifestation as *property rights* as important vehicles to reduce *transaction costs.* This latter aspect is based on the belief that, in contrast with neoclassical assumptions of full information and choice rationality, economic actors are constrained by incomplete information and process it through mental constructs that can result in inefficient paths. They act under *bounded rationality*, which is also one of the key assumptions of evolutionary economics. When it is costly to transact (and usually it is), then institutions matter.

North and Wallis (1994), in a rather unnoticed but inspiring article, looked at the interplay between institutional and technical change at the level of the firm, two areas that are usually studied separately, assuming that either technology or institutions are given. By considering the transformation and transaction functions of a firm simultaneously, North and Wallis argue that a typical firm is not concerned with minimizing either transformation costs (optimal technique) or transaction costs (optimal institutions) in isolation; a firm is interested in minimizing total costs. Neither type of cost is independent – changes in transaction costs may lead to changes in transformation costs and vice versa. While the introduction of a new technology reduces transformation costs, it may at the same time increase transaction costs. A good example is the recent introduction of genetically modified (GM) crops. The European market requires GM crops to be kept strictly separate from their non-GM counterparts, which has unexpectedly increased transaction costs and reduced the profitability of the new technology.[23] Another example is how the shift from subsistence to commercial agriculture depends on the development and adoption of institutions that can facilitate the significantly increased volume of transactions and lower their costs.

By differentiating transformation from transaction costs, North and Wallis (1994) provide a framework that helps to disentangle the effects of institutional and technical change on both types of cost and, in particular, the less-known cross cases of technology affecting transaction costs (e.g., the use of ICT) and institutions affecting transformation costs (i.e., environmental regulations). This framework provides a deeper understanding of the complex interdependent structure of an economy as it evolves, enabling us to see more

[22] A notable exception has been Ruttan (1978) and Hayami and Ruttan (1985). They extended their induced innovation perspective to *induced institutional innovation*. While there is general agreement that technological and institutional innovation come in tandem and that they are complementary, the evidence for induced institutional innovation is considerably less convincing than that for induced technological innovation. Political and social processes are a lot more complex than what can be explained by the relative scarcity of production factors only. They are just one of many factors at stake in such a process.

[23] In this case, new legislation is needed to define the maximum level of contamination that is acceptable as well as the way such contamination will be tested; responsibility for implementing and supervising the certification has to be delegated; international agreements on standards have to be negotiated, etc.

clearly the interplay between technical and institutional change. However, while conceptually enlightening, empirically, transaction costs have been assumed by most economists as either not measurable or only partially so.[24] North and Wallis (1994) themselves argue that, "Under that assumption, theories that propose an important role for institutional change in explaining the development of economies must necessarily be content with making assertions that can rarely be confirmed or falsified, since the economic variable they rely on, transaction costs, is unobservable." In that sense, economists have made far more progress in the empirical analysis of technical change than of institutional change – an imbalance that severely restricts our understanding of how innovation processes affect productivity.

2.4.3 *Game theory*

In an ideal competitive market, an economic actor can make rational economic decisions in a "stand alone" fashion – that is, without considering her or his interactions with other economic actors. An economic actor only needs to consider his or her own situation and the "conditions of the market." However, in situations where competition is incomplete (which is often), this assumption becomes flawed and *strategic advantage* vis-à-vis other economic actors starts to play a role in making rational decisions.

The contribution of *game theory* is that it provides alternative models that can deal simultaneously with profit maximization and strategic advantage arguments. The variety of game-theoretic models that one can choose from is endless. However, what they all have in common is that a game consists of a set of rules governing a competitive situation in which players choose actions designed to maximize their own winnings or to minimize their opponent's winnings; the rules specify the possible actions for each player, the amount of information received by each as the game progresses, and the amounts won or lost in various situations. A player's strategy is a plan for actions in each possible situation in the game. A player has a *dominant* strategy if that player's best strategy does not depend on what other players do.

A *Nash* equilibrium is a solution in a strategic game with the property that no player can increase his or her payoff by choosing a different action, *given* the other players' actions. A strategic game, however, does not necessarily have a Nash equilibrium, or for that matter a single one.

Game-theoretic models are applied widely to situations involving strategic decision, including various aspects of technological innovation. One of the more standard textbook examples of game theory is that of patenting. By casting it as a "race horse" game (i.e., the winner takes all), it shows that the market will invest substantially more in R&D (resulting in duplication of effort) than what is optimal from a social point of view. In other words, the technical change attained is costlier than strictly necessary. By

[24] Transaction costs that are particularly hard to measure include the time needed to acquire information, queuing, bribery, and so forth, as well as losses from imperfect monitoring and enforcement (North 1990).

introducing the possibility in the patent race game of licensing the technology, one increases the profit incentive but also lowers the costs of being the loser, which reduces the competitive threat (i.e., the strategic argument). Therefore, the overall effect on R&D investments of licensing technology cannot a priori be established (Shapiro 1985).

The interaction between market structure and innovative activity has been another area in which game-theoretic modeling has provided major insights. In particular, Arrow (1962) and Dasgupta and Stiglitz (1980) have made important contributions to our understanding of how the market may generate levels of innovation activity that are suboptimal relative to a socially managed market. More recent work along the same lines by Beath, Katsoulacos and Ulph (1995), focuses on the intriguing strategic trade-off between product differentiation and cost reduction, and its implications for innovation and R&D investment.

Game-theoretic modeling has also been applied in studies of technology diffusion. Insights derived from such studies include the following ideas: (a) strategic rivalry can force companies to adopt technology too early (technology has not yet been fine-tuned sufficiently and so learning costs are high) and (b) early adopters, by taking a risk, create positive spillovers for followers (their learning costs are lower). Excess inertia may occur when none of the potential adopters wants to take the first step (Beath, Katsoulacos and Ulph 1995).

The traditional or “rationalistic” game theory is static in the sense that it solves the game with a given number of players. Evolutionary game theory improves upon traditional game theory by providing a dynamic describing how the population of players may change over time. In this way, for example, the question can be addressed as to whether the dynamic process of competition is one in which incumbents maintain or extend their position of technological supremacy (*persistent dominance*) or whether they are taken over by some rival whose incumbency is in itself short-lived (*action/reaction*). Given the variety of factors at work in determining the outcome of strategic dynamic competition among firms, it is not surprising that the existing game theory literature on this topic can be rather confusing, with different models yielding different and often conflicting results. However, this is true for all game-theoretic models in the sense that their outcomes very much depend on how the game is structured. Change one assumption and the outcome can be quite different.

As argued earlier, the standard neoclassical innovation theory treats much of the innovation process as a black box. The three extensions or critiques of the standard theory discussed in the previous sections each try to model the innovation process in a more realistic way. In all three approaches, however, profit remains the lead incentive to investing in R&D. While evolutionary economics drops the assumption of profit *maximization*, the other two approaches reveal how profit maximization can be constrained by institutional factors or strategic considerations due to imperfect markets.

2.5 *Alternative perspectives on the innovation process*

The previous sections focused on the dominant economic perspectives on technical change, which all remained rather abstract. This section briefly summarizes some of the other perspectives on innovation that stem from the more general S&T literature. With contributions from political and social scientists as well as historians, this literature is considerably more descriptive. Nevertheless, it may provide important clues about what triggers innovation or what holds it back.

2.5.1 *Technological innovation: supply push or demand pull?*

While the *linear model of innovation*, based on Schumpeter's sequence of *invention-innovation-diffusion* in strict temporal order, has prevailed for a long time, during the 1970s, scholars began to recognize that such strict linear interpretation does not hold.[25] Innovation processes in real life are much more complex, with a great deal of feedback. In particular, the idea that all technological innovation is based on science was seriously questioned and, hence, the relevance of public support for basic science.[26]

In this climate, quite a number of studies were published that argued that the innovation process is not supply-driven by developments in basic sciences, but it depends mainly on market demand. Innovations are in some sense "called forth" or "triggered" in response to demands for the satisfaction of certain classes of "needs." Or, to put it more simply, necessity is the mother of invention. In a critical (and now classical) review of studies that emphasize the influence of market demand upon innovation, Mowery and Rosenberg (1979) showed that the empirical evidence presented does not support the primacy of market demand forces within the innovation process. Besides the flawed conceptual and methodological framework of most studies, the demand-pull case is admittedly weakest for the most significant innovations. Therefore, Mowery and Rosenberg (1979, p. 143) conclude that:

> . . . rather than viewing either the existence of a market demand or the existence of a technological opportunity as each representing a sufficient condition for innovation to occur, one should consider them each as necessary, but not sufficient, for innovation to result; both must exist simultaneously.

While there are instances in which one or the other may appear to predominate, most evidence points to the conclusion that a satisfactory theory of innovation must take into account both the supply and demand factors. Or, as Freeman and Soete (1997, p. 201) argued, "Necessity may be the mother of invention, but procreation still requires a partner."

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[25] These three stages differentiate between the development of a new technological idea (invention), its first use in economic production (innovation), and the spread of the innovation (diffusion).

[26] There are many examples of innovations that preceded the scientific understanding of their working (e.g., the steam engine, the use of fertilizers, and many medicines).

The emerging consensus is that neither the technology-push nor the demand-pull models adequately capture the technological innovation process. Instead, innovation is seen as an interactive process with various complex and diverse feedback processes (David 1993; Clarck and Guy 1998). Ruttan (2001) proposes a third way to look at invention, which he bases on ideas formulated by Usher in the 1950s (Usher 1954). Rather than considering invention as an act of a genius (the technology push) or as resulting from the stress of necessity (the demand pull), Usher proposes a third approach, namely that of *cumulative synthesis*. Based on Gestalt psychology, Usher argues that major inventions emerge from the cumulative synthesis of many relatively simple inventions, each of which requires an individual "act of insight." In the case of an individual invention, there are four essential steps (Ruttan 2001, p. 67):

(1) *Perception of the problem*, in which an incomplete or unsatisfactory pattern or method of satisfying a want is perceived. Perception of the unsatisfactory performance is often induced by changes in the external economic environment.
(2) *Setting the stage*, in which elements or data necessary for a solution are brought together through some particular configuration of events or thought. Among the elements of the solution is an individual who possesses sufficient *skill* in manipulating the other elements.
(3) *The act of insight*, in which the essential solution of the problem is found. Usher stresses the fact that large elements of uncertainty surround the act of insight. It is this uncertainty that makes it impossible to predict the timing or the precise configuration of a solution in advance.
(4) *Critical revision*, in which the new invention is redesigned or reengineered to meet the technical and economic requirements for successful adoption and diffusion.

A major or strategic invention represents the cumulative synthesis of many individual inventions, each of which has usually gone through all the separate steps.

Ruttan (2001) considers Usher's cumulative synthesis theory particularly appealing as it provides a unified theory of the social processes by which "new things" come into existence, one that is broad enough to encompass the whole range of activities characterized by the terms *science*, *invention*, and *innovation*. In addition, it clarifies the points at which conscious efforts to speed the rate or alter the direction of innovation can be effective, namely, at the second and fourth steps. By setting the stage, fewer elements are left to chance, which increases the probability of success. However, it is in step four – the critical revision – where most conscious effort is usually concentrated. In this step, invention is also more an *act of skill* rather than an *act of insight*.

2.5.2 *Small steps, big jumps, and dead ends*

A frequently made distinction is that between *continuous* and *discontinuous* technological innovation. According to Schumpeter (1928), innovation always creates a discontinuity. Some innovations differ more from what they substitute for. It is just a matter of degree, but there is no objective scale to separate continuous from discontinuous innovations. Still, the notion that there are significant differences between *major or radical breakthroughs* and *incremental, cumulative improvements* is quite pervasive in the S&T literature.

Enos (1958), for example, distinguishes between an *alpha phase* and a *beta phase* in the innovation process. The alpha phase covers the introduction of a completely new product or production process, while the beta phase covers the later improvements of the product or the production process.[27] In his study on the oil refinery industry, Enos found that the beta phase generated far higher cost savings than the former. Rosenberg (1982) cites several other studies with similar results. The Green Revolution in agriculture has unfolded in a similar way.

In a broad analogy with Kuhn's concept of a "scientific paradigm," Dosi (1982) introduced the concept of a *technological paradigm* and a *technological trajectory*. The latter constitutes a pattern of "normal" problem-solving activities on the grounds of a technological paradigm, resulting in incremental, cumulative improvements. Similar to a scientific paradigm, a technological paradigm sets the stage for the innovation process by defining the problem as well as the method of how to solve the problem and thereby defining images of possible paths of technological improvement. It reduces as well as focuses the innovation process. Improvements along the technological trajectory are usually shaped by economic incentives, while shifts in technological paradigms are more the result of scientific breakthroughs.

Others, clearly with more tangible technologies in mind, have labeled this concept of the technological paradigm/trajectory a *design configuration,* within which "technology develops in terms of sequences of innovations improving products and processes within the constraints of given design principles" (Metcalfe 1995, p. 459-461). A further distinction can be made between the architecture of a configuration, its core, and the component parts, which make up complex artifacts. A great deal of innovation takes place in an incremental fashion with the architecture of design altered little and the focus being on improved components. More radical innovations alter the architecture and, in doing so, redefine the knowledge base on which the configuration depends. For example, the automobile is a design configuration that has already lasted for more than 100 years, but its components have been improved continuously.

Related to these concepts of technological paradigms and design configurations is the notion of *path-dependency* in technical change (e.g., Arthur 1989). A central idea of this line of thought is that the development or use of some technologies may be subject to self-reinforcing, positive feedback cycles that, once set in motion by what may be considered small, random events, may become "locked in" to a particular path of development. However, the particular path that emerges need not be socially optimal ex

[27] The first automobile was not much more efficient than the horse car (probably even less efficient). It was only because of a steady stream of improvements that the automobile became the superior technology.

post, which suggests that the invisible hand does not necessarily work its magic in such settings.[28] Much of the research on this theme focuses on the emergence of a technical standard in the early phases of a new technology and the long-term impact this has on further technological developments.

Technological paradigms and design configurations can become dead ends at a certain point of time, leading to declining returns to R&D. A shift in the technological paradigm or a new design configuration is needed to open up a new trajectory, with new opportunities and chances. Machlup (1962) made a similar and enlightening distinction between *agenda enhancing R&D* and *agenda reducing R&D*. The latter type of R&D explores the opportunities along a given technological trajectory, while the former opens up new trajectories and new innovation opportunities. Similarly, conceptualizing R&D as a stochastic search process, Evenson and Kislev (1976) argue that basic science increases the productivity of applied research by increasing the pool of technological opportunities from which one can choose.

Abernathy and Utterback (1978) provide yet another perspective and argue that product markets experience a *life cycle* over which the nature of innovation changes in a predictable manner. Initially, in an emerging product market, the emphasis is on product innovation, as numerous small firms compete to establish a market position. Radical new product ideas are tested, and eventually a dominant design emerges. With a dominant design come product standardization and a shift towards process innovation. Innovation efforts at this stage are concentrated on realizing the benefits of large-scale production, mechanization, and cutting product costs. As a result, the industry becomes more concentrated, the potential for further process innovation is eventually exhausted, and ultimately, the industry becomes subject to external threats from competing products that eschew the dominant design. A new product life cycle can start. While the development of some industries fits this sequential model quite nicely, there are others where the different stages of the life cycle are rather blurred (Cohen 1995).

2.5.3 *National systems of innovation*

In recent years a *national system of innovation* (NSI) school of thought has emerged in the S&T literature. It looks upon the process of technological innovation as embedded in a complex network of interacting organizations and institutions. The term *national system of innovation* first appeared in the literature in the late 1980s.[29] However, with the Organization for Economic Cooperation and Development (OECD) as one of the very

[28] A classic example is the QWERTY typewriter keyboard, which was adopted quite early in the development of the typewriter for technical reasons rather than being the most efficient layout from the point of view of the typist. Even after the original technical problems had been resolved, the keyboard layout could not be changed because it had become the accepted standard (David 1985). Perhaps today's equivalent to this story is that of word-processing software.

[29] It was the title of a section in Dosi *et al*. (1988) to which several of the later key authors contributed.

early proponents of the NSI concept, it rather quickly entered the vocabulary of national and international policymakers.[30]

The study of national systems of innovation started off with rather simple and descriptive analyses of innovation systems that tried to explain differences in innovation activity and performance across countries. In more recent years, however, the theoretical underpinning of the NSI approach has been substantially improved by the addition of insights from various streams of (economic) thinking, including evolutionary economics, institutional theories, theories of learning, and systems theory.

Metcalfe (1995, p. 462-463) defines a national system of innovation as follows:

> . . . that set of distinct institutions which jointly and individually contribute to the development and diffusion of new technologies and which provides the framework within which governments form and implement policies to influence the innovation process. As such it is a system of interconnected institutions to create, store, and transfer the knowledge, skills, and artifacts, which define new technologies. The element of nationality follows not only from the domain of technology policy but from elements of shared language and culture which bind the system together, and from the national focus of other policies, laws and regulations which condition the innovative environment.

Being such a young field of study, definitions have not settled down yet and the analytical emphasis changes from author to author. Some interpret an NSI narrowly and regard it as a specific sector of the economy (e.g., universities and R&D organizations) supported by specific institutions (e.g., patent rights), while others look upon it more broadly as a certain aspect of the economic process located in almost every part of the economy (Johnson 1997). Lundvall (1992, 1996), for example, emphasizes that the everyday *learning* experiences and activities of engineers, sales representatives, and other employees, as well as of consumers, make important contributions to innovation. Such learning is most intense where economic actors interact. Hence, innovation is strongly embedded in the prevailing *economic structure.* It determines to a large extent what is going to be learned and in which areas innovations are going to take place. DeBresson *et al*. (1996) show, using input-output matrix techniques, how innovative activities tend to cluster in that part of the economic space where forward and backward linkages between industries are the most intense. Moreover, the concentration of innovative activity usually exceeds that of input-output flows by quite a margin.

In contrast to North (1990), who makes a clear distinction between institutions (the rules of the game) and organizations (the players), most of the NSI literature makes no clear distinction between the two. All authors stress the crucial importance of connectivity between institutions in a complex system such as NSI. Institutions, however, differ

[30] Three major publications during the 1990s set the stage for NSI thinking, namely, *National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning,* edited by Lundvall (1992); *National Innovation Systems: A Comparative Analysis,* edited by Nelson (1993); and *Systems of Innovation: Technologies, Institutions and Organizations*, edited by Edquist (1997).

significantly with respect to (a) focus (policy, innovation, diffusion, production), (b) motivation (profit, non-profit), (c) commitment to the dissemination of the knowledge they generate (public, private), and (d) size. In addition, the composition of the institutional framework can vary considerably according to the technological area in question. Moreover, connections are not the simple, one-way streams of knowledge assumed in the traditional invention-innovation-diffusion models.

In practice, connectivity is achieved through a variety of mechanisms. Some are formal, such as collaboration agreements among firms and between firms and universities, but many mechanisms are informal and go easily unobserved. In recent years, increased attention has been devoted to these informal *networks* within NSI. For example, attention has been drawn to the significance of the informal but balanced trading of knowledge that takes place between engineers in different firms in the same industry, as well as to the knowledge exchange between user firms and their suppliers. Such informal networks are important routes for technology transfer and for the transfer of more tacit knowledge (Metcalfe 1995). Hence, networks operate at the brink of organizational integration and formal markets, neither of which is necessarily optimal. Networks can be considered as non-market devices to reduce the transaction costs of knowledge exchange.

According to Edquist and Johnson (1997), institutions (more in the sense of North's "rules of the game") have the following three general functions in an NSI context:

(1) *To reduce uncertainty by providing information*. Institutions can help to structure and streamline information streams and thereby reduce the genuine uncertainty of innovation activities. Technological service systems reduce uncertainty about technical solutions. Patent laws and other intellectual property rights reduce uncertainty about appropriation, while at the same time making the (encoded) details of the innovation publicly available. The emergence of English as the language of science par excellence is an example of how an informal institution can help to facilitate and speed up the exchange of information.

(2) *To manage conflict and cooperation*. Another important function of institutions is to manage conflicts that arise from innovation. When new products and processes are introduced, old ones often have to give way. This leads to internal restructuring of firms as well as of whole industries. Old skills and knowledge may become obsolete, while new ones are required. The adjustment costs of innovation can be quite high and are often unevenly distributed. Innovations may therefore provoke resistance and conflict. Institutions such as job security, social security arrangements, re-schooling opportunities, and labor market arrangements can temper such conflicts.

(3) *To provide incentives*. Institutions provide incentives for learning and innovation, such as remuneration schemes for innovators, taxes, royalty payments, and scientific prizes, but there is also competition and loss of status and prestige, to name some of the incentives that come as sticks rather than as carrots.

Together, these various institutions form a complex system that affects both the cohesion and the change of the economy. The system is relatively stable and changes are mostly incremental; resistance to institutional change is a lot fiercer than resistance to technical change. However, with the increasing specialization of economic activities, inter-dependencies between economic actors are becoming increasingly complex and placing greater pressure on the rules of the game.

The NSI approach stresses and focuses on the differences between the various systems rather than abstracting from them, as is done in neoclassical economics. They usually take a strong historical perspective because differences in today's institutions and organizations have their origins in the economic and socio-political history of a country. In that sense, a unique, optimal NSI does not exist; instead, there are multiple NSIs with varying strengths and weaknesses.

The NSI approach stands out as a very eclectic one, incorporating ideas coming from evolutionary theory, institutional theory, theories of learning, and systems theory. It seeks to provide a holistic and integrative perspective that can bring these various views on innovation together. Its value-added lays not so much in providing a completely new view, but in providing a framework that can accommodate various perspectives. This also means that it can mean different things to different authors from different schools of thought. For example, some limit NSI to the formal institutions involved in innovation, while others see innovation as an activity that takes place throughout the whole economy. In all cases, however, the emphasis is on the *interaction* between institutions or economic actors. The assumption is that the intensity and quality of this interaction defines the ultimate success of an innovation system as much as the size and quality of each of the elements of the system taken individually. How to measure system performance empirically, however, is unclear.

2.6 *Conclusions*

The two questions raised at the beginning of this chapter were (a) what are the economic incentives to invest in agricultural R&D and (b) what are the constraints that research investors may find on their way?

With regard to the incentive question, the simple answer of neoclassical economics is profit maximization. There is certainly considerable truth in it, but the profit argument very much abstracts from many other factors that may also play a role. As many authors have pointed out, a major weakness of the neoclassical (induced) innovation theory is its weak foundation in microeconomics. This makes it incapable of capturing the way the interaction between economic actors in a market affects the ultimate outcome of the innovation process at the macro level.[31] In addition, neoclassical (induced) innovation theory has a blind spot for the role of institutions. It ignores the fact that high transaction costs at various stages of the innovation process may slow down or even block technological innovation. In other words, if we want to understand why innovation rates differ or why investments in R&D differ over time and across industries and countries, institutions and market structures constitute an important part of the puzzle. This is also reflected in the innovation system approach.

Another frequently mentioned binding constraint is that of the scientific frontier. Will there be an end to how far we can push our control over the material world? In the very long run, perhaps yes, but for the time being, it is unlikely. Nevertheless, the S&T literature is full of theories that stress that innovation processes sooner or later run out of steam and predict that returns to R&D will diminish. While for discrete innovation processes, this may be true, the question is whether it is also true in the aggregate. The contribution of the endogenous growth theory is that it has completely reversed this argument by assuming increasing returns to knowledge, particularly knowledge created through R&D. It is an idea that sits very uncomfortably with what economists (and most other people) usually think, but, if true, it suggests a very optimistic future.

While it is easy to critique the dominant neoclassical paradigm, formulating alternatives is a lot more difficult. Evolutionary economics, institutional economics, and game theory all provide very useful insights into the innovation process, which standard neoclassical economics cannot provide. They do so by removing or altering one or more of the standard assumptions made by the neoclassical economic theory: profit maximization, market equilibrium, full information, and perfectly functioning markets. However, these insights always come with a price tag in the form of less transparency in other parts of the theory. Evolutionary-simulation and game-theoretic models have a critical dependence on assumed parameters, while, in the case of institutional economics, transaction costs are difficult if not impossible to measure. What is lacking is a theory that can integrate the various perspectives (Ruttan 1997, 2001).

Theoretical insights regarding innovation incentives and constraints will reappear in part III of this dissertation, which will critically review the widely shared idea that there is underinvestment in agricultural R&D. It will attempt to do this by establishing a link between R&D investment and impact. First, however, part II will provide an overview of how much is invested in agricultural R&D worldwide and sort out the differences and changes in agricultural R&D investment intensities across countries and over time.

[31] Dasgupta and Stiglitz (1980), for example, show that in markets with low levels of concentration, industrywide R&D expenditures can exceed the socially optimal level, even though technical change (i.e., cost reduction) is lower than socially optimal because of excessive duplication of research efforts.

Part II: Trends and Patterns in Agricultural R&D Investments

Knowledge, and scientific knowledge in particular, is generally considered to be one of the major driving forces of economic growth. For this reason, the creation of new knowledge and technology by means of R&D stands out as an important economic activity. What is somewhat problematic, however, is that the direct output of the R&D sector can not be valued easily in economic terms because markets for ideas, scientific publications, patents, and plant varieties (to name just a few possible outputs) are nonexistent, incomplete, or imperfect. Output measures of R&D that only use output quantities but no values get stuck with an aggregation problem.[1] In some instances, artificial weights are introduced for different categories of outputs, which implicitly means attaching a relative (but artificial and fixed) price to each category. Nevertheless, these output measures remain very crude and often arbitrary approximations. Instead, the common practice is to use a measure of R&D input (i.e., R&D expenditures or R&D personnel) as a proxy for R&D output. The implicit assumption, of course, being that R&D productivity is the same across all agencies and over time.

Part II of this dissertation focuses on the questions of "How much do we invest in agricultural R&D?" and "What are the major trends and differences in investments in agricultural R&D?" The answers to these questions should ultimately provide a key to a better understanding of trends and differences in agricultural production and productivity, an issue that will be addressed later in part III. Here, however, agricultural R&D investments will be looked at in isolation, with the implicit assumption that the greater the investment in agricultural R&D, the better. This assumption is based on the widespread belief that there is significant (and some would argue, systemic) underinvestment in agricultural R&D.

The trends and differences in agricultural R&D investments will be highlighted in four articles, taking a global (chapters 3 and 4), regional (chapter 5), and national perspective (chapter 6). In addition to R&D investment levels and trends, these chapters address the following issues in varying detail and emphasis:

(a) the financing of agricultural R&D (i.e., public/private, national/donor);
(b) the "optimal" combination of factor and intermediate inputs needed to ensure an efficient R&D operation (including the education profiles of research staff and ratios of support staff to researcher);[2]

[1] This problem of valuing outputs also exists in sectors such as health, defense, and many other government services.
[2] In retrospect, the search for the optimal combination of factor and intermediate inputs has been something like searching for the Holy Grail. Extreme cases that deviate significantly from the sample average (such as spending more than 90% on salaries) can be identified as being sub-optimal, but any further fine tuning cannot be tackled without a realistic measure of R&D output. Moreover, there is no universal answer to what is the optimal combination of factor and intermediate inputs.

(c) institutional and political factors affecting the level of resources that are devoted to agricultural R&D.

The definition and measurement of agricultural R&D statistics are discussed in annex A to this dissertation.

3. Sustaining growth in agriculture: A quantitative review of agricultural research investments

By Jock R. Anderson, Philip G. Pardey, and Johannes Roseboom[3]

Policy-makers are having to contend with unprecedently rapid changes in the market for agricultural science and technology services. In the less-developed countries, the rapid expansion of agricultural research capacity experienced during the 1960s and 1970s slowed considerably in the 1980s. Particularly in debt-ridden regions, such as sub-Saharan Africa, and Latin America and Caribbean, investment in agricultural research stagnated or even declined. In addition, the level of development aid to less-developed countries stalled during the 1980s (OECD 1989) while the small but significant share that was channeled to agricultural research is threatened by other demands. A reversal of these trends seems unlikely in the near future and therefore resources for public agricultural research in less-developed countries could well tighten even further in the coming years. In the more-developed countries, public support for agricultural research is under close review and there is a strong tendency to have those who most directly benefit from research pick up at least part of the bill. Moreover, agricultural surpluses, declining agricultural prices, and a continuing decline in farm numbers in many of the more-developed countries have led to populist calls for a moratorium on further public investment in agricultural research.

Against this backdrop of fiscal stringencies, the demands being placed on national, and indeed international, research systems are intensifying. In addition to the traditional emphasis on stimulating productivity growth within agriculture, many of these systems are also being called upon to broaden their research agendas and to give greater attention to concerns of environmental degradation and resource management. The international system is also restructuring its research portfolio with regard to forestry, fisheries and vegetable research in addition to its traditional emphasis on basic food crops and livestock. These changes raise major policy issues about the appropriate division of labor and problem focus between the national, regional and international centers that are yet to be resolved.

[3] This chapter is a verbatim reprint of an article published earlier in *Agricultural Economics* Vol. 10, No. 2 (April 1994): pp. 107-123. Not included are the abstract, while all headings have been renumbered in order to match with this dissertation. References are included in the reference list of this dissertation. The research data reported here are largely from a study undertaken by ISNAR with assistance from the then Agriculture and Rural Development Department of the World Bank (Pardey, Roseboom and Anderson 1991). The monetary values throughout this paper have been expressed in constant 1980 PPP dollars. PPP stands for purchasing power parity and represents a synthetic exchange rate that attempts to reflect the purchasing power of a currency. Monetary values in current local currency were first deflated to base-year 1980 with a local (GDP) deflator and then converted into constant 1980 dollars using 1980 PPP exchange rates taken from Summers and Heston (1988) and, for China, Summers and Heston (1991). The authors thank Hugh Quigley for his assistance in preparing this paper.

There are large variations across countries and over time in the level of investment in agricultural research. As a country's per-capita income grows, its support for agricultural research – as indexed by an agricultural research intensity (ARI) ratio that expresses research expenditures relative to agricultural output – tends also to grow. But there are offsetting tendencies, including one whereby agricultural research expenditures rise less than proportionately with agricultural output, due possibly to economies of size or economies of scope in research. In this paper we present a quantitative review of the global pattern of investment in agricultural research using a new compilation of data that serves to completely revise and update the data series reported by Evenson and Kislev (1975), Oram and Bindlish (1981) and Judd, Boyce and Evenson (1986). Our intention is to illustrate what is actually happening in the world of agricultural research and to help move the policy dialogue beyond merely qualitative impressions toward a process that is underpinned with a set of basic data and quantitative indicators.

3.1 *Public investments in national agricultural research*

3.1.1 *Investment trends*

Differences in patterns of agricultural growth are in large part the result of national differences in factor and environmental endowments and in the policies adopted towards agriculture and, more specifically, agricultural research. For two decades, up to the mid-1980s, global investment in public agricultural research increased substantially.[4] Between 1961-65 and 1981-85, the total number of public-sector agricultural researchers grew at an average annual rate of 4.2%. The number of researchers in less-developed countries increased by 7.2% a year, just over four times the annual rate in more-developed countries (table 3.1).

In the period 1981-85, the less-developed countries employed 59% of the world's agricultural researchers, compared with 33% in 1961-65. Annual growth rates in research investment in less-developed countries have slowed during the 1980s, most noticeably in sub-Saharan Africa, and Latin America and Caribbean, both of which have been struggling to contain soaring international debts. In fact, the 1976-80 to 1981-85 annual rate of growth in real research expenditures was only 0.7% for sub-Saharan Africa and 0.9% for Latin America and Caribbean compared with a more- and less-developed country average of 2.9% and 4.3%, respectively. Although spending on agricultural research increased faster in less-developed than in more-developed countries during the past two decades, the less-developed countries' share of total expenditure on research rose only to 48% from its 37% in 1961-65.

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[4] The global comparisons presented in this paper do not include the former USSR, Eastern Europe, Cuba, Vietnam, Cambodia, the Republic of South Africa, and a number of very small countries for which no data were available.

Table 3.1: *Annual agricultural research personnel and expenditures, regional totals*

Region	1961-65	1971-75	1981-85	Growth rate (%)[a]
Agricultural research personnel (full-time equivalents per year)				
Sub-Saharan Africa (43)[b]	1323	2416	4941	6.8
China	7469	11781	36335	8.2
Asia and Pacific, excl. China (28)	6641	12439	22576	6.3
Latin America and Caribbean (38)	2666	5840	9000	6.3
West Asia and North Africa (20)	2157	4746	8995	7.4
Less-developed countries (130)	20256	37221	81848	7.2
More-developed countries (22)	40395	48123	56376	1.7
Total (152)	60651	85344	138224	4.2
Agricultural research expenditures (millions 1980 PPP dollars per year)				
Sub-Saharan Africa (43)[b]	149.5	276.9	372.3	4.7
China	486.7	874.8	1712.7	6.5
Asia and Pacific, excl. China (28)	316.7	651.5	1159.6	6.7
Latin America and Caribbean (38)	229.1	486.6	708.8	5.8
West Asia and North Africa (20)	126.9	300.7	455.4	6.6
Less-developed countries (130)	1308.9	2590.5	4408.7	6.3
More-developed countries (22)	2190.7	3726.3	4812.9	4.0
Total (152)	3499.6	6316.8	9221.6	5.0

Source: Most of this table is drawn from Pardey, Roseboom and Anderson (1991a, p.200), as are most of the data reported in this paper. The China data are from Fan and Pardey (1992).
Note: Totals may not add up exactly because of rounding.
[a] Compound annual average growth rate between 1961-65 and 1981-85.
[b] Bracketed figures indicate the number of countries in the regional totals. The appendix to Pardey, Roseboom and Anderson (1991a) indicates which specific countries were included in the regional aggregates.

Of the less-developed regions, only in Asia and Pacific did annual growth in research expenditures exceed the annual increase in researchers. In more-developed countries, on the other hand, spending on research increased twice as fast as the number of researchers.

3.1.2 *Expenditures per researcher*

Average spending per researcher in less-developed countries has been falling since the early 1970s. In 1981-85, it was actually lower in real terms than in 1961-65. In more-developed countries meanwhile, spending per researcher has been rising steadily and the emphasis has consistently been towards greater investment in human capital within the NARSs.

One reason for the relatively lower spending per researcher in less-developed countries is that, of late, the rapidly expanded university systems in these countries have produced many more graduates than previously. Many governments in less-developed countries insist that public bodies, including research systems, employ graduates, but then fail to provide adequate matching funds.

In the Asia and Pacific region, expenditure per researcher has always been lower than in other less-developed regions. This is partly because relative prices for labor are lower, which induces a substitution of labor for other inputs in the system. But is also because they are dominated by larger research systems that may well be able to realize economies of scale and scope.

In sub-Saharan Africa, expenditure per researcher has for a long time been higher than in other regions. During the 1960s, the NARSs in this region continued to be heavily staffed by relatively expensive expatriates from the former colonial powers. The poor quality of Africa's infrastructure and the need to import nearly all equipment also drive up the research costs in this region. Although still higher than in most other less-developed regions, spending per researcher in sub-Saharan Africa is falling, in part a reflection of the fact that expatriate researchers are increasingly being replaced by less expensive national research staff, and in part because of the above-mentioned budgetary crises.

3.1.3 *Human capital*

One of the fundamental strengths (or, too often, weaknesses) of NARSs, and a major factor in determining the success of agricultural research, lies in the quality, composition and deployment of their research staff.

Developing meaningful measures of this human capital component is challenging both conceptually and practically. Indicators such as university qualifications and years of research experience may explain much of the difference in quality between research systems, but they are not the only factors. The composition of the research staff will depend, among other things, on the NARS's size and the type of research it is conducting. These influences vary greatly between regions and will change within a system over time. For instance, a smaller NARS whose activities are focused more on capturing research spillovers and adapting them to local circumstances is unlikely to need a cadre of researchers similar to that required by a large NARS that is likely to confront an altogether different scale and set of research problems. Similarly, while a system dominated by researchers holding PhDs and 20 years of experience may be considered highly qualified, it is not necessarily the most appropriate labor force to confront the applied and site-specific problems that face many national research systems today.

Data for the period 1981-85 indicate that roughly one-half of agricultural researchers, including expatriates, in less-developed countries held a postgraduate research degree (table 3.2). If expatriate researchers are excluded from the calculation, no less-developed region has a share of researchers with a postgraduate qualification greater than 60%. For a significant number of countries it is even lower than 40%. Somewhat surprisingly, poorer less-developed regions have a relatively high proportion of qualified staff, although that is much lower if expatriate researchers are excluded from the calculation.

Table 3.2: *Nationality and degree status of agricultural researchers, 1981-85 average (%)*

Region/country	Expatriates	Share of postgraduates [a]
Sub-Saharan Africa [a]	29	45
Asia and Pacific [b]	11	53
Latin America and Caribbean	2	51
West Asia and North Africa	18	27
Less-developed countries	12	48
Australia	na	57
New Zealand	na	78
United States	na	93

[a] Measures the proportion of national researchers holding a PhD or MSc degree or equivalent. Figures for Australia and New Zealand are for 1981, and for the United States for 1980 only.
[b] Does not include China and India, the two major NARSs in the region

In many less-developed countries, the early agricultural research institutes were established by European colonial powers and, during the first half of this century, these institutes were staffed with expatriate researchers. On independence, most former colonies moved to replace expatriates with national researchers. In some countries, this change took place gradually but in others it was a more abrupt process and caused major disruptions in agricultural research programs. At present, only the smaller countries of sub-Saharan Africa, the Caribbean, the Pacific and the oil-rich countries of West Asia have relatively large proportions of expatriates on their research staffs. The share of expatriates is declining rapidly, however. In sub-Saharan Africa, for example, the share of expatriates in NARSs was about 90% in 1960 but had declined to some 30% in the early 1980s. Making the plausible assumption that the numbers of expatriate researchers working within the Chinese and Indian systems are negligible, the percentage of expatriate researchers working throughout the less-developed world in 1981-85 is estimated to be around 3%.

Although economic development can be expected to increase the supply of university graduates, research systems in some of the wealthier les-developed countries appear to have difficulty recruiting or retaining qualified staff. In part, this is because salaries and conditions in public agricultural research institutes are not competitive with other employment opportunities. In a number of countries, for example, universities employ large numbers of PhDs in the agricultural sciences, while the national public agricultural research institutes employ few or none.

On the other hand, as argued earlier, a large proportion of PhDs on the research staff does not necessarily indicate a successful or a mature research program. The contemporary systems of Australia and New Zealand, for instance, have apparently achieved significant successes with a high proportion of staff trained only to the BSc or MSc level, as did the U.S. system in earlier years. While certainly not discounting the value of training researchers to the PhD level, these observations would suggest that greater attention should be given to the research orientation and training within BSc and especially MSc programs at local universities rather than simply seeking a high proportion of PhDs through training abroad, particular when such training may be of questionable relevance.

3.1.4 *Commodity orientation*

In less-developed countries, agricultural research is directed predominantly at crops. Based on a sample of 83 countries, roughly two-thirds of all agricultural researchers are engaged in work related to crops. For the remainder, 19% are engaged in livestock research, 7% in forestry research, and 6% in fisheries research.

There are some limited regional disparities in the share of resources devoted to a particular commodity orientation (table 3.3). While such disparities are inevitable, given regional variations in the pattern of production, it has been argued by some that less research is devoted to fisheries and forestry than their reported economic importance warrants (see Mergen et al., 1988, on forestry research). In fact, the data – as shown in table 3.3 – do not generally support this proposition. Research into forestry attracts more resources that its congruent share in agricultural output in all regions. In Asia and Pacific, and West Asia and North Africa, this is also true of fisheries.

Table 3. 3: *Regional congruence between agricultural GDP and research personnel, 1981-85 (%)*

	Crops and livestock		Forestry		Fisheries	
Region	AgGDP	Research	AgGDP	Research	AgGDP	Research
Sub-Saharan Africa (22)[a]	88.6	87.3	4.7	7.3	6.6	5.4
Asia and Pacific, excl. China (10)	89.7	81.1	5.2	9.4	5.0	9.6
Latin America and Caribbean (20)	94.2	92.8	2.9	5.4	2.8	1.8
West Asia and North Africa (7)	95.9	91.6	2.4	5.7	1.7	2.7
Less-developed countries (59)	90.7	87.0	4.6	7.3	4.6	5.7

Note: Data may not add up exactly because of rounding.
[a] Bracketed figures represent number of countries included in the regional samples on which the AgGDP breakdown is based. The research breakdown is based on regional samples that include a somewhat larger number of countries

Nevertheless, the actual facilities for research into forestry and fisheries are limited, primarily because NARSs in less-developed countries are generally mall. The majority (73%) of them employ fewer than 200 researchers in total, while only small percentages of these are engaged in research into fisheries or forestry.

3.1.5 *Factor shares*

A major challenge for managers of research systems is to make the most effective use of available resources. The best mix of spending on capital equipment, personnel and operating costs will depend to a large degree on the relative availability and cost of research inputs, their quality, and the type of research being conducted. Since the most effective combination will differ between regions and change within a system over time, it is unrealistic to propose standards for determining the 'optimal' mix of inputs in research. The data presented in this section should be regarded as indications of magnitude based on a sample of countries, not as economic optima necessarily to be targeted.

The available data suggest that, in 1981-85, NARSs in less-developed countries on average devoted 19% of annual expenditures to capital investment, compared with 8% in the U.S. The higher share of spending on capital equipment by NARSs in less-developed countries supports the conclusion, also evidenced by their rapid growth, that most are in an expansionary phase. During this phase, not only must capital stock be replaced but additional capital stock must be acquired. The pattern of expenditures in the U.S., on the other hand, reflects that of a mature system, most of whose capital spending entails replacement of existing equipment. The emphasis in the U.S. system has, moreover, been consistently towards greater investment in human capital rather than physical capital in recent years. Today the system performs with around 14 cents of physical capital for each dollar of human capital, compared with about 27 cents 50 years ago (Pardey, Eveleens and Hallaway 1991).

The contemporary pattern of expenditure in less-developed countries mirrors that of U.S. experiment stations in their early years at the turn of this century, when the share of capital in total expenditures rose steadily to peak at 29% in 1912, before steadily falling. Capital (i.e., land, buildings, equipment, etc.) has claimed the same share of overall spending in U.S. research stations (about 8%) for the past three decades.

A second factor in the higher share of capital costs in less-developed country NARSs is that capital items are often relatively more expensive in less-developed countries and they often lack adequate repair and maintenance facilities, leading to an early write-off of equipment. Factor substitution, where less expensive inputs are substituted for more expensive, may counterbalance this effect somewhat, but it is not likely that it will outweigh it.

Whereas salaries and operating costs in agricultural research expenditures represent service flows, capital expenditures represent additions to a stock. Thus, the high share of capital in annual spending may also exaggerate the actual share of capital in the services used to perform research. Capital equipment can last for many years, and a measure of service flow, rather than of expenditure, would probably reduce the share of capital actually used by a research system in any given year, particularly if such a system expands rapidly.

The recurrent costs of NARSs can be divided between salaries and operating costs. In less-developed countries, salaries tend to be lower and operating costs higher than in more-developed countries. In 1981-85, a sample of 43 less-developed countries spent an average of $48,100 in constant 1980 dollars per researcher, compared with $91,200 per researcher in the U.S. The contemporary level of spending per researcher in less-developed countries again appears to reflect the situation in the early years of the U.S. experiment stations. In fact, in the U.S., total spending per researcher fell steadily in the early years as the recruitment of researchers outpaced rises in research expenditures. In the first 30 years, real operating expenditures per researcher fell to roughly one-third of original levels and did not recover until the 1970s – some 60 years later!

One of the major difficulties in making plausible cross-country comparisons of factor shares is that cross-country differences in price levels, which are not consistent across different expenditure items, act to confound the comparisons. Thus, if spending on operating costs and salaries is adjusted to take account of price differences between countries, research in less-developed countries is seen to be more labor-intensive relative to the U.S. Looked at this way, the share of operating costs in recurrent expenditures in 1981-85 averaged 15% in less-developed countries.

After adjusting for cross-country price differentials, operating expenditures per researcher are also much smaller in less-developed regions than in the U.S. Agricultural researchers in sub-Saharan Africa, Asia and Pacific, Latin America and Caribbean, and West Asia and North Africa work with only 50%, 43%, 74% and 22%, respectively, of the operating resources provided to a U.S. researcher. However, the salary component of recurrent expenditures (including the salaries of both scientific and support staff) in the less-developed regions is much closer to the U.S. level. And in sub-Saharan Africa it is even higher. This may be accounted for by the relatively high numbers of expatriates still working in African NARSs and the fact that the employment policies of many governments in less-developed countries result in NARSs employing large numbers of support staff.

3.1.6 *Size, scope, and spillovers*

Since 1961-65, the average size of NARSs has more than doubled, from around 400 to 910 researchers, as has average expenditure per system. In less-developed countries the average size of NARSs has increased from 155 to 630 full-time equivalent researchers. Nevertheless, 95 of the considered 130 NARSs in less-developed countries still employ fewer than 200 researchers, while 39 systems employ fewer than 25 researchers. Only 14 employ more than 1000, illustrating that the growth and development of NARSs in the past two decades has diverged significantly.

When analyzing the cost structures and effectiveness of a NARS, one needs to consider both the overall size and diversity of its operations and the agricultural system it serves.

The evidence on whether or not research operations are subject to economies of size is limited and far from definitive. In the case of a NARS, considerations of economies of size are confounded by the fact that these systems generate a wide diversity of products and services that vary in their commodity, technology, and agroecological specificity. For example, certain activities can relate to improving crops or to developing new breeds of plants suitable for specific agroecological zones within a country. Alternatively, research can be devoted to developing improved crop and soil management practices that will allow farmers across a range of agroecological zones to increase yields or improve pest and disease control.

Even in the absence of size economies with regard to any particular line of research (e.g., a particular commodity research program), a system may well be able to generate economies of scope through a judicious choice in its portfolio of research activities. Such scope economies arise when a system can undertake a whole range of research endeavors more cheaply than if these endeavors were undertaken by separate research entities. These economies can be achieved, for example, by sharing staff, equipment, information, or know-how between different lines of research.

An important implication is that, when a system can create sufficiently strong economies of scope, these can, in turn, lead to economies of size across the whole range of its activities, even if such economies of size do not arise for some individual research programs (Baumol, Panzar and Willig 1988). Of course, there can also arise diseconomies of scope, particularly among small systems that spread their limited resources across numerous research areas. Thus, small NARSs will be unable to conduct research in all areas that may warrant attention in the agricultural systems they serve. They will have to make choices between areas of study and this, in turn, requires some specialization and flexibility in response to opportunities as circumstances change.

The efficiency of a research system can also be increased by adapting research conducted elsewhere to local circumstances. The ability to capture research spillovers is particularly important for small NARSs with the capacity to do little more than search and screening for suitable technologies. The best source of spillover would seem to be neighboring countries with similar agricultural systems and agro-ecological features. This strategy would require a policy of hiring staff for their ability to adapt research to local situations rather than necessarily to carry out original research. It also requires flexibility in the research system to identify and act upon opportunities arising from developments elsewhere.

There is some disturbing evidence that many smaller NARSs are unable to take up information quickly enough and that the knowledge they work with is increasingly out-of-date. In a world of growing international interconnectedness, adapting spillovers from other research systems is most effective if they can be adapted to local circumstances in a timely manner. Using out-of-date information only undermines a country's relative technological capacity and therefore its competitiveness.

3.1.7 *Research and productivity*

Research is best seen as an investment activity. The research process itself takes time, and a further period elapses before the results of research are taken up. Recent evidence suggests, furthermore, that the benefits of research can still have an effect in increasing output for as long as 30 years after the research was initiated. To consider gains in agricultural gross domestic product (AgGDP) as a measure of the impact of contemporaneous research expenditure could thus be misleading. Differences in the quality of land and labor, and in the intensity of use of other inputs such as fertilizers and machinery, will influence output and so distort international comparisons of output that are measured only in terms of research.

In fact, all the more- and less-developed regions steadily increased their research intensities during that period (table 3.4). In 1981-85, less-developed countries spent an average of nearly $4 per agricultural worker on research, 2.5 times the amount spent two decades before. In more-developed countries, spending on research increased 4.4 times over the same period, to $214 for every agricultural worker.

A final factor urging caution in assessing the benefits of research in terms of increasing AgGDP is that a large share of agricultural research may be directed towards maintaining gains from earlier research rather than enhancing output levels per se. Recent estimates suggest that, in the U.S., around one-third of research expenditures are spent on maintenance, and it is probable that many less-developed countries devote at least as much proportional effort to such work (Adusei and Norton 1990).

3.2 *International investments in agricultural research*

Contrary to the situation in many areas of scientific research, there has always been an important element of international cooperation in agricultural research. Much of this is due to the legacy of the colonial relationships that existed at the time institutionalized agricultural research was developing.

One of the leading international organizations in the field is the Consultative Group on International Agricultural Research (CGIAR), an umbrella body of around 40 donor countries and international agencies that foster the activities of some dozen supranational research centers. (Recently the number was enlarged to 18 but our discussion here refers to the original 13.) Ten of these centers have their headquarters in less-developed countries. Most are engaged in research into either food commodities or agricultural production problems in a particular tropical region, and three undertake worldwide research into specific commodities.

Table 3.4: *Agricultural research factor-intensity ratios*

Region	1961-65	1971-75	1981-85
Agricultural research expenditures per economically active person in agriculture			
Sub-Saharan (37) [a]	1.7	2.7	3.1
China	1.7	2.5	4.1
Asia and Pacific, excl. China (15)	1.2	2.2	3.4
Latin America and Caribbean (26)	6.5	12.8	17.7
West Asia and North Africa (13)	4.5	10.5	14.3
Less-developed countries (92)	1.8	3.2	4.6
More-developed countries (18)	48.6	119.1	213.5
Total (110)	4.7	7.5	9.5
Agricultural research expenditures per hectare of agricultural land			
Sub-Saharan (37)	0.2	0.4	0.6
China	1.2	2.1	4.1
Asia and Pacific, excl. China (15)	1.0	2.1	3.6
Latin America and Caribbean (26)	0.4	0.7	1.0
West Asia and North Africa (13)	0.4	1.0	1.4
Less-developed countries (92)	0.6	1.1	1.8
More-developed countries (18)	1.8	3.1	4.0
Total (110)	1.0	1.8	2.5

Note: All expenditures are in constant 1980 PPP dollars.
[a] Bracketed figures indicate the number of countries in regional totals.

Established in 1971, the stated objective of the CGIAR (CG for short) was to assist efforts to increase food production in the less-developed world. The goals were extended in 1990, in recognition of agriculture's broader role in economic development, to helping less-developed countries achieve self-reliance in food. Self-reliance is taken to mean the capacity of a country to provide sufficient food for its population, either directly through local food production or indirectly by generating agricultural exports that will allow food to be imported.

In 1981-85, the CG accounted for only 1.8% of global public-sector spending on agricultural research, 4.3% if related to spending by and for less-developed countries. Its budget rose, in nominal terms, from \$20 million contributed by 20 donors in 1971, to \$280 million from 40 donors in 1990. If corrected for inflation, the CG expenditures show clearly different phases of growth: rapid expansion during the 1970s, slower growth during the 1980s, and apparent stagnation or even decline in the past few years.

The U.S. was the largest single donor to the CG, although both Europe and Japan increased their share of contributions during the 1980s. The World Bank acted as a balancing "donor of last resort," allocating its funds after other donor intentions were known. It lately has contributed around 15% of the system's total budget each year.

During the 1980s, although the CG was established partly in response to the high levels of poverty and hunger in Asia, the emphasis in the allocation of funds has shifted to sub-Saharan Africa. Between 1986 and 1988, sub-Saharan Africa accounted for 39% of the CG's core expenditures, compared with 26% to Asia, 21% to Latin America and Caribbean, and 14% to West Asia and North Africa.

The "appropriate" regional allocation of funds is just one of the policy issues facing the CG. Although much of the increase in funding to sub-Saharan Africa has been for special projects, it is arguable that the concentration of resources has swung too much towards that region at the ultimate expense of Asia, which has several-fold more poor than sub-Saharan Africa.

The commodity orientation of the system has been subject to change over time. As the system expanded, the share allocated to cereals research declined steadily to about 40%, of which rice research still accounts for the largest share at 17% of the system's total. Food crops, such as potatoes, other roots and tubers, and legumes, account for 24% of the total, while livestock research accounts for around 20%. The remaining resources are allocated to noncommodity programs, including farming systems, food policy, genetic resources, and NARS capacity building. The recent expansion of the system has broadened the commodity coverage to include fisheries, agroforestry and forestry, and bananas and plantains. It may also eventually include horticultural commodities.

The recent reorientation of CG objectives to emphasize self-reliance instead of self-sufficiency in food was a recognition of the fact that increasing food production is not, in itself, a solution to the hunger problem. Future policies must reflect the role of agricultural growth as a means of generating additional on-farm and off-farm income and employment, and the need to sustain the natural-resource base on which continued gains in agricultural productivity depend.

The CG's initial efforts were largely targeted toward more favorable production environments. Technology packages were developed that involved higher rates of fertilizer application, improved water management and cultural practices, along with new crop cultivars that were particularly responsive to more intensified production regimes. While the dramatic contribution of these technology packages to increasing global food supplies is unquestioned (Anderson, Herdt and Scobie 1988), by the mid-1970s the CG had also begun to address production constraints in the more marginal environments of the semi-arid and (sub-)humid topics.

At present, about 30% of CG funding is targeted towards technology for marginal lands, which is roughly equal to the percentage of the poor population in less-developed countries that live in these areas. The issue of the relative merits of seeking to improve or maintain productivity of favorable versus marginal lands will continue to be an important one for the CG, particularly with respect to the potential opportunity costs (in terms of productivity gains foregone) of diverting scarce research resources away from more responsive areas towards the more marginal ones. Analyses of the type reported by Byerlee and Morris (1993) will be needed for guiding future investment policy in this regard.

Research on resource management will become more important as the need for continued increases in food production places an ever greater strain on the world's natural resources. The CG has taken the first step in this direction. Strategies on how best to include agroforestry and resource management concerns into its research program are currently being implemented. This is being done by expanding the system and redesigning its approach in order to incorporate institutional entities that specifically address research concerns within an agroecological perspective. Aware of the fact that socio-economic – not just natural – conditions constrain the effectiveness and spillover potential of the system's research, this agroecological aspect is being overlaid on a geopolitical or regional dimension to generate a so-called "ecoregional" perspective (TAC/Center Directors Working Group 1993).

3.3 *Private investment in agricultural research*

Any formulation of future public-sector research policy must take into account the level of activity and changing role of the private sector in agricultural research. As farmers use more purchased inputs and the value-added in agriculture increasingly moves off-farm to the marketing and processing sectors, it is likely that the incentives for private-sector investment in research will grow. While there is a general perception that the private-sector has increased its participation in and funding of agricultural research, there are no available data to give an accurate quantitative or even qualitative perspective of these developments at the global, regional, and, in many instances, even country-level.

There are various reasons why these data are not readily available. Firms may feel their competitive interests are not well served by a full and frank disclosure of their R&D activities and so may be less than forthcoming in this regard. Even when such data are reported, there are genuine difficulties in identifying the R&D component that relates specifically to agriculture. This is particularly a problem for multiproduct firms in the chemical, pharmaceutical, biological and mechanical industries that pursue economies of scope by sharing research resources across a number of lines of research. Apportioning these R&D expenditures to a particular country in any meaningful way is also problematic, especially when dealing with multinational firms that centralize various aspects of their global or regional R&D operations.

Recent estimates by Pray and Neumeyer (1989) for the U.S. and Thirtle *et al.* (1991) for the UK suggest that private-sector investments in agricultural and food (i.e., largely post-harvest) R&D are substantial and at least as great as the public effort. Reliable global estimates of private expenditures on agricultural R&D are simply unavailable. Persley (1990, p. 48) reports that about 540 million dollars were spent worldwide by the private sector on agricultural biotechnology research in 1985, accounting for roughly 60% of the 900 million dollars spent on modern biotechnology research for agriculture in that year. This private-sector R&D figure is significantly larger than the 36 million dollars Pray and Echeverría (1991) estimate was spent annually by multinational companies on all types of agricultural (including post-harvest) R&D in less-developed countries during the latter half of the 1980s. Taken together these figures suggest that an overwhelmingly large share of private-sector spending on agricultural R&D occurs in the more-developed countries.

The data reported by Pray and Echeverría (1991) support this view. During the mid-1980s, spending by U.S. firms on R&D in the food and agricultural sectors was around 2.4 billion dollars per annum (with about 58% of this total going to agriculture). Comparable figures for the UK and France are 530 million and 270 million dollars, respectively. Much of the privately sourced funds for agricultural R&D in the less-developed regions of the world comes form Latin America and Asia and, according to Pray and Echeverría (1991), it is concentrated in a few large countries such as Brazil, Mexico, Argentina and India.

Our understanding of the scale and scope of these private-sector efforts is, unfortunately, woefully inadequate. The recent and careful efforts by Falconi (1992, 1993) to compile time-series data on private-sector, agricultural R&D expenditures in Ecuador and Colombia are quite revealing in this respect. These new data show that, in both countries, private-sector spending on agricultural R&D grew much more rapidly than publicly sourced expenditures during the 1980s. By 1991, the private sector accounted for 37% of total agricultural R&D expenditures in Colombia (compared with 22% in 1970) and in Ecuador the private-sector share is now 27% (up from 19% in 1986). To the extent these developments are representative of the situation in other Latin American (and perhaps some Asian) countries, they call for a radical rethink of the roles of the public-sector research agencies in these regions.

Having said this, however, there are still many countries, especially in Africa, where the low level of purchased inputs in agriculture limits the size of the derived market for privately produced agricultural technologies. This situation is likely to continue for some time to come. Nevertheless, governments have a number of policy instruments with which to influence private R&D. Public-sector research can foster private-sector research by providing (or selling) research results and by training the personnel needed by private companies to conduct research. Patents and plant-variety protection laws, if they are well designed and enforced, can create the necessary incentives for private companies to invest in R&D. Technology imports can stimulate local R&D, so more liberalized technological trade could also increase local private-sector R&D activities.

Innovative institutional arrangements can also help foster those complementarities that exist when the generally more upstream or “pretechnology” types of research best suited to the public domain are married with the more applied, technology-generating types of research best suited to the private domain. For instance, joint-venture research endeavors, where both public and private agencies jointly undertake and/or cofinance a program of research are becoming more frequent. Fee-for-service or contract research is also increasingly being used to privatize the financing of research being performed by public-sector research institutions.

Private, for-profit research should not be seen as something intrinsically detrimental to the public good, but neither is it likely that an unfettered private sector has the incentives to invest sufficiently in researching those problems that will optimize social welfare. Public-policy formulators will need to become increasingly sensitive to a rapidly changing technological and institutional environment in order to take advantage of the opportunities that exist to mobilize both private and public research resources in a socially desirable manner.

3.4 *Political and financial support for agricultural research*

A fundamental task facing NARSs is to win public support for research and translate it to financial support. This must be done in the context of a public sector subject to competing claims on its scarce resources from various interest groups in society, be they producers, consumers, or taxpayers.

From this perspective, governments give differential preference to various programs both within and between sectors of the economy in response to such pressures. Thus, agricultural expenditures are committed to such programs as rural infrastructure, education and credit as well as to the generation and dissemination of new agricultural technologies. In addition, many poor countries implement distortionary pricing and marketing policies in the (short-run) pursuit of cheap-food policies and the like, that ultimately tax agriculture and accelerate the transfer of resources from the sector. These same policies, in part by undervaluing the sector-specific assets in agriculture (e.g., land, irrigation facilities, etc.), can also lead to an underinvestment in agricultural research and the level of effort invested by farmers in searching for, evaluating, and adapting new agricultural technologies and practices.

To gain a full understanding of the observed disparities in the nature and level of support for agricultural research (and the ultimate productivity effects that flow therefrom) would require detailed consideration of these “political economy” forces – an exercise that would take us well beyond our present brief (Gardner 1990; Roe and Pardey 1993; Alston and Pardey 1994). Rather, the aim here is to present some comparative evidence on the level of support for public agricultural research, and to place publicly funded research in the context of the overall level of support for agriculture.[5]

[5] For an earlier version of these data, see Pardey, Kang and Elliott (1989).

A traditional measure of the level of support for agricultural research is the agricultural research-intensity ratio that expresses levels of research spending as a percentage of agricultural gross domestic product (AgGDP). Although the majority of the less-developed countries spent well above 0.5% of AgGDP on agricultural research in 1981-85, the weighted average was only 0.4% (table 3.5). This apparent difference between simple and weighted average is caused by the fact that the smaller less-developed countries tend to have substantially higher agricultural research-intensity ratios that the large less-developed countries. The weighted average of the more-developed countries barely reached 2% in 1981-85. The Southern European countries lagged significantly behind the other more-developed countries. When calculated by income group, a (not so surprising) strong correlation appears between per-capita income and the agricultural research intensity ratio.

Table 3.5: *Agricultural research-intensity ratios by region and income group, total weighted average percentages (%)*

Region/income group [a]	1961-65	1971-75	1981-85
Sub-Saharan Africa (37) [b]	0.26	0.42	0.49
China	0.42	0.40	0.41
Asia and Pacific, excl. China (15)	0.14	0.22	0.32
Latin America and Caribbean (26)	0.30	0.46	0.58
West Asia and North Africa (13)	0.28	0.50	0.52
Less-developed countries (92)	0.26	0.34	0.41
More-developed countries (18)	0.96	1.41	2.03
Low (30)	0.25	0.30	0.37
Lower-middle (28)	0.24	0.35	0.40
Middle (18)	0.25	0.46	0.57
Upper-middle (18)	0.27	0.44	0.55
High (16)	1.08	1.57	2.23
Total sample (110)	0.48	0.63	0.71

[a] Countries assigned to income classes based on 1971-75 per-capita GDP averages where low is < \$600; lower middle is \$600-1499; middle is \$1500-2999; upper middle is \$3000-5999; and high is ≥ \$6000.
[b] Bracketed figures represent number of countries in each region or income class.

Although agricultural research-intensity ratios approximately doubled in both more- and less-developed countries between 1961-65 and 1981-85, they declined in the latter half of that period in 37% of the less-developed countries, one-half of which were in sub-Saharan Africa.

Research investment has traditionally produced high levels of return compared with investments in other areas, up to and exceeding 35% in some instances (Echeverría 1990). This fact, and the gap in investment compared with more-developed countries, has led some authorities to conclude that many less-developed countries underinvest in agricultural research. It has also led to calls from the World Bank, for example, to set a research investment target of 2% of AgGDP (World Bank 1981).

Research-intensity ratios are useful to policymakers because they indicate the importance other countries attach to agricultural research. But they may be an unreliable indicator of the appropriateness of a nation's research investment because the efficacy of a country's research endeavor differs between regions and over time. It could, therefore, be more helpful, instead of setting arbitrary targets for research investment, to fix a desired rate of return from the investment made – to set targets that would push rates of return to below 20%, for example.

The data presented in table 3.6 show that low-income countries spend a considerably greater share of overall public expenditures on agriculture and agricultural research than high-income countries, around 11% on agriculture and 0.7% on agricultural research, compared with 2.7% and 0.2%, respectively, in high-income countries. Moreover, the share of public expenditures on agriculture directed specifically to research remains surprisingly constant, at around 8% in 1981-85, for both poor and rich countries alike.

Table 3.6: *Agricultural and agricultural research shares in public-sector expenditures*

Income group [a]	1971-75	1976-80	1981-85
Percentage of agricultural expenditures in total government expenditures			
Low (13) b	10.5	11.7	11.2
Lower-middle (18)	7.5	8.1	9.3
Middle (12)	6.5	5.7	5.2
Upper-middle (12)	6.7	4.7	4.3
High (15)	3.0	2.7	2.5
Total sample (70)	7.1	6.9	6.8
Percentage of agricultural research expenditures in total government expenditures			
Low (13)	0.8	0.7	0.7
Lower-middle (18)	0.7	0.5	0.6
Middle (12)	0.5	0.4	0.4
Upper-middle (12)	0.2	0.2	0.2
High (12)	0.3	0.2	0.2
Total sample (70)	0.5	0.4	0.4

Note: All data represent simple averages across all countries in each income class.
a Countries assigned to income classes based on 1971-75 per-capita GDP averages where low is <$600; lower middle is $600-1499; middle is $1500-2999; upper-middle is $3000-5999; and high is ≥ $6000.
b Bracketed figures represent number of countries in each income class.

To understand why this is so would involve, at a minimum, a detailed consideration of the decision-making processes whereby public research investments, pricing policies and the like are jointly determined. Particular attention would need to be given to the relative incidence of research benefits and costs (across producers, consumers and taxpayers) in relation to alternative policy instruments, be they investing in rural public goods such as agricultural research versus taxes, subsidies and production quotas (Alston and Pardey 1994). In the absence of available case-by-case data, the macro-level figures in table 3.7 are suggestive of some of the political economy forces at work here.

Table 3.7: *Public spending per capita on agriculture and agricultural research*

Income group[a]	Government expenditure on agriculture			Agricultural research expenditures		
	1971-75	1976-80	1981-85	1971-75	1976-90	1981-85
Per head of agricultural population						
Low (13)[b]	14.0	18.9	21.1	0.9	1.1	1.3
Lower-middle (18)	44.0	69.5	102.1	3.7	4.0	5.3
Middle (12)	77.8	94.8	119.2	5.5	6.1	7.6
Upper-middle (12)	218.8	358.7	552.3	12.4	19.8	26.5
High (15)	1338.2	1423.1	1801.0	91.8	113.2	140.6
Total (70)	362.4	404.1	531.2	23.9	29.9	37.6
Per head of total population						
Low (13)	10.0	13.4	14.1	0.7	0.8	0.9
Lower-middle (18)	20.9	29.6	38.7	1.5	1.8	2.3
Middle (12)	31.6	35.3	38.1	2.4	2.3	2.6
Upper-middle (12)	66.0	62.1	93.0	2.2	2.5	2.7
High (15)	111.5	112.4	115.0	7.3	8.1	8.5
Total (70)	47.9	50.9	56.3	2.9	3.2	3.5

Note: All data represent simple averages across all countries in each income class and are expressed in constant 1980 PPP dollars.

[a] Countries assigned to income classes based on 1971-75 per-capita GDP average where low is <$600; lower-middle is $600-1499; middle is $1500-2999; upper-middle is $3000-5999; and high is ≥ $6000.

[b] Bracketed figures represent number of countries in each income class.

While total government spending on agriculture, indexed over the agricultural population, increases dramatically by a factor of 85 times, from around $21 per capita in the low-income countries to $1800 per capita in the high-income countries, there is only a corresponding 8-fold increase in agricultural spending indexed over the total population. Per-capita spending on agricultural research follows a similar pattern. Thus, as one moves from low- to high-income countries, the level of per-capita “benefits” or transfers accruing to rural-based coalitions may well increase at a disproportionately larger rate than the per-capita incidence of “costs” associated with such programs. If this were the case, the willingness of rural-based coalitions to lobby governments in support of agricultural research (and other forms of interventions that transfer resources to agriculture rather than the nonagricultural sector) may, in turn, be positively associated with per-capita income. Modeling and quantifying governments' incentives to invest in rural public goods such as research is necessary but far from sufficient to develop policies that help sustain support to public-sector agricultural research.

Donor support. While funding for agricultural research is only a small part of international development aid programs, it constitutes a significant contribution to the financing of numerous less-developed NARSs. Aid from donor countries or organizations is particularly vital for countries where high levels of international debt and an inadequate tax base make it virtually impossible for the national government to adequately support a viable agricultural research program.

There is a serious lack of data available on precise levels of donor support to NARSs. What available data there are, are difficult to standardize given the disparate reporting methods used by NARSs as well as donors. Figures from donor countries and organizations for the period 1981-85 put contributions to agricultural research at an average of $658 million a year, which amounts to a very modest 1.9% of total official development assistance to less-developed countries. Based on data from the NARSs, donor contributions in that period amounted to only about $355 million a year. This discrepancy can probably be explained by the fact that NARSs commonly underestimate the full extent of contributions they receive. In estimating donor support, NARSs, quite understandably, often exclude payments in kind, such as the salaries and expenses of expatriates working for them, which can be a substantial element of aid contributions. It is also difficult to compile accurate figures on the amount of aid to a research system when it is given as part of a wider package of aid that is distributed through the country's national government.

The available data suggest that, in real terms, donor aid to NARSs has fallen since 1980 as overall levels of development aid have stood still. The World Bank accounts for around 25% of donor funds applied to agricultural research in the less-developed world, but the Bank's support for individual national research endeavors declined during the 1980s. Moreover, this support is concentrated in just a few NARSs. Of the $817 million it allocated to strengthen less-developed NARSs during the period 1981-87, two-thirds went to only six projects.

The levels of external funding to national systems vary enormously, from none in Venezuela and South Korea to 85% in Tuvalu. Sub-Saharan Africa had the highest rate of donor funding, receiving on average 35% of its expenditures from donors. NARSs in the Asia and Pacific region received an average of 26% of their funding from donors. The levels of donor support to NARSs in Latin America and Caribbean, and West Asia and North Africa were much lower, 7% and 11%, respectively.

3.5 *Concluding observations*

While the past contributions of agricultural research to productivity gains and the improvements in living standards that followed have been impressive, the challenges that lie ahead are considerable indeed. There will be unprecedented increases in the demand for additional food and fibre production while the threats to even achieving, let alone sustaining, such levels of output in the face of a degrading natural resource base for agriculture loom large. Such threats appear as real for the more-favored, intensively cultivated production environments as they are for the more marginal areas (Pingali 1994).

There are unlikely to be any quick technological "fixes" to addressing these concerns. In fact, for the more immediate term at least, maintaining as well as enhancing past productivity increases is likely to come from the incremental gains arising from a whole array of new technologies and management practices (Byerlee 1994). While individually less "newsworthy" than the Green-Revolution technologies of the past, these sources of growth, when taken as a group, will nevertheless be just as real.

But to realize these output gains in a manner that preserves the environment will require a sustained commitment to national and international research endeavors. While many countries experienced a substantial growth in their research capacity in the 1960s and 1970s, a considerable number saw an erosion of their public-sector research capacity in the 1980s. Although privately sponsored research endeavors are sure to grow in the future, the corollary is not necessarily to cut back on public-sector investments. In fact, the substantial growth in privately sponsored research in the U.S. over the past several decades occurred in conjunction with a continued, albeit slower, growth in public-sector research investments.

To fully harness the potential complementarities and synergy between public and private research endeavors will require that more attention be given to each sector's comparative research advantage. In particular, the gains to researching improved agricultural management and production practices – those that will play a large role in realizing sustainable improvements in agricultural output – are generally difficult to appropriate and likely to remain the domain of the public sector. So too are the more basic, pretechnology types of research that, in turn, lay the foundations for the privately-sponsored applied and adaptive research programs of tomorrow. Failure to support and nurture today's research endeavors may well reap many unfortunate and undesired consequences in the not-too-distant future.

4. Financing agricultural research: International investment patterns and policy perspectives

By Julian M. Alston, Philip G. Pardey, and Johannes Roseboom[1]

4.1 *Introduction*

Public agricultural research funds have become tighter in recent years, and in some places funding has fallen in nominal as well as real terms. This reversal of funding trends, following a long period of sustained growth, has been shared in national and international agricultural research programs, in rich and poor countries alike. Paradoxically, reduced support for agricultural research appears to have coincided with a new wave of concerns over the world's future capacity to feed itself while sustaining the natural resource base.

Tighter funding for agricultural science has been associated with a general tightening of government budgets for all purposes, and for all science in particular, perhaps reflecting a reduced faith in the capacity of science to do good. In addition to these general forces, some influences relate more specifically to agricultural science. In many places, especially in the more developed countries, agriculture has a shrinking constituency, and diminishing influence on policy. Some have questioned the value of investing in productivity-enhancing research and development (R&D) in an era of chronic surpluses driven by government subsidies, where research would exacerbate the subsidy drain on the public purse, at least in a developed-country context – an attitude that reflects an incomplete appreciation of the distinction between productivity and production, and the determinants of research benefits. Concerns over the environment have also become intertwined with agriculture. Taking an international perspective, some evidence of donor fatigue is apparent, reflecting a reduced humanitarian resolve to alleviate the plight of the world's poor, and notions that helping Third World agriculture through R&D is against the commercial and economic interests of First World farmers.

What seems not to be fully appreciated is that the rationale for government intervention to overcome an underinvestment in agricultural research remains no less relevant today than it was in the recent past. Recent developments in the technology of science itself, including modern biotechnology and information technologies, mean that the potential remains for substantial achievements in agricultural science, with profound potential to alleviate world poverty – possibly on the scale of the Green Revolution of the 1960s and

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[1] This chapter is a verbatim reproduction of an article published earlier in *World Development* Vol. 26, No. 6 (June 1998): pp. 1057-1071. Not included are the summary and keywords. All headings and footnotes have been renumbered in order to fit with this dissertation. References have been included in the reference list to this dissertation. The authors wish to thank Nienke Beintema for her excellent research assistance and Peter Hazell and two anonymous referees for their useful comments on an earlier draft of this paper which was presented at the International Association of Agricultural Economists (IAAE) conference held at Sacramento, California, in August 1997. Partial support for this work was provided by the University of California, Pacific Rim Project. Final revision accepted: 4 November 1997.

1970s – as well as enormous benefits for rich country producers and consumers of food and fiber. But in spite of changes in intellectual property protection, incentive problems persist. Unfortunately, the long lags between investment in research and its impacts mean that serious consequences of reduced funding today will not be visible for many years, and could persist for a long time into the future.

The purpose of this article is to defend global investments in public agricultural research, and to propose institutional changes to support more effective ways of generating agricultural R&D funds and allocating them. In the first part of the paper, we lay out the economic principles supporting government intervention in agricultural research, including a discussion of the alternative forms that such intervention may take, and their relevance for multinational government intervention to deal with global underinvestments in certain types of research. These in-principle arguments are supported with some empirical evidence on the past successes in public agricultural research policy in practice. In the second part we present new, detailed data on global patterns of investment in R&D. We contrast public- and private-sector investment patterns, and richer and poorer countries, as well as the international research investment patterns. In the conclusion of the paper we discuss the nature of the persistent market failures in agricultural research, especially in relation to international research spillovers, a context in which the institutional arrangements for correcting market failures are especially inadequate.

4.2 *Economic principles for government intervention in research*[2]

4.2.1 *Rationales for government intervention*

Market failure in agricultural R&D seems to be widely taken for granted. The main reason is inappropriability of benefits. Often, those who invest in R&D cannot capture all of the benefits – others can "free-ride" on an investment in research, using the results and sharing in the benefits without sharing in the costs. Hence, private benefits to an investor (or group of investors) are less than the social benefits of the investment and, as a result, some socially profitable investment opportunities remain unexploited.

Specifically, in the absence of government intervention, the investment in agricultural research is likely to be too little, for several related reasons. First, the nature of research activity, which is usually long-term, large-scale, and risky, means that the typical firm in agriculture is not able to carry out effective research (although it can help to fund it). Hence, institutions may need to be set up on a collective basis to fund or carry out research.[3] Second, the returns to new technologies or processes are often high, but the firm responsible for developing a technology may not be able to appropriate all the

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[2] Many of the ideas sketched in this section and the next are developed in greater detail in Alston and Pardey (1996), Alston and Pardey (1998).

[3] There are exceptions to the *typical* situation, but even when firms are large enough to find it profitable to carry out some research there is still likely to be too little research for the other reasons (appropriability and externalities).

benefits accruing to the innovation, often because fully effective intellectual property protection (e.g. patenting or secrecy) is not possible.[4] Third, some research benefits (or costs) accrue to people other than those who use the results. In particular, agricultural R&D is characterized by very long lags between research investments and impacts, which means that benefits from today's research investments may accrue primarily to some future generation of producers and consumers. These reasons for private-sector underinvestment in agricultural R&D also help explain the empirical finding that agricultural R&D has been, on average, a highly profitable investment from society's point of view.

Other reasons for government intervention in agricultural R&D relate to more general market failures, including distortions arising from externalities.[5] The existence of externalities means that marginal *private* costs (or benefits) from economic activities differ from the corresponding marginal *social* costs (or benefits) and, as a result, private decisions will not be socially optimal: a market failure. Hence, in the absence of government intervention, commercial decisions will tend to produce too much pollution and preserve too little pristine wilderness. Agricultural R&D can affect the balance by generating technologies that are both privately profitable and, say, environmentally friendly, relative to the current technology. But the very nature of (negative) externalities means that it does not pay private investors to make an effort to reduce them, either in the choice of production practices with given technology, or in the choice of the direction of technology to evolve through research, development, and adoption decision.

Similar arguments apply to the development and adoption of technologies that consume stocks of unpriced or underpriced natural resources. Hence, private incentives are liable to lead in the direction of the development and adoption of excessively consumptive technologies unless government acts to modify the incentives and "internalize" the externalities. These arguments mean that, even in the absence of market failures associated with the atomistic nature of agricultural production, there will be distortions in incentives so that the direction of research will be biased against externality-mitigating technologies in favor of externality-exacerbating technologies. There is too little R&D due to inappropriability; the mix of R&D is biased due to externality effects (Alston *et al.* 1995).

These conclusions from in-principle arguments are backed up by empirical evidence on the payoff to past investments in agricultural R&D across different commodities and different countries. For example, Echeverría (1990) and Alston *et al.* (1997) document the results of a large number of studies of rates of return to agricultural research. Notwith-

[4] This appropriability problem extends beyond relations among single individuals to relations among collectives such as one producer cooperative or industry group versus another, and among states and even countries.

[5] Externalities arise when one individual's production or consumption activities involve spillover effects on other individuals who are not compensated through markets. Groundwater pollution with agricultural chemicals is an example of a *negative* externality. Free-riding by others on an individual's research results, as discussed above, is a type of externality, too – a *positive* externality, having favorable spillover effects.

standing concerns that the rate of return evidence has on balance been biased upward, the general conclusion is that rates of return to agricultural research have been comparatively high; certainly high enough to justify past investments, and, as many have argued, to warrant increased public investment or other forms of government interventions designed to increase overall investment.

4.2.2 *International market failures*

There is no particular reason to expect the fundamental forces giving rise to market failures in agricultural research to pay much attention to national borders. Indeed, national borders may well exacerbate market failures in research by adding to the costs of organizing institutional arrangements for collective action by producers where research is applicable on both sides of a border. In other words, when research undertaken by producers or the government in one country is applicable in another country, the international spillovers of technology (and the price effects of the technology) give rise to a market failure since the benefits from research by one country are not fully appropriable. There is no difference from spillover problems arising within a country (say among different states), except that there is no encompassing global government that can play the role that the national government would play in resolving within-country market failures. International spillovers must be dealt with by cooperative action among national governments. It would be easy to understate this issue.

Past efforts in developing collaborative international research programs were not instigated by the impulses of national governments to cooperate and raise research efficiency globally. Rather, it was the actions of private benevolent foundations (Ford and Rockefeller), more clearly pursuing a humanitarian aid objective than any other, that led the way to the development of the current system of international centers known as the Consultative Group on International Agricultural Research (CGIAR, or CG for short). Over time, the relative importance of the private foundations in the CG system has weakened, and support from some national governments, notably in North America, has slipped as well. This phenomenon should not be surprising. It is the essence of market failure that cooperative solutions among self-interested groups are hard to sustain when free-riding on the efforts of others appears to be a viable alternative. By the same token, financial support from the less-developed countries – targeted as the primary beneficiaries from the CG system – has never been strong. And private research organizations have also provided minimal financial support for a system from which they clearly benefit directly. Market, political, and institutional failure is pervasive in international agricultural research.

International research remains a relatively small part of the global agricultural research business, at least in terms of the annual investments in R&D, if not in terms of their impacts on agricultural technology. Recent research has shown, however, that the past and future potential returns to international agricultural research are very high. For instance, Maredia and Byerlee (1997) have shown that most countries cannot operate a wheat-breeding program of sufficient size to take full economic advantage of the available economies of size and scope. In addition, several studies (e.g. Brennan and Fox 1995; Pardey *et al*. 1996) have documented evidence that benefits from wheat and rice research conducted in international centers have yielded major payoffs in Australia and the United Stated (which are more often viewed as donor countries rather than recipients of benefits from the CG system) as well as in less-developed countries. These studies have shown huge rates of return to this investment, from both a global perspective and from the perspective of donors who have been "doing well, by doing good" (Tribe 1991).[6] The confounding of self-interest of donors in the technologies to be generated, with the humanitarian objective in giving research aid, exemplifies the complexity of the economic efficiency and distribution issues that arise in designing institutions for international research.

4.2.3 *Forms of government intervention*

It is one thing to establish a case of market failure. It is another to determine the best action for government to take to reduce the social costs of the market failure. Indeed, taking *no* action may sometimes by the optimal policy. Many interventions are used in relation to agricultural R&D. They include the definition of private property rights (e.g. recent changes in intellectual property protection involving plant variety protection certificates or utility patents for plants), enhanced incentives for private R&D (e.g. through the provision of tax breaks, direct subsidies, or other incentives), the provision of public funds for publicly or privately executed R&D through competitive grants, or the creation of public- or private-sector R&D institutions (e.g. legal arrangements under which an industry funds research cooperatively). The dominant strategy around the world has been to use government revenues to finance public- or private sector R&D. This includes the provision of tax concessions and other financial incentives for private R&D, which involves a loss of government revenues, as well as the direct use of government funds both to finance private R&D, through grants and contracts, and to finance the production of knowledge in a variety of publicly administered R&D organizations.

These alternatives may all differ in terms of their incentive effects, and in their implications for the net social (deadweight) cost of distortions in the quantity and mix of research, and the total social cost of financing R&D. An intervention is justified only if it improves the situation by reducing the social costs of market failure – the benefits of the intervention must be greater than the costs. Different interventions will be more or less effective at correcting different types of market failures; they will also have different distributional (or equity) consequences.

[6] For instance, Pardey *et al*. (1996) showed that by the early 1990s, about one-fifth of the total US wheat acreage was sown to varieties with CIMMYT ancestry, and around 73% of the total US rice acreage was sown to varieties with IRRI ancestry. This meant, for example, that US wheat producers gained at least $3.4 billion over 1970-93 from CIMMYT wheat variety improvements, which implies a ratio of benefits to costs borne by the United States of at least 40:1. The same study found that California alone could have profitably financed the entire CIMMYT research program, given the benefits flowing to California's wheat producers.

4.3 *Financing research: principles and practices*

The economic justification for government intervention in agricultural R&D is that economic efficiency will improve as a result. In this context, economic efficiency is an inclusive concept that refers to the achievement of the greatest net benefits for the society as a whole, taking a broad view of net benefits. For instance, it includes benefits such as sustainability (to the extent that there are net benefits from the development and adoption of more sustainable resource-use patterns), environmental objectives (e.g. where R&D can lead, economically, to a reduction in pollution), and nutritional objectives (to the extent that there are net benefits from R&D directed towards improving dietary quality and health). Such non-pecuniary benefits are included along with pecuniary benefits, in a broad concept of net national benefits. The idea of economic efficiency is to make those net national benefits as great as possible.

Agricultural R&D is generally a blunt and ineffective instrument for objectives other than economic efficiency. Hence, distorting the agricultural R&D portfolio away from economic efficiency in the pursuit of non-efficiency objectives is likely to involve a high social opportunity cost. However, while the research program may be designed primarily to increase the size of the total economic pie, inevitably the shape of the pie and the way it is sliced among groups will be affected to some extent by the choice of research priorities. Unless other policies are in place that can correct fully for any unintended side-effects of agricultural research on other objectives, it may be necessary to trade off efficiency gains from research for other objectives such as equity or security. In our view, such trade-offs should be limited, and it is appropriate to focus largely, if not exclusively, on economic efficiency considerations when choosing how to finance, organize and manage public-sector agricultural R&D.[7]

Whether the potential improvements in economic efficiency are realized will also depend on how the public-sector R&D is financed – whether by patents, federal or state government revenues, industry levies, sales of services or products, or gifts. The economic gains achieved by intervening to provide government-produced R&D also depend on the details of the institutional arrangements affecting the organization of research and management of research resources (in terms of incentives and procedures for allocating resources). Hence, these administrative aspects, too, are the subjects of policy.

4.3.1 *Financing strategies*

A mix of private and public funding is used to support national and international agricultural research, and in many countries national and provincial governments conduct separately administered programs of research. The primary source of funding for these

[7] One possible exception to this general position is that it may be economically efficient to use agricultural R&D rather than existing farm programs if the objective of the farm programs is to transfer income from taxpayers to farmers. While raising net income to society as a whole, agricultural research also raises farm incomes, an outcome that is clearly superior to making society as a whole worse off in order to transfer income to farmers.

expenditures is general tax revenues, an expensive source of revenues. Recent studies in the United States and Australia, for instance, have shown that it costs society well over a dollar to provide a dollar of general taxpayer revenues to finance public expenditure; in less-developed countries, the taxation systems are likely to be less efficient and the marginal opportunity cost of government spending is likely to be even higher than in the developed countries.[8] Alternative sources of revenue may be less expensive, fairer, and politically more sustainable, when used to finance certain types of research and achieve an expanded total public-sector R&D budget.

Different agricultural R&D programs and projects call for different funding arrangements. Agricultural R&D may be a public good in the sense of (at least partial) non-excludability and non-rivalness, but this does not mean that everybody in a country, or the world, benefits and it does not mean that everybody should pay. Both fairness and efficiency are promoted by funding research so that, as much as possible, the costs are borne in proportion to the benefits. This can be promoted by choosing funding arrangements that reflect the geographic focus and the commodity orientation of the research, which implies a greater use of both subnational and multinational, regional, or commodity R&D programs.

In addition, following Alston and Pardey (1996), a greater use of commodity levy funding (i.e. levy per unit of commodity output of value) is suggested for three reasons. First, industry funding is a potential complement to other sources of funds which, as a practical matter, are likely to continue to leave total funding inadequate. Second, commodity levies are likely to be a relatively efficient (and fair) tax base.[9] Third, industry funding arrangements can be organized to provide incentives for efficient use of both the levy funds and other research resources.

[8] Fullerton (1991) and Ballard and Fullerton (1992) provide a general discussion of the marginal excess burden of taxation in the United States. Findlay and Jones (1982) provide estimates for Australia. See also Chambers (1995) and Corden (1974). Fox (1985) and Dalrymple (1990) discuss the implications of the deadweight costs of taxation for the measures of benefits and costs of research. Alston and Pardey (1996) summarize much of this discussion and its relevance for financing agricultural R&D.

[9] One can take issue with this position. In an ideal world, with efficient general taxation measures (e.g. income taxes), general taxation revenue would be obtained in the least-cost way, and general taxation would be at least as cheap as a specific commodity tax to fund agricultural research. In such a world, arguments for earmarked commodity taxes to fund specific research programs would have to follow the general form of arguments for earmarked taxes. In reality, however, least-cost taxation measures seem not to be applied. This issue then is whether, in a general equilibrium setting, at the margin a commodity tax would be a cheaper source of funds for research than the general taxation measures already being applied. In most developed-country settings, in which agriculture is relatively effectively subsidized, it could more easily be presumed that a small tax on agricultural commodity production would be more likely to reduce, rather than exacerbate, the social costs of existing distortions. More generally, a view about the particulars of the situation may be required before a judgment can be made about whether commodity levies are efficient sources of funds for research. Chambers (1995) provides a general equilibrium model of the incidence of agricultural policies.

Levy funding is clearly applicable to research on a particular commodity. By definition, this is not basic research involving the acquisition of knowledge with no particular application or use in view (OECD 1994). Levies are also more applicable for commodities that are traded through markets in developed industries and less applicable to, say, subsistence crops or commodities for which markets are not well developed and where, in consequence, the costs of raising levy funds would be prohibitively expensive. Similarly, levy schemes tend to be less applicable to research that affects multiple commodities and research that applies to particular factors of production or that has an environmental focus. However, these issues notwithstanding, commodity levies could be used more extensively to support the significant proportion of research that can be identified with a well-defined commodity (or other) interest group. Around the world, such mechanisms are relatively underutilized in the sense that only a small fraction of total R&D resources are generated in this fashion.

4.3.2 *Research organization*

The appropriate regional and institutional structure for organizing research programs ought to vary according to the nature of the research. Some issues are clearly national issues and are appropriately addressed by national programs. But a national government can choose whether to address an issue using national funds in national research institutes, or in sub-national or international public organizations (or, for that matter, in private organizations), or by using incentives to encourage other organizations to take joint action. Some other issues (such as the development of new crop varieties or the preservation of germplasm stocks) clearly have multinational aspects, calling for international approaches. Unfortunately, in many cases the R&D jurisdictions of states and nations overlap in complicated ways, and the solution is not clear – or, if it is, the appropriate institutional arrangements are absent. Moreover, for some of these policy problems the relevant economic framework has not yet been fully developed.

4.3.3 *Research management*

Some of the potential benefits from the agricultural research enterprise may have been wasted in inefficient resource allocation. In many countries, the current set of institutional arrangements apportions research funds among alternative research-executing agencies in ways that make little use of economic concepts. Buzzwords and fads seem to increasingly dominate the evolving research agenda in a good many places. Having a well-defined and appropriate set of objectives is a necessary first step to making informed policy and resource allocation choices. With a single objective, decision making is relatively easy.[10]

Any research resource allocation mechanism nevertheless involves costs, including (i) information costs, (ii) transactions costs, and (iii) costs of resource misallocation. Different processes involve different amounts of these different types of costs. Those who

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[10] We argue for economic efficiency (broadly conceived) as the primary and sole objective, but not everyone agrees with that position (Alston *et al.* 1995; Alston and Pardey 1996).

favor block grants or funding by formula, because they save wasteful expenditure on competitive processes or rent-seeking, must consider that these costs are more important than the potential inefficiencies in research resource allocation that arise from not allowing others to compete for the funds allocated according to the formula. Moreover, for a competitive grant scheme to dominate other processes, the costs of additional paperwork, submission of grant applications, and reporting procedures, must be seen to be less than the benefits from improved information and efficiency of allocation of research resources. It seems likely that different types, or combinations of types, of research resource-allocation procedures may be warranted depending on the nature of the research institution, and the research itself, being undertaken. Over time, resource misallocation costs are likely to become relatively large in a formula funding context; on the other hand, too frequent accounting in a competitive grant context is wasteful and uninformative. But even if funds are allocated primarily by formula, there will be benefits to be gained from the introduction of an economic way of thinking, and a view towards maximizing total net benefits, as an element of research management, as advocated by Alston *et al*. (1995)

4.4 *Agricultural research investment patterns*[11]

As we near the end of the twentieth century there are notable, and seemingly accelerating, changes in the amount and sources of support for agricultural R&D, the national and international roles in research, and the respective roles of the private and public sectors too. This section presents new, updated data on investments in agricultural R&D that provides a quantitative perspective on some of these developments.

4.4.1 *Measurement issues*

Measuring agricultural R&D investments is becoming increasingly difficult as the institutions involved in funding, managing, and performing agricultural R&D evolve and become more complex. Publicly managed research providers are increasingly spending private funds (e.g. farmer levies or corporate funds), while privately managed agencies are spending more public dollars (either directly or via tax concessions), and we see a growing number of joint public and private arrangements. Distinguishing between those who fund agricultural R&D (and, perhaps, manage the funds) and those who perform the research provides a clearer picture of changing institutional roles within programs of national agricultural research.[12]

[11] Some parts of this section draw heavily on data presented in Pardey *et al*. (1997) although some new, additional data are introduced an discussed here for the first time.
[12] Another, economically important, distinction is to identify who benefits from particular investments in or uses of agricultural R&D. Those who benefit from R&D can be quite distinct from those who bear the costs of the research, or those who adopt the results.

Another aspect that confounds international comparisons concerns differences in the meaning given to the term "agriculture." Readily available statistics often fail to distinguish between, farm-focused R&D and R&D directed toward the input supply, and food- and fibre-processing sectors. In addition, as the environmental emphasis given to agricultural R&D has increased, non-traditional agencies have begun to carry out research of relevance to agriculture, while some agricultural research spills over to sectors beyond commercial agriculture (e.g. pest and weed control methods from agriculture are used in urban gardens and golf courses).

The agricultural research expenditure series reported here are separated where possible into public and private categories, primarily on the basis of research performers rather than funders. In compiling these data, care was taken to maintain a consistent institutional coverage over time, and to make the data comparable across countries.[13] Although some unavoidable differences in data quality remain, these figures provide a reasonable and informative basis for making broad international comparisons.

4.4.2 *Global investment trends in public agricultural research*

Worldwide, investments by national governments in public agricultural research almost doubled in real terms over the past two decades; from $7.3 billion (1985 international dollars) in 1971 to nearly $15 billion in 1991 (table 4.1).[14] Expenditures on publicly performed agricultural research in developing countries grew by 5.1% per annum from $3 billion (1985 international dollars) in 1971 to $8 billion in 1991. Across the developed countries, public agricultural spending grew by 2.3% per annum from $4.3 billion (1985 international dollars) in 1971 to $6.9 billion in 1991 and $ 7.1 billion by 1993.

For all regions of the world, however, real R&D spending grew at a much slower pace during the 1980s than in the 1970s. In 1971, as a group, developing countries, accounted or 41% of the spending. By 1991 the situation had changed markedly. Developing-country R&D spending had grown to more than half (about 54%) of public-sector R&D spending worldwide. In 1991, Asian countries accounted for 62% of the developing world's publicly performed agricultural-research expenditures (19% for China alone), the Latin America and Caribbean as well as sub-Saharan African regions (including South Africa) each accounted for 12%, and 14% of the expenditures occurred in West Asia and North Africa.

[13]Agricultural research is taken here to include crop, livestock, forestry, and fisheries research. See OECD (1994) for additional, definitional details related to the compilation of science indicators.

[14] These "global" totals are preliminary estimates that exclude Eastern European and former Soviet Union countries. The principal data source for 1961-85 is Pardey *et al*. (1991). These data were revised and updated for African countries using various ISNAR *Statistical Briefs*; for most of the principal Asian countries (including China and India) with data from Pardey *et al*. (1996); and for the developed countries from Pardey *et al*. (1997). Semiprocessed data from numerous other sources were obtained for most of the mid-to-larger-sized NARS and a number of smaller systems. The less-developed countries for which we have direct estimates account for approximately 85% of the less-developed-country total.

Table 4.1: *Public agricultural research expenditures in developed and developing countries, 1971-91*

	1971	1981	1991
	(millions of 1985 international dollars)[a]		
Expenditures			
Developing countries (131)[b]	2,984	5,503	8,009
Sub-Saharan Africa (44)	699	927	968
China	457	939	1,494
Asia and Pacific, excl. China (28)	861	1,922	3,502
Latin America and Caribbean (38)	507	981	944
West Asia and North Africa (20)	459	733	1,100
Developed countries (22)	4,298	5,713	6,941
Global total (153)	*7,282*	*11,217*	*14,951*

	1971-81	1981-91	1971-91
		(percentage)	
Average annual growth rates			
Developing countries	6.4	3.9	5.1
Sub-Saharan Africa	2.5	0.8	1.6
China	7.7	4.7	6.3
Asia and Pacific (excl. China)	8.7	6.2	7.3
Latin America and Caribbean	7.0	-0.5	2.7
West Asia and North Africa	4.3	4.1	4.8
Developed countries	2.7	1.7	2.3
Global total	*4.3*	*2.9*	*3.6*

Source: Pardey *et al.* (1997).
Note: The 153 countries included in these totals correspond to the coverage reported in the appendix tables in Pardey *et al.* (1991). Notably, countries from the former Soviet Union and Eastern Europe are excluded, but here we include South Africa.
[a] Research expenditures denominated in current local currency units are first deflated to 1985 prices using local implicit GDP deflators taken from World Bank (1995a) and then converted to international dollars (where one international dollar is set equal to one US dollar) using the purchasing power parities taken from Heston *et al.* (1995).
[b] Figures in parentheses indicate the number of countries in the respective totals.

An alternative perspective on agricultural R&D spending is provided by the agricultural research intensity (ARI) ratio presented in table 4.2. The most commonly constructed ARI ratios express agricultural research expenditures as percentages of agricultural GDP.[15] In 1991, as a group, developed countries spent $2.39 on public agricultural R&D

[15] Agricultural GDP is a "value-added" measure of agricultural output that represents the gross value of output minus the value of purchased inputs such as fertilizer, pesticides, and machinery. Hence, these

for every $100 of agricultural GDP; a sizable increase over the $1.38 they spent per $100 of output two decades earlier. Developing countries, as a group, have much lower ARI ratios. In the early 1970s their ARI ratio averaged 38 cents per $100 of output, growing to only 50 cents by 1991.

Table 4.2: *Agricultural research intensity ratios (percentage)*

	1971-75	1976-80	1981-85	1986-90	1991
Developing countries	0.38	0.47	0.50	0.49	0.50
Sub-Saharan Africa	0.78	0.84	0.86	0.74	0.70
China	0.40	0.48	0.41	0.38	0.36
Asia and Pacific	0.26	0.36	0.44	0.50	0.55
Latin America	0.43	0.51	0.57	0.49	0.54
West Asia and North Africa	0.50	0.49	0.52	0.52[a]	0.52[a]
Developed countries	1.38	1.60	1.98	2.18	2.39
Global total	*0.67*	*0.76*	*0.81*	*0.79*	*0.81*

Source: Pardey *et al.* (1997).
Note: See table 4.1 for country coverage. Agricultural research intensity measures agricultural research spending relative to agricultural GDP.
[a] Extrapolated data.

Hence, it is still the case that richer countries invest public funds in agricultural R&D more intensively than poorer countries do. Using data on 64 developed and developing countries for 1991, figure 4.1 suggests an overall positive relationship between public agricultural research intensity and per capita income. Nevertheless, many low-income countries invest more intensively in agricultural research than a consideration of income alone would suggest. Figure 4.2 provides part of the explanation for this unexpected variation in research intensity: it indicates a negative relationship between a measure of the importance of agriculture in the domestic economy (agricultural GDP as a share of GDP) and agricultural research. So some low-income countries with comparatively small agricultural sectors invest relatively intensively in agricultural R&D (e.g. Botswana, Lesotho, and South Africa). Remaining differences in ARI ratios are attributable to a host of other factors, including the preferences of international donors, the policy stance each country takes in public support of its agricultural sector, and economies of scale and scope in agricultural R&D programs.[16]

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research intensity ratios are higher than, and not directly comparable with, other research intensity ratios that dived agricultural research spending by the *gross* value of output.

[16] See Alston and Pardey (1994) for a discussion of these issues in this context.

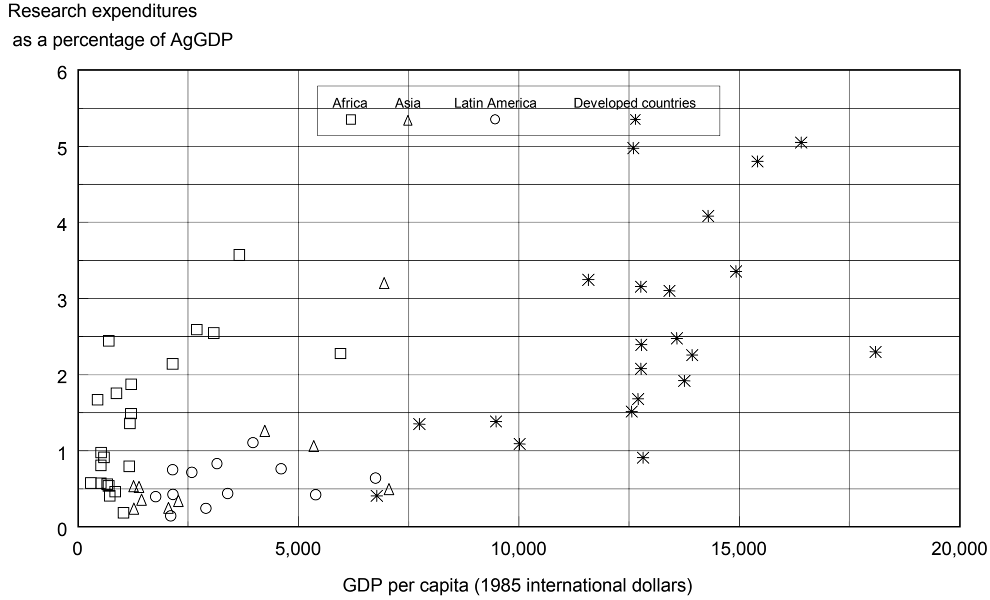

Figure 4.1: *Agricultural research intensities and per capita income, 1991*

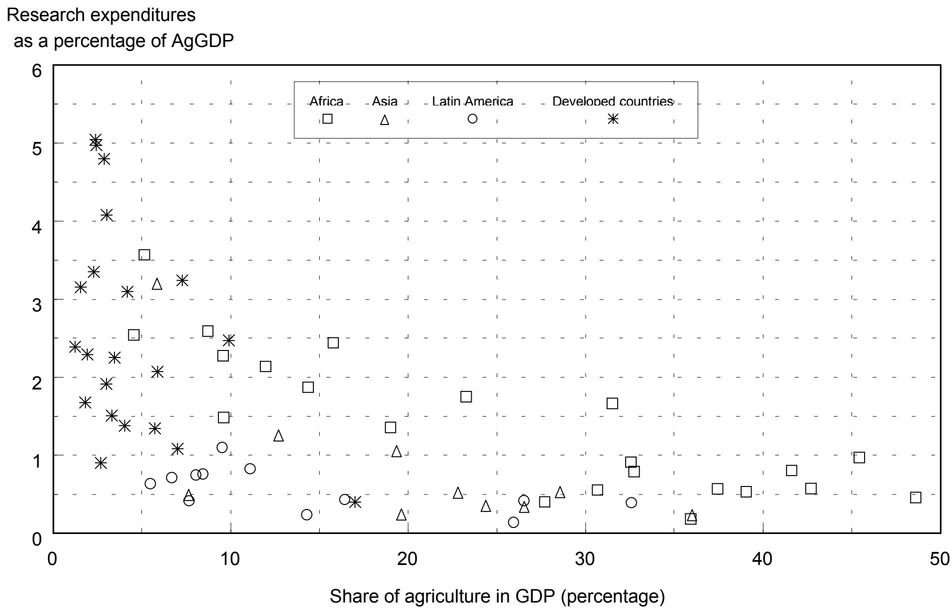

Figure 4.2: *Agricultural research intensities and the share of agriculture in GDP, 1991*

Other research intensity or spending ratios can be calculated, and two of these are reported in table 4.3. One measures agricultural R&D spending relative to the size of the economically active agricultural population; the other, relative to total population. In 1991, developed countries spent about $354 (1985 international dollars) per agricultural worker, approximately 2.5 times the corresponding 1971 figure. In 1991, developing countries spent $7 per agricultural worker, nearly two times the spending per agricultural worker in 1971. These differences between more- and less-developed countries are not too surprising, given the substantially higher proportion of developing-country workers employed in agriculture, and the more rapid contraction in the agricultural labor force in the developed countries over the past several decades. Research spending per capita has risen too, by an average of 40% for developed countries (from $6.30 per capita in 1971 to $8.84 in 1991), and by an average of 79% in developing countries (from $1.10 per capita in 1971 to $1.97 in 1991).[17]

Table 4.3: *Agricultural research spending ratios*

	1971-75	1976-80	1981-85	1986-90	1991
	(1985 international dollars per year)				
Research spending per economically active agricultural population					
Developing countries	3.81	4.83	5.75	6.45	6.99
Sub-Saharan Africa	8.67	9.20	8.76	7.98	7.60
China	1.62	2.14	2.71	3.07	2.98
Asia and Pacific	3.05	4.36	5.58	7.21	8.55
Latin America	13.04	17.81	20.13	19.36	21.80
West Asia and North Africa	13.08	15.46	20.43	24.22	27.05
Developed countries	144.0	190.64	250.03	304.10	354.25
Global total	*9.29*	*10.69*	*11.92*	*12.65*	*13.44*
Research spending per capita					
Developing countries	1.18	1.46	1.69	1.85	1.97
Sub-Saharan Africa	2.66	2.66	2.39	2.07	1.19
China	0.65	0.87	1.12	1.30	1.28
Asia and Pacific	0.91	1.24	1.53	1.88	2.17
Latin America	1.85	2.28	2.35	2.02	2.11
West Asia and North Africa	2.62	2.73	3.23	3.38	3.53
Developed countries	6.60	7.26	7.95	8.35	8.84
Global total	*2.36*	*2.65*	*2.90*	*3.03*	*3.18*

Source: Calculated by authors using R&D data from Pardey *et al.* (1997) and agricultural labor data from FAO (1995).
Note: See table 4.1 for country coverage.

[17] Alston and Pardey (1994) report comparable measures for developing countries and use these indicators to discuss the political economy aspects of public investment in agricultural R&D.

4.4.3 *Investments in private agricultural research*

A common perception is that agricultural research is primarily the domain of the public sector, while research in other sectors of the economy is the province of the private sector. But the new data presented in table 4.4 reveal that privately performed R&D is a prominent feature of contemporary agricultural R&D in rich countries. Indeed, the private share has trended up significantly since 1981 and now almost half the OECD's agricultural R&D is performed by the business sector. Privately performed agricultural R&D totaled $7 billion in 1993 compared with $4 billion in 1981; an annual rate of growth of 5.1% compared with 1.8% for publicly performed agricultural R&D, and 4.3% for private research in all (agricultural and non-agricultural) sectors in the OECD.

Table 4.4: *Privately performed agricultural R&D in OECD countries*

	1981	1986	1991	1993	Annual rate of growth 1981-93
	(millions of 1985 international dollars)				(%)
Expenditures					
United States	1,417	1,964	2,256	2,381	4.3
Japan	791	1,146	1,577	1,660	6.7
United Kingdom	404	474	593	614	5.0
France	256	390	504	565	7.2
Germany	426	492	520	459	1.3
Other OECD	701	955	1,199	1,351	5.7
OECD total [a]	*3,995*	*5,420*	*6,649*	*7,030*	*5.1*
	(percentage)				
Private share of total national agricultural R&D					
United States	46.6	52.1	52.7	53.7[b]	-
Japan	39.4	47.5	51.4	51.4	-
United Kingdom	52.1	55.8	62.0	62.4	-
France	38.4	47.4	52.5	52.9	-
Germany	58.7	61.8	61.6	58.0	-
Other OECD	28.1	31.0	34.4	37.0	-
OECD total [a]	*41.1*	*46.2*	*48.9*	*49.6*	-

Source: Calculated by authors using data from Pardey *et al.* (1997).
Note: Data does not include expenditures on agricultural machinery research.
[a] Includes 22 OECD countries.
[b] 1992 figure.

The relative importance of private R&D in total agricultural R&D varies across the OECD countries. In Belgium, Ireland, and the United Kingdom, the business sector performs over 60% of the agricultural research, and in Germany and the Netherlands the private share is now in excess of 55%. The United States and Japan, two countries that collectively account for over one-half of all privately performed agricultural research throughout the OECD, now also spend more on private than public R&D. The private share in the remaining OECD countries is smaller (about one-third in 1993), but the private orientation of agricultural research in these countries has been growing quite rapidly too. Private sector R&D in developing countries typically accounts for 10-15% of total agricultural R&D.[18]

Private and public agencies do different types of R&D. Around 12% of private research focuses on farm-level technologies whereas over 80% of public research has that orientation. Food-processing and other post-harvest research accounts for 30 to 90% of private agricultural R&D, and in countries like Australia, Japan, New Zealand, and the Netherlands it is the dominant focus of privately performed research related to agriculture. Chemical research (including agriculturally related pharmaceutical research) is of comparatively minor importance in Australia and New Zealand, but accounts for more than 40% of private research in the United Kingdom and the United States, and nearly three-quarters of private agricultural research in Germany. There is a clear concentration of particular lines of private R&D in particular countries. Japan, the United States, and France account for 33, 27, and 8%, respectively, of all food-processing research carried out by the private sector in the OECD. Chemical research related to agriculture is even more concentrated; the United States, Japan and Germany represent 41, 20, and 10% of all reported private-sector research.[19] This pattern of concentration of private agricultural research is unlikely to be altered significantly if counterpart research in developing countries was also considered.

4.4.4 *Investments in international agricultural research*

Internationally conceived and funded agricultural R&D is a relatively recent institutional innovation. Beginning in the mid-1940s, and at an accelerating pace through the 1950s, the Ford and Rockefeller foundations placed agricultural staff in less-developed countries to work alongside scientists in national research organizations on joint-venture projects. These efforts became the model for many of the subsequent programs in international agricultural research, and later evolved into the International Rice Research Institute (IRRI) at Los Baños, the Philippines, in 1960 and the International Maize and Wheat Improvement Center (CIMMYT) et El Batan, Mexico, in 1967. Soon after, other inter-

[18] Pray and Umali-Deininger (1998) estimate that in 1995 private spending on agricultural R&D in countries like Argentina, Brazil, Chile, Colombia, Peru and Venezuela was less than 10% of total agricultural R&D spending. Beynon (1996) reports corresponding, contemporary (exact year not documented) private sector shares of at least 15% and 30% for Kenya and Zimbabwe, respectively.
[19] These data exclude Switzerland, whose share of agricultural chemical R&D is likely to be substantial but unlikely to place it among the top three performers.

national centers were established at Ibadan, Nigeria (IITA), in 1967 and at Cali, Colombia (CIAT), in 1968.

The further development of international agricultural research centers took place largely under the auspices of the Consultative Group on International Agricultural Research (CGIAR), which was established in 1971.[20] The CG system began modestly. During 1960-64, of the institutes that would become the CG only IRI was operating as such. After an initial funding of $7.4 million (nominal US currency) – mainly spent on capital to establish IRRI – in 1960, annual expenditures were quite small. Total funding had risen to only $0.6 million per year in 1964. But by 1970, the four founding centers were allocated a total of $14.8 million annually. During the next decade, the progressive expansion of the total number of centers, and the funding per center, involved a tenfold increase in nominal funding, to $142 million in 1980. During the 1980s, funding continued to grow, more than doubling in nominal terms to reach $288 million in 1990. The rate of growth had slowed but was still impressive. In the 1990s, however, although the number of centers grew – from 13 to 18 at once point, but now 16 – funding did not grow enough to maintain the funding per center, let alone the growth rates.

While the CG system has captured the attention of the international agricultural R&D and aid communities, through the impact of its scientific achievements, and through its pivotal role in the Green Revolution, it has spent only a small fraction of the global agricultural R&D investment. In 1991, the CG represented 1.8% of the nearly $15 billion in public-sector agricultural R&D.

Over time, the number of donors grew, and the pattern of support varied. In 1995, 44 donors provided a total of $328.1 million to the CG. In the beginning (using 1972 figures), the private foundations provided 50.9% of the total; Europeans as a group provided 12.6%; the United States, 18.8%; and the World Bank, 6.3%.

The picture is now very different (table 4.5). If providing seed money and being eventually displaced was their vision, the private foundations were successful. Their funding support has fallen in nominal terms and now constitutes less than 2% of the total. In 1995, European countries as a group (excluding multilateral support through the EU) provided 113.1 million nominal US dollars – 34.9% of the total. In the same year, the World Bank provided $50 million (15.2%); the United States provided $40.5 million (12.4%), and Japan provided $37.3 million (11.4%).

[20] For more details on institutional developments related to the CGIAR see Baum (1986), Gryseels and Anderson (1991), Pardey *et al*. (1997), and Anderson (1998).

Table 4.5: *Funding support to the CGIAR*

	1972-75	1981-85	1991-94	1995
	(millions of 1993 dollars per year)			
United States	18.3	69.0	57.4	39.1
Japan	0.9	13.3	31.9	36.0
Europe	19.2	53.7	98.6	109.0
Other countries	9.6	20.5	27.7	21.6
Total from developed countries	*48.0*	*156.5*	*215.6*	*205.7*
World Bank	6.7	28.9	41.2	48.2
Foundations	22.8	4.3	6.2	6.4
Others	10.1	54.5	50.6	56.1
Total	*87.6*	*244.2*	*313.5*	*316.5*

Source: Taken from Pardey *et al.* (1996) and based on financial reports of the CGIAR Secretariat.

The rise of support from Japan and the World Bank has been an important factor in the overall support for the system in recent years. Through institutional and government aid programs, the developed countries as a group contributed $326.1 million in 1995; 98% of the total allocation. Some developing countries who host CGIAR centers, and those who engage in collaborative programs of research with the international centers, have made substantial in-kind contributions to the CGIAR, but developing countries as a group have provided comparatively little funding to the CGIAR. In 1995 a group of 10 developing countries provided $5.8 million – a small (2%), but of late increasing, share of CG funding. Colombia, India, and Iran were the largest of the less-developed country donors, each contributing about $1.2 million.

Developed- and developing-country farmers alike have also provided little funding for the CGIAR, although some agencies such as Australia's Grains Research and Development Corporation (which is partially supported through commodity levies) have funded small amounts of international research in recent years. Funding for CG research from other, private sources has also been sparse.

4.5 *Conclusion*

The main messages in this paper are relatively simple ones. There is scope for a more economic approach to financing, organizing and managing public-sector agricultural R&D in national systems and in the international research system. Financing can be made more efficient – in terms of a more efficient total quantity of research resources, a lower cost of raising the revenues, and greater allocative efficiency – by using more industry levy funds. The organization of research could be made more efficient by the development of alternative institutions, to bridge the gap between state, national, and multinational jurisdictions, and the greater use of economic efficiency criteria to determine the balance between different types of R&D organizations. Finally, the management of R&D can be improved by substituting economic incentives for central directions, by applying economic efficiency as the objective of research, and by using more competition rather than committees to allocate resources.

The past 25 years have witnessed an overall rapid growth in real support for agricultural R&D in rich and poor nations, and in the international centers. The world's poorest countries have increased their share of global public agricultural research investments during this era. This is not an inappropriate shift, given that most less-developed countries are still investing little relative to the size of their agricultural sectors, and still seemingly underinvesting. International research aid may be good for global economic efficiency, but continues to be motivated largely on humanitarian grounds. It is only because less-developed countries grossly underinvest in research, that donor support for less-developed country NARSs (National Agricultural Research Systems) is a good form of aid for these countries. It is in the interest of every country (although not necessarily every person in every country) to do more to reduce its own persistent underinvestment in research. By the same token, it is in the immediate self-interest of many more- and less-developed countries alike to see greater support for the international centers conducting research that has important spillover effects. International research may be sustainable even if individual nations were not underinvesting in their own NARSs, and donor support for such research may be an efficient and effective form of aid when international transaction costs mean that the international centers are undersupported.

The past five years or so have been characterized by a break in the trends of the previous 20 years, with weakening government support for national and international research. Such a withdrawal of support for domestic and international agricultural research does not seem to be justified by the available evidence on the past returns to like investments. The implication is that political and institutional failure has taken over from market failure as a factor in the chronic global underfunding of agricultural research.

Institutional failure arising from spillover technology is nowhere more clearly apparent than in the international context. There is no global government with the capacity to impose Pigovian taxes and finance an economically optimal, international research system. Yet many technologies know no national boundaries, and emerging evidence suggests that all but the few very largest NARSs are too small to achieve economies of scale and scope in certain fields of research, and intellectual property rights provide inadequate protection for the inventor. Even if we can persuade ourselves that within-country institutions are adequate, say, within the richest countries, to provide efficiently and effectively an appropriate total R&D effort, and an appropriate research mix, we cannot deny the political and market failure in international agricultural research.

5. Investments in African agricultural research

By Philip G. Pardey, Johannes Roseboom, and Nienke Beintema[1]

5.1 *Introduction* [2]

There is a perception the world over that public agricultural research systems need to be revamped and revitalized. This perception is particularly prevalent regarding African agricultural research systems. After significant increases in investments in public sector agricultural research and development (R&D) throughout much of Africa in the 1960s and 1970s, the 1980s saw a reversal of this trend. Growing levels of international indebtedness and programs of structural adjustment spurred government austerity programs that curtailed public sector spending in general and scaled down public investments in agricultural research. Bilateral and multilateral grants and loans made up for some of the shortfall although many national systems experienced stagnant or declining funding support over recent years.

Consequently, renewed attention is being paid to the policy options for public agricultural research in Africa and elsewhere. To think meaningfully through these options requires a good grasp of the current situation regarding African agricultural R&D and some understanding of the history behind the present policies and institutional arrangements. In this paper we present and summarize an entirely new set of data that represents the first attempt to give a comprehensive, quantitative account of the evolution and current status of national agricultural research systems throughout Africa.[3] Some preliminary, and necessarily partial, reflections on the policy implications of these data are also provided. In presenting and commenting on investments in public research we note the growing awareness that simply seeking more dollars is not the answer. The financing, organization, and management of public R&D will have to be dealt with in an integrated way (Alston and Pardey 1996).

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[1] This chapter is a verbatim reproduction of an article published earlier in *World Development* Vol. 25, No. 3 (1997): pp. 409-423. Not included are the summary and keywords, while headings and footnotes have been renumbered to match with the rest of this dissertation. References are included in the references to this dissertation. The work reported here was jointly financed by the Danish International Development Agency, the United States Agency for International Development, and the Special Program for African Agricultural Research of the World Bank. The authors are grateful for the comments they received from three anonymous reviewers. Final version accepted: October 16, 1996.

[2] Previous accounts of the development of African agricultural R&D are given by Lipton (1988), Lele, Kinsey, and Obeya (1989), Eicher (1990), Pardey, Roseboom, and Anderson (1991b), Anderson, Pardey, and Roseboom (1994), Pardey, Roseboom, and Beintema (1995), Weijenberg *et al*. (1995), and Taylor *et al*. (1996).

[3] The data and institutional details summarized here are reported in greater detail in a series of 24 country statistical briefs available from the authors on request. These briefs provide an historical perspective of the past and present institutional structure for agricultural research in each country, and for many variables report time series from 1961 disaggregated to the level of a specific institute. These data were compiled in close collaboration with knowledgeable individuals and institutions in each country using the Frascati manual (OECD 1981) guidelines for developing science and technology indicators.

This paper is organized as follows. Section 5.2 provides a brief historical review of institutional developments regarding national agricultural research systems (NARSs) in sub-Saharan Africa (referred to as Africa hereafter). Next we describe the pattern of growth of R&D personnel and then present parallel data on R&D expenditures, highlighting institutional differences in spending per scientist and cost structures more generally. In section 5.5 we give more details on the financing of agricultural R&D in Africa, paying particular attention to the marked differences in sources of support among government and semi-public agencies, changes in various measures of research spending intensities, and the role of donors in supporting African agricultural R&D. Section 5.6 gives a brief summary of relevant international agricultural research and section 5.7 concludes the paper.

5.2 *Institutional developments*

5.2.1 *A brief history*

With political independence in the late 1950s and early 1960s, most African countries inherited agricultural research structures that operated as part of a regionalized system. As colonial structures collapsed many smaller countries found themselves effectively cut off from the network of research services to which they previously had direct access. Other countries were left with highly specialized research agencies that did not necessarily address local production problems. There were major incongruencies across countries regarding the existing research capacity. Moreover, research was largely oriented to meeting the demands of export agriculture and paid little attention to the production constraints faced by subsistence farmers.

The transition to postindependence followed different paths in the former British and French colonies (see also Eisemon, Davis, and Rathgeber 1985). Throughout much of British Africa the local agricultural research infrastructure and administrative control was ceded to the new governments as an integral part of the country's administrative structure. In many cases, the flow of financial and technical support for research from Great Britain to its former colonies contracted quite quickly, leaving the financing and management of research as a largely national, often government, responsibility.

In contrast, France continued to manage, execute, and fund agricultural research in most of her former colonies for many years following political independence. A series of bilateral agreements between France and the host governments were signed wherein research costs were shared. In most instances France continued to provide scientists and related costs, while the host country provided support staff. Eventually these arrangements collapsed as domestic governments sought complete managerial and operational control over the public agricultural research activities in their countries. This usually coincided with the establishment of a national agricultural research organization (NARO) into which the activities of the various French commodity research stations were incorporated.[4]

5.2.2 *Size*

During the past three decades African national agricultural research systems (NARSs) grew substantially in size. Particularly, the number of mid-sized systems (those employing 100-400 researchers) increased; in 1961 there were only three mid-sized systems, by 1991 there were 18. Similarly, only eight NARSs in Africa currently employ less than 25 full-time equivalent researchers, compared with 33 such systems three decades ago.

While the general trend was toward larger NARSs, a number of systems have either completely collapsed or contracted markedly since independence because of political instability and civil war. This includes Angola, Mozambique, Uganda, Zaire, and, more recently, Liberia, Somalia, and Rwanda.

5.2.3 *Institutional structure*

Public sector agricultural research in Africa is done mainly by government agencies (table 5.1). Semi-public agencies and universities play only a minor role. In 1961 government agencies employed 90.7% of the full-time-equivalent researchers working in African NARSs; semi-public agencies accounted for 4.2% and universities 5.1%. Three decades later, the full-time-equivalent shares of government and semi-public agencies had shrunk to 86.5% and 3.5% respectively, while the universities share doubled to 10% of the total.

Table 5.1: *Sectoral composition African NARSs*

	Share of FTE researchers				Annual
Category	1961	1971	1981	1991	growth rate 1961-91[a]
			(percentage)		
Government	90.7	89.1	89.0	86.5	5.0
Semi-public	4.2	3.8	3.1	3.5	3.6
Academic	5.1	7.1	7.9	10.0	7.1
Total	100	100	100	100	5.1

Note: Data includes 21 countries.
[a] Annual average growth rates were calculated using a least-squares regression method.

[4] INERA in Burkina Faso, IRA and IRZ in Cameroon, IDESSA and IDEFOR in Côte d'Ivoire, IRAF in Gabon, FOFIFA in Madagascar, IER in Mali, INRAN in Niger, and ISRA in Senegal.

Government R&D agencies are those directly or indirectly administered by government, such as the research departments of ministries of agriculture or agricultural research institutes directly under a ministry. In contrast, semi-public agencies are not directly controlled by government and have significant "autonomous" sources of funding, usually a compulsory cess or marketing-board profits.[5] They usually provide R&D services for a particular and often economically significant export commodity. Examples include agencies doing research on coffee (Kenya), sugar (Mauritius and South Africa), tea (Kenya and Malawi), and tobacco (Zimbabwe). All the semi-public research institutes noted here were in former British colonies and virtually all were established during colonial times. Very few semi-public agencies have been established since 1961, consequently they employed a shrinking share of the region's agricultural researchers.

As noted, university-based agricultural research has expanded considerably. The total number of full-time-equivalent researchers at universities grew on average by 7.1% per annum during the past three decades and 10% per annum if South Africa is excluded. In 1961 only a few countries had the capacity to provide training in the agricultural sciences to the BSc level. Now, almost all African countries have some such capacity. Considerably fewer countries, however, provide postgraduate training.

Although university-based agricultural R&D in Africa has grown rapidly it was from a small base, so universities are still a small share of the overall research effort. Initially, university faculty throughout postindependence Africa were fully engaged educating graduates to staff the newly emerging national bureaucracies. Although the time they spent doing research gradually grew over the years, most faculty still allocate less than 15% of their time to this endeavor. Further, the research they do is mainly discipline-based rather than applied research aimed at solving specific production problems faced by farmers. Nevertheless, university personnel represent the better qualified component of most NARSs. The challenge is to usefully mobilize and manage this highly fragmented potential without undermining (and indeed hopefully enhancing) their important role in training future generations of African researchers.

5.3 *R&D personnel*

5.3.1 *Overall trends*

Many African countries have made significant strides in the number of scientists working in their agricultural research agencies. In 1961 there were about 2,000 full-time equivalent researchers working in sub-Saharan Africa (including South Africa). By 1991

[5] Semi-public research agencies constitute those agencies not directly controlled by government and with no explicit profit-making objective. We required that an agency be governed by an autonomous board and that it also exhibit a certain degree of financial independence from the government before classifying it as a semi-public agency. As a practical matter we required that an autonomously governed agency received more than 25% of its income from sources other than government and international donors before classifying it as semi-public.

this number had grown to more than 9,000.[6] In addition, African agricultural research agencies employ an average of 1.7 technicians and 7.9 other support staff (including secretaries and agricultural labourers) per researcher, bringing the total number of staff working for national agricultural research agencies in the region to around 96,000 person years in 1991.

For 19 countries, accounting for over two-thirds of the region's researchers, more complete time-services data are available (table 5.2). Building from a rather small base that was initially made even smaller by the exodus of expatriate scientists in the years immediately following independence, the number of scientists grew by 6.2% per annum throughout the 1960s, 4.8% in the 1970s, slowing further to an average of 2.8% in the 1980s. These totals mask a good deal of crosscountry variation. Agricultural research staff in Ethiopia, Madagascar, and Rwanda grew by 8% to 10% per annum during the 1980s, while the number of scientists working in Botswana, Nigeria, and Senegal failed to grow during this decade.

5.3.2 *Expatriate researchers*

The composition of the scientific workforce has also changed substantially. Expatriates account for only 11% of the researchers currently working in national agencies throughout sub-Saharan Africa (excluding South Africa), down dramatically from 90% in the early 1960s. This percentage, however, varies widely across countries. In 1991 more than a quarter of the agricultural scientists working in Botswana, Cape Verde, Central African Republic, Côte d'Ivoire, Mozambique, Rwanda, Senegal and the Seychelles were expatriates, while in Nigeria, Mauritius, South Africa, Sudan, and Tanzania they constituted less than 5% of the total. Former French colonies typically employ a higher proportion of expatriate researchers (21% in 1991) than former British colonies (7% in 1991), reflecting the comparatively slower transition to full national control of local agricultural research facilities in the francophone countries.

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[6] This total includes 48 sub-Saharan African NARSs. For 11 (usually small) national systems an informed estimate, often involving extrapolations from secondary data or semi-processed but incomplete survey data was used in constructing the respective 1961 and 1991 regional totals. These data exclude personnel working at or for international or regional agencies.

Table 5.2: *Trends in African agricultural researchers*

	Researchers				Annual growth rate [a]			
Country	1961	1971	1981	1991	1961-71	1971-81	1981-91	1961-91
	(full-time equivalents)				(percentage)			
Botswana	1.1	16.3	46.5	53.9	31.9	11.1	-0.2	12.5
Burkina Faso	10.1	25.3	90.9	142.4	11.3	12.3	2.8	9.8
Côte d'Ivoire	66.7	135.4	191.8	266.5	6.4	3.9	3.7	4.2
Ethiopia	14.0	65.9	153.0	386.8	17.1	7.3	9.6	11.0
Ghana	56.6	131.7	180.1	277.9	9.6	2.8	4.4	4.2
Kenya	120.8	325.9	483.6	818.7	10.5	3.0	4.8	6.4
Lesotho	1.0	7.0	16.8	27.5	19.2	8.3	5.2	10.4
Madagascar	69.6	113.8	95.0	194.7	5.2	-2.7	8.6	2.2
Malawi	30.2	80.8	126.2	184.9	12.0	4.8	3.2	6.1
Mauritius	11.7	39.1	72.5	106.1	12.9	5.7	3.8	7.3
Niger	11.5	14.4	49.5	101.6	1.0	17.6	6.6	9.3
Nigeria	136.0	364.4	944.3	1,012.8	10.4	10.8	-0.3	7.5
Rwanda	5.0	16.0	28.3	57.1	9.0	7.0	9.5	8.8
Senegal	60.0	71.4	184.3	174.5	2.2	11.5	-1.1	5.4
South Africa	736.8	956.8	1,140.4	1,339.1	2.7	1.6	1.3	2.0
Sudan	48.0	125.2	324.0	424.4	9.4	8.6	2.3	8.4
Swaziland	6.0	12.4	5.4	19.9	5.7	-9.8	5.6	3.8
Zambia	25.7	100.8	174.7	279.4	14.4	4.6	4.1	8.0
Zimbabwe	114.4	166.5	173.2	290.8	3.4	-0.5	5.9	2.7
Subtotal (19 countries)	1,525.2	2,769.1	4,480.6	6,158.9	6.2	4.8	2.8	4.9
Tanzania	48.7	142.3	345.2	545.9	11.9	8.6	3.9	8.8
Togo	2.3	15.0	38.2	87.1	20.2	9.3	9.7	11.6
Total (21 countries)	1,576.2	2,926.4	4,864.0	6,791.9	6.4	5.1	3.0	5.1

Note: Data include crop, livestock, forestry, and fisheries researchers working in government, semi-public, and academic agencies. Tanzania and Togo are listed separately because no corresponding expenditure time-series data are currently available.
[a] Growth rates were calculated using a least squares regression method.

5.3.3 *Degree status*

Not only has the number of agricultural researchers in Africa increased fourfold since 1961 (sixfold if South Africa is excluded), but their levels of formal training have improved as well. Nearly 65% of the national researchers in the 21 countries in our sample have postgraduate degrees. Just a decade ago only 45% were trained to that level. An estimated 1,372, or about 22%, of these researchers hold a PhD degree, although 63% of these doctorates work for just three NARSs; Nigeria, South Africa, and Sudan. Indeed, 52% of the researchers working in Sudan hold a PhD, which is an exceptionally high proportion compared with most other countries.

5.4 *R&D expenditures*

Real agricultural research expenditures grew rapidly during the 1960s, moderately during the 1970s, and ceased to gross throughout the 1980s and early 1990s for the 19-country sample reported in table 5.3. But the more detailed data reveal a substantial degree of volatility and crosscountry variation around this trend. Long-term growth rates ranged from a high of 13.2% per annum for Botswana to a low of -2.4% for Madagascar. Nigeria’s pattern of growth is noteworthy. After substantial growth during the 1960s and 1970s, largely financed by revenues from a booming oil sector, Nigeria’s agricultural research expenditures contracted sharply during the 1980s. They are presently less than half the 1970s levels. Severe economic crises and consequent structural adjustment programs have taken their toll throughout Africa with regard to the funding of agricultural research.

Table 5.3: *African agricultural research expenditures*

	Agricultural research expenditures				Annual growth rate [a]			
Country	1961	1971	1981	1991	1961-71	1971-81	1981-91	1961-91
	(millions 1985 int. dollars)				(percentage)			
Botswana	0.18	2.67	10.84	9.82	30.3	13.8	-3.8	13.2
Burkina Faso	1.61	2.85	7.11	19.13	7.9	9.3	9.5	8.1
Côte d'Ivoire	18.04	34.69	39.39	37.61	5.5	1.1	0.1	1.8
Ethiopia	1.90	9.19	21.14	40.53	19.4	7.7	10.6	10.4
Ghana	12.15	17.91	13.54	32.52	4.8	-3.2	14.4	2.1
Kenya	22.36	49.69	62.28	95.97	8.4	1.7	4.0	4.4
Lesotho	0.25	1.85	3.78	3.60	20.6	6.6	-1.8	8.1
Madagascar	17.89	29.28	11.45	15.63	4.7	-7.4	3.0	-2.4
Malawi	8.11	17.36	21.95	27.31	9.9	2.4	2.4	4.0
Mauritius	3.20	7.59	9.63	12.63	9.1	1.8	1.3	4.0
Niger	1.99	4.31	8.04	9.83	8.2	12.6	3.9	6.7
Nigeria	42.15	92.07	211.86	86.90	6.4	7.1	-9.1	1.9
Rwanda	1.97	3.63	5.76	10.03	5.8	6.7	11.4	5.7
Senegal	17.82	25.48	37.36	23.85	2.9	4.7	-4.3	2.7
South Africa	74.91	140.47	140.17	163.93	6.0	-0.6	1.8	2.0
Sudan	12.99	34.94	39.90	21.46	9.9	0.5	-5.5	1.5
Swaziland	1.05	2.87	3.53	5.89	8.4	-1.2	-2.4	6.6
Zambia	4.18	14.81	19.66	24.67	14.3	4.0	0.0	5.3
Zimbabwe	13.61	26.43	33.65	43.25	6.3	1.1	4.2	3.6
Total (19 countries)	256.37	518.10	701.03	684.55	6.8	2.6	0.1	2.9

Note: Data correspond in coverage with tables 5.1 and 5.2.

[a] Growth rates were calculated using a least-squares regression method.

To obtain an internationally comparable measure of the quantity of resources used for research, expenditures in local currency units were first deflated to base year 1985 with a local GDP deflator and then convened to 1985 international dollars using 1985 purchasing power parities (Pardey, Roseboom, and Craig 1992).[7] Purchasing power parities are synthetic exchange rates designed to reflect the purchasing power of currencies. Using purchasing power parities as conversion factors to denominate value aggregates in international dollars results in more realistic and directly comparable measures of the quantity of resources devoted to agricultural research in each country than if market exchange rates were used to do the conversion.[8] Using official exchange rates to convert local currencies to US dollar denominated expenditures gives substantially lower totals, although the currency conversion procedures we use preserves the pattern of growth within each country.

5.4.1 *Resources per researcher*

Overall trends: The pattern of growth of real research expenditures contrasts starkly with that of research personnel. The number of research personnel and the amount of resources committed to research developed largely in parallel from 1961 to 1981 but thereafter followed dramatically different paths (figure 5.1a). Real expenditures stalled after 1981 while the number of researchers continued to climb. As a result, the quantity of resources per researcher in 1991 for this group of 19 countries averaged about 66% of the amount allocated in 1961. Only Botswana, South Africa, Swaziland, and Zimbabwe committed more real resources per scientist in 1991 than was the case three decades earlier.

The national research systems in Nigeria and South Africa –two countries that together accounted for about 25% of the region's total investment in agriculture R&D in 1991– developed in distinctively different ways from each other and the rest of the region during the past 30 years. The South African system grew comparatively slowly but steadily and the rate of growth of its real research expenditures kept pace with the growth of its research staff (figure 5.1b).

Nigeria developed in an erratic fashion (figure 5.1c). Fueled by a boom in public revenues from oil exports, research spending and staff numbers grew rapidly throughout the 1960s and 1970s. But during the 1980s, research spending declined dramatically while the number of research staff stayed constant. The drop in research spending not only coincided with the rapid contraction of overall government revenues but also reflected a shift in government priorities away from agricultural R&D. Public spending on agricultural research accounted for 0.84% of consolidated government expenditures in

[7] The purchasing power parity indexes we used were developed by the UN International Comparisons Program and published by Summers and Heston (1991) as the Penn World Tables (Mark 5).

[8] This is because the overwhelming share of agricultural research expenditures involves labour costs and other operating expenditures that are denominated in largely local not international prices. Purchasing power parity indexes arc constructed using a broad basket of goods and services that better reflect these local price differentials across countries. Exchange rate relativities are based on a narrower basket of internationally traded goods.

1981 but a mere 0.27% in 1991. The earlier rapid growth in the publicly funded R&D in Nigeria was characteristic of NARSs throughout the region at that time. Many African countries pursued policies that led to a rapid growth in their national agricultural research systems, though often from a small base.

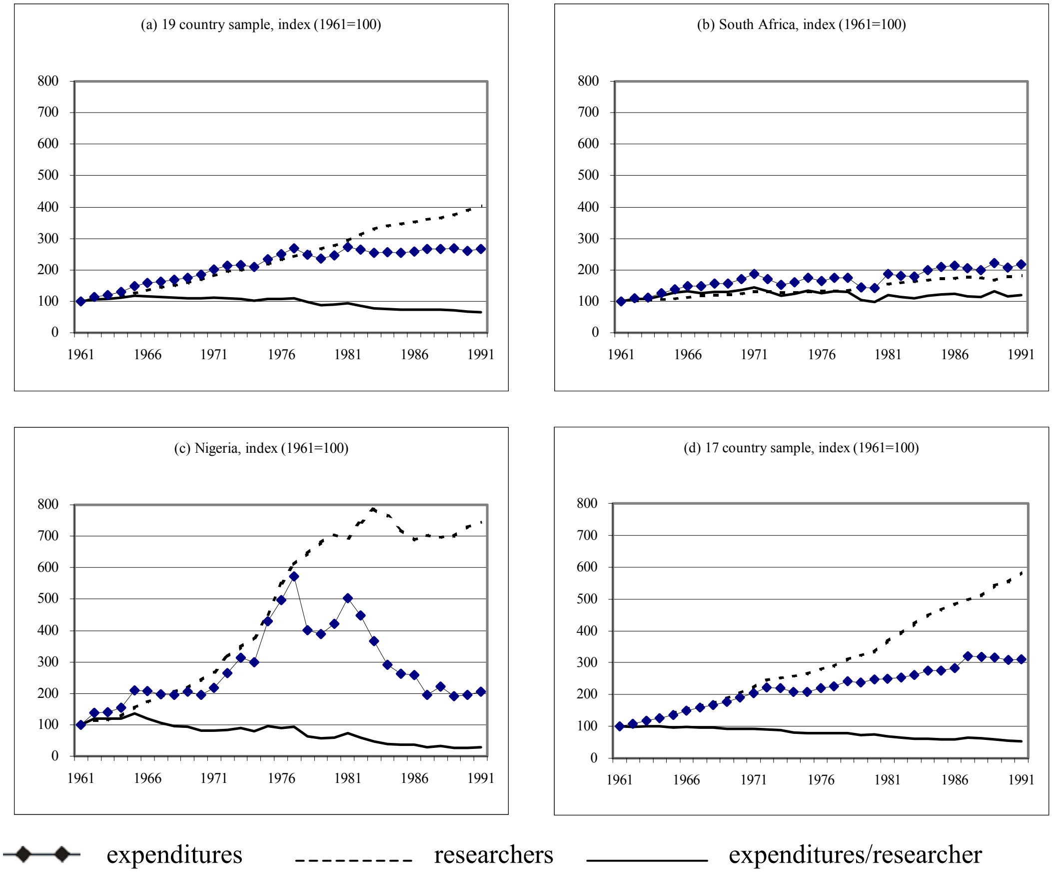

Figure 5.1 (a-d): *Research expenditures, staff, and spending per scientist, 1961-91*

Excluding the Nigerian and South African systems from the African average changes the quantitative but not the qualitative spending-per-scientist picture presented in figure 5.1a. Like the 19-country sample, the number of research personnel in the 17-country sample in figure 5.1d continued to climb throughout the post-1961 period but at a faster rate. For the larger group of countries growth in real research spending ceased after 1981 while for the smaller sample it grew throughout the whole period - albeit much more slowly after 1971 compared with the 1960s. The combined effect was to hasten and speed up the overall rate of decline in spending per scientist in the smaller sample compared with the rate noted above for the 19-country sample. As a consequence, spending per scientist for the 17-country sample in 1991 had fallen to about 53% of the resources made available per scientist three decades earlier.

Differences due to colonial ties: Since 1961 both the number of research staff and the amount of expenditures grew more slowly in francophone than in anglophone Africa[9] – respectively, 5.0% and 6.4% per annum for research staff and 2.2% and 3.3% per annum for expenditures. Spending per scientist, however, is about 20 to 25% higher in francophone compared with anglophone countries. This partly reflects the higher dependence on relatively expensive expatriate researchers in francophone Africa.

Institutional differences: Government and semi-public agencies developed in very different ways. Since the large majority of the researchers work in government agencies, the country aggregates are driven mainly by developments in those agencies. Figure 5.2 reports spending-per-scientist ratios for eight major semi-public institutes spread across five countries, employing 236 researchers, and spending 50.4 million 1985 international dollars in 1991. For these agencies, the longer run growth in real expenditures slightly exceeded the growth in personnel.

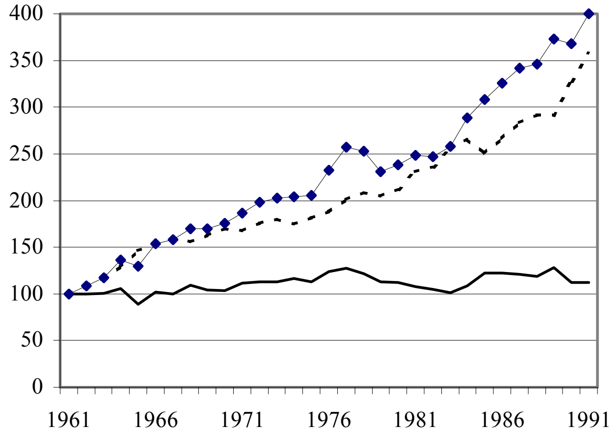

Figure 5.2: *Research expenditures, staff, spending per scientist by semi-public agencies (1961=100)*

Note: For legend see figure 5.1.

Their spending per scientist ratio in 1991 was 12% higher than in 1961 compared with 36% lower for the government agencies. These interinstitutional differences are less dramatic but still discernable when the government agencies are drawn from the same

[9] The francophone sample includes Burkina Faso, Côte d'Ivoire, Madagascar, Niger, Rwanda, and Senegal and the anglophone countries are Botswana, Ghana, Lesotho, Malawi, Mauritius, Nigeria, Sudan, Swaziland, Zambia, and Zimbabwe.

five countries in which the sample of semi-public agencies operate (i.e., Kenya, Malawi. Mauritius, South Africa, and Zimbabwe). In contrast to the decline in spending per government scientist observed for the larger sample, government agencies in this smaller sample committed about the same quantity of resources per scientist in 1991 as they did three decades earlier.[10]

5.4.2 *Cost structures*

The spending per scientist patterns shown in figures 5.1 and 5.2 reflect a number of factors. Aside from the obvious asymmetries between the growth in total spending and the growth in the number of scientists supported by those expenditures, there are significant differences across agencies and changes over time in the composition of these personnel and expenditure aggregates.

There were several partially offsetting developments regarding the researcher aggregates. First was the widespread move to replace relatively expensive expatriate scientists with less costly national researchers.[11] Working in the opposite direction was the considerable upgrading of the degree status of local scientists. The training and additional salary costs implied by these developments are substantial. Another aspect that affects spending per scientist estimates is the size and composition of the support staff. Although some research agencies shed excess support staff in recent years, this tendency has been far from universal. Overstaffing with support personnel is still a problem for many government research agencies. In addition, changes in the mix of support staff – for example, semi-skilled versus trained technical staff – also affect spending per scientist ratios.

Similar, and clearly related issues are reflected in the cost structures that underlie the expenditure aggregates. Systems that undergo major programs of capital investments are likely to have higher spending per scientist ratios than those that simply maintain existing physical infrastructure. Although no comprehensive cost-share data for the earlier years are available, more detailed data were collected for the post-1985 period. Cost shares were reasonably stable throughout this period for government and semi-public agencies alike although there are substantial interinstitutional differences in the underlying cost structures (table 5.4). Government agencies direct a much higher proportion of their budget to personnel costs (i.e., the salaries and benefits of scientific, administrative, and support staff) and a smaller share toward operational costs than do semi-public agencies. Both sets of agencies spent around 14% of total costs on capital items.

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[10] This overall pattern masks a good deal of crosscountry variation, even in the smaller sample of countries. Spending per government scientist rose by 20% from 1961-91 in Zimbabwe and South Africa but fell between 40 and 60% for scientists employed by the government of Kenya, Malawi, and Mauritius.

[11] During 1981-91, about 11.5% of the decline in expenditures-per-researcher for the 19-country sample can be attributed to the decline of the share of expatriates in the total research staff. When Nigeria and South Africa are excluded from the sample – two countries that by 1981 already employed few expatriate researchers – over one-third of the decline in expenditures per researcher is attributable to the drop in expatriate researchers.

Table 5.4: *Cost components for research and development*

Cost category	Expenditures per researcher						Cost shares					
	1986	1987	1988	1989	1990	1991	1986	1987	1988	1989	1990	1991
	(thousands 1985 int. dollars)						(percentage)					
Government agencies												
Personnel	74	68	71	72	67	67	59.3	56.0	57.1	59.1	60.3	61.2
Operating	35	32	33	32	30	27	27.7	26.2	26.5	26.1	26.7	24.9
Capital	16	22	20	18	14	15	13.0	17.7	16.3	14.9	13.0	14.0
Total	125	122	124	121	111	109	100.0	100.0	100.0	100.0	100.0	100.0
Semi-public agencies												
Personnel	130	111	119	118	104	103	52.2	49.6	51.0	46.3	47.1	50.4
Operating	83	76	76	82	77	72	33.3	34.1	32.5	32.1	34.9	35.0
Capital	36	36	38	55	40	30	14.4	16.2	16.4	21.6	18.0	14.6
Total	249	224	233	255	221	204	100.0	100.0	100.0	100.0	100.0	100.0
Total agencies[a]												
Personnel	76	70	73	73	68	68	58.8	55.6	56.7	58.1	59.3	60.4
Operating	36	34	34	33	31	29	28.1	26.7	26.9	26.5	27.3	25.6
Capital	17	22	21	19	15	16	13.1	17.6	16.3	15.4	13.4	14.0
Total	130	125	128	126	115	113	100.0	100.0	100.0	100.0	100.0	100.0

Note: These data cover the following 17 countries: Burkina Faso, Cape Verde, Côte d'Ivoire, Ethiopia, Ghana, Kenya, Madagascar, Malawi, Mali, Mauritius, Niger, Nigeria, Rwanda, Senegal, South Africa, Togo and Zimbabwe. The personnel cost data represent the salaries and benefits received by both national and expatriate researchers plus the personnel costs of all technical, administrative, and other support staff. All cost data are then divided by the number of full-time equivalent researchers.
[a] Government plus semi-public agencies.

Table 5.4 also reports these cost components on a per-researcher basis. The quantity of research resources per scientist in the semi-public institutes is nearly twice that of the government institutes, and this difference persists across the personnel, operating, and capital cost components. This points to significant, and possibly very important, differences in the way government and semi-public agencies allocate their research budgets. These interinstitutional differences also hold if we limit our comparison to include only those countries that have semi-public research agencies.

The anecdotal information suggests that research throughout Africa is severely curtailed because of inadequate operational resources. Our evidence seems to contradict this view, however, particularly for the semi-public institutes. But, it may be that a disproportionate share of operational funds are consumed by burdensome administrative overhead and the maintenance and upkeep of an extensive network of (comparatively small) research stations and farms. This seems especially so for government agencies. These funds might never find their way into bench-level research. Much of the personnel costs, for instance, are used to employ larger numbers of support staff that may have little direct input into research. For the semi-public institutes, the relatively high operational costs per researcher may partly arise because these institutes commonly earn much of their income from estate farm operations that employ significant numbers of field staff. Disentangling farm costs from research-related costs is difficult.

The data in table 5.4 clearly point to the salary crunch that has bedeviled scientists working in government agencies. Researchers salaries are constrained by civil service regulations, which often do not adequately reflect the differences of conducting R&D versus other government services. For many African countries the purchasing power of civil servants deteriorated dramatically during the past two decades because governments only partially compensated for inflation.[12] The result has been widespread absenteeism in many research agencies as staff work at other, additional jobs and a rather rapid rate of turnover of senior scientific staff. Research managers face a dilemma in dealing with this problem. Freeing resources by reducing staff is often made difficult by public service regulations. Likewise, the same regulations make it difficult to raise the salaries of scientists above the general public-service salary structure.

Comparative cost calculations based on official market exchange rates are more familiar to those who actually fund research. So for an alternative look at spending per scientist ratios, table 5.5 presents the 1991 ratios in US (rather than international) dollars per researcher and distinguishes between local and foreign personnel costs. A noteworthy feature of these data is the large share of expenditures per researcher due to technical assistance costs: nearly 13,000 US dollars per researcher, or 30% of overall personnel costs, are used to pay the salaries and benefits of expatriate researchers. And for nine out of the 17 countries in table 5.5 the personnel costs of expatriate researchers exceeds that spent on local staff. There is often little NARS managers can do about this aspect**,** as technical assistance costs are generally incurred by donors and there is little fungability between local and expatriate expenses.

[12] Robinson (1990) provides ample evidence of the declines in the real salaries of civil servants in many African countries. He also noted a tendency to compress the salary scale by increasing lower salaries faster than higher ones. These trends are bound to reduce the motivation and effectiveness of the higher grades, accelerate staff turnover, and increase the rate of informal absenteeism as government workers moonlight at additional jobs.

Table 5.5: *Expenditures per researcher by cost category in US dollars, 1991*

	Personnel costs					
Country	Local	TA[a]	Total	Operating	Capital	Total
Burkina Faso	21,469	33,117	54,586	22,074	22,056	98,716
Cape Verde	36,560	41,379	77,939	30,330	4,678	112,947
Côte d'Ivoire	35,878	56,471	92,349	25,316	2,707	120,372
Ethiopia	16,171	8,586	24,757	10,530	10,088	45,374
Ghana	25,074	10,185	35,259	9,859	22,813	67,930
Kenya	19,118	12,660	31,778	10,771	6,772	49,320
Madagascar	11,727	25,140	36,866	8,680	2,664	48,210
Malawi	20,054	22,599	42,653	19,133	7,477	69,262
Mali	14,676	16,190	30,866	12,173	8,812	51,851
Mauritius	35,307	0	35,307	25,737	9,298	70,341
Niger	34,134	27,273	61,407	3,920	1,615	66,942
Nigeria	9,748	1,812	11,560	5,477	4,490	21,527
Rwanda	28,813	36,735	65,547	17,072	4,533	87,152
Senegal	34,484	45,031	79,515	17,965	3,498	100,978
South Africa	66,088	0	66,088	18,929	6,133	91,150
Togo	20,753	30,000	50,753	15,079	6,115	71,946
Zimbabwe	34,610	16,744	51,355	15,791	9,281	76,426
Weighted average	30,026	12,760	42,786	13,505	7,087	63,377

[a] TA indicates technical assistance.

5.5 *Financing agricultural R&D*

The common claim is that market failures in agricultural R&D lead to underinvestment in research if left to the private sector; research opportunities that would be socially profitable go unexploited. These market failures arise because some research is privately unprofitable due to appropriability problems – whereby the innovator (or investor) cannot appropriate all or sufficient benefits to warrant the investment – or the transaction costs involved in having farmers take collective action to finance (or execute) research that is beyond their individual reach are too high. In these instances markets will fail to provide the socially optimal mix of research and government action may be warranted.

Alston and Pardey (1996) give a comprehensive and critical review of the evidence regarding market failures in agricultural research and discuss the principles and practices involved in designing ideal arrangements to finance or conduct research.[13] The arrangements one may recommend to solve the underinvestment depends on which type of market failure that is being rectified. Developing a detailed understanding of the existing pattern of investments and the institutional context within which research funds

[13] See also Thirtle and Echeverria (1994) who discuss some of the roles of public and private agricultural research agencies in sub-Saharan Africa.

are raised, allocated, and spent is an invaluable first step in designing appropriate policy interventions to deal with the problem.

5.5.1 *Institutional differences*

Table 5.6 presents data on the financing arrangements for agricultural research in 13 African countries. There are substantial differences in the sources of support for government versus semi-public agencies. While government agencies developed in ways that are broadly consistent with the aggregate country data, semi-public agencies receive about 80% to 90% of their funds from earmarked taxes or industry levies and own income. Moreover, since the mid-1980s the share of funds for semi-public agencies coming from general taxpayer revenues shrank while there was a noticeable increase in donor-sourced funds being channelled to these agencies.

Table 5.6: *Funding Sources, 1986-91*

Source of funding	1986	1987	1988	1989	1990	1991
			(percentage)			
Government research agencies						
Government	57.9	51.5	52.6	51.1	51.4	49.9
Own income	5.3	5.4	6.1	5.5	4.5	4.2
Taxes	0.1	0.1	0.0	0.0	0.0	0.0
Donor	35.5	41.7	39.8	42.5	43.1	45.1
Other	1.3	1.3	1.4	0.9	1.0	0.7
Total	100	100	100	100	100	100
Semi-public research agencies						
Government	11.3	8.5	6.2	7.4	5.8	4.4
Own income	32.1	15.0	17.6	11.3	17.8	17.6
Taxes	50.0	66.6	65.3	59.5	69.1	69.6
Donor	3.9	8.3	9.7	19.4	5.8	7.3
Other	2.8	1.5	1.3	2.4	1.6	1.1
Total	100	100	100	100	100	100
Total research agencies[a]						
Government	55.9	49.6	50.4	49.0	49.0	47.5
Own income	6.5	5.8	6.7	5.8	5.1	4.9
Taxes	2.3	3.5	3.6	3.9	4.0	4.2
Donor	34.0	39.7	37.9	40.3	40.9	42.7
Other	1.4	1.4	1.4	0.9	1.0	0.8
Total	100	100	100	100	100	100

Note: Based on data from Burkina Faso, Côte d'Ivoire, Ghana, Kenya, Madagascar, Malawi, Mali, Niger, Nigeria, Rwanda, Senegal, Zambia and Zimbabwe.
[a] Government plus semi-public research agencies.

5.5.2 *Donor funding*

Funding in the form of loans and grants from international donors accounted for around 34% of total research expenditures in Africa (excluding South Africa) during the early 1980s (Pardey, Roseboom, and Anderson 1991c). African NARSs became increasingly reliant on donor-sourced funds in recent years as this percentage increased to about 43% for a group of 22 countries (excluding South Africa) in 1991. Whether this reflects a temporary trend to shore up cash-strapped government research systems in African countries that continue to carry extraordinarily high levels of foreign debt, or a crowding out of alternative, local sources of finance is unclear. Analogous arguments were made by Alston and Pardey (1996) regarding the crowding out of private sources of support by state and federal public funding of agricultural R&D in the United States.

The dependence on donor funding varies markedly among countries. At one extreme is Nigeria which received only 6% of its funds from donors during the latter half of the 1980s, while countries as diverse as Burkina Faso, Cape Verde, Mali, Rwanda, Senegal, Tanzania, and Zambia got more than 60% of their support from international sources. Grouping countries in various ways provides different perspectives on the nature of donor support for African agricultural research (table 5.7). Per capita income differences definitely matter. The share of donor support is considerably higher in the poorest African countries (62%) compared with the richer African countries (2.7%, or 14% if South Africa is excluded).

Table 5.7: *Donor support of African agricultural R&D, 1991*

	Donor share (percentage)
GDP/capita (1991)	
$ 750 <	62.4
$ 750-1500	31.8
>$ 1500	2.8
Population (millions, 1991)	
Small (<5)	20.2
Medium (5-20)	53.8
Large (>20)	24.3
Former colonial	
Anglophone	26.3
Francophone	60.7
Other	48.2
Weighted average	*33.7*

Note: Data include 23 countries.

Previous analysis, using a much larger sample including NARSs from around the world, showed that developing countries with small populations invest relatively more in agricultural research than developing countries with large populations (Pardey, Roseboom, and Anderson 1991c). This partly reflects the disproportionately large amount of donor funds directed to "small" countries when funding is measured on a per capita basis. The data in table 5.7, however, do not fully support this earlier finding. One observes the lower intensity of donor support to NARSs in countries with large compared with medium-sized populations, which is consistent with the earlier results. But those African countries with relatively small populations receive a much lower intensity of donor support than expected. It may well be that the effects of smallness are offset by the preponderance of relatively rich countries (such as Botswana, Mauritius, and Namibia) with less than five million people in our sample, because, as noted, richer African countries receive much lower levels of donor support for R&D than poorer ones.

Colonial precedents appear to have persistent influences in terms of the amount of foreign support to agricultural R&D. In 1991, donor funding accounted for 61 % of total support to the national agricultural research effort in francophone countries and only 26% in anglophone countries (36% if South Africa is excluded). Part of the difference between francophone and anglophone countries reflects the higher proportion of expatriate researchers working in francophone systems.

The fragile state of many African economies and the large array of demands placed on the public sectors in these countries make it likely that continued, and in some cases substantial, donor support for research will be necessary for some time to come. It is questionable, however, whether these high levels of support can be sustained indefinitely. Certainly serious thought should be given to the appropriate amount to spend on R&D, the design of mechanisms for disbursing donor funds to avoid crowding out domestic sources of support (which may well have been the case over the past few years at least), and the development of means by which funds can be mobilized and deployed to stimulate rather than dissipate the productive potential of the resources committed.

5.5.3 *Research spending intensities*

To place agricultural research expenditures in a more meaningful context, it is common to scale these measures according to the size of the agricultural sector measured, for instance, in terms of agricultural output (AgGDP). Figure 5.3 provides an overview of the long-term development of this intensity ratio. The 19-country average increased throughout the 1960s and much of the 1970s then declined steadily from a peak in 1981 of 0.93% down to 0.69% by 1991 below the level intensity that prevailed two decades earlier.

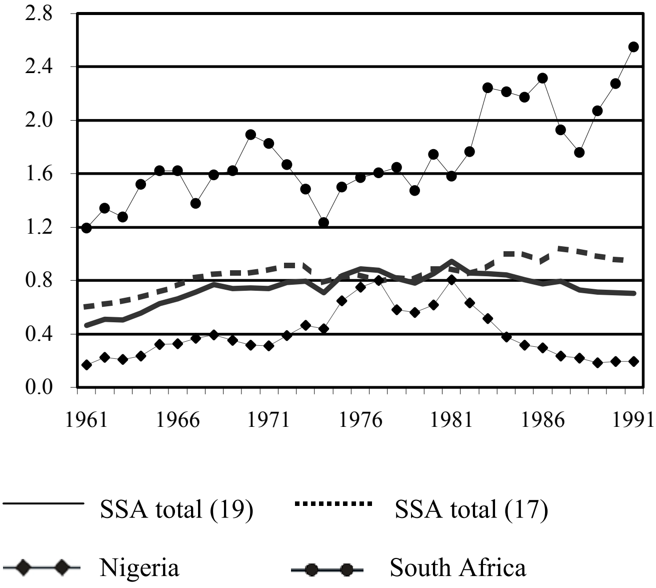

Figure 5.3: *Expenditures as a percentage of AgGDP, 1961-91*

This sample average masks some major differences in research intensity among Nigeria, South Africa, and the rest of Africa. South Africa's research intensity ratio trended upward for much of the post-1961 period. At 2.6% in 1991 it is significantly higher than most other countries in the region. The instability in the ratio evident from figure 5.3 reflects weather induced fluctuations in agricultural output rather than any significant year-to-year fluctuation in research spending.

In contrast to South Africa's persistent upward trend, Nigeria's research intensity ratio grew steadily throughout the 1960s and early 1970s but declined precipitously during the past decade from 0.81% in 1981 to a lowly 0.19% in 1991. In 1991 a 17-country African average (excluding Nigeria and South Africa) was 0.92% compared with 0.69% for the 19-country sample that includes these systems.

Figure 5.4 presents the 1991 research intensity ratio decomposed by country and by source of funding. If all sources of funds are included, the 23-country sample average of the intensity ratio is 0.72% (0.69% for the 19-country sample); ranging from a high of 6.3% for Cape Verde to a low of 0.19% for Nigeria. Measuring research spending intensities in terms of spending by research agencies from domestic sources only (i.e., net of international loan and grant funds) changes things considerably. The average spending intensity is lowered by a third from 0.72% to 0.48%. Moreover, the ranking of countries in terms of research intensities based on spending from all sources versus those intensities that include spending from domestic sources only are quite different. Botswana (rather than Cape Verde) invests its own funds more intensively in agricultural R&D than any other country in the sample. A relatively large and quite prosperous nonagricultural sector forms the basis for this government support. At the other end of the spectrum, Burkina Faso, Nigeria, Rwanda, and Sudan spend less than 0.2% of their AgGDP on agricultural research using local funds.

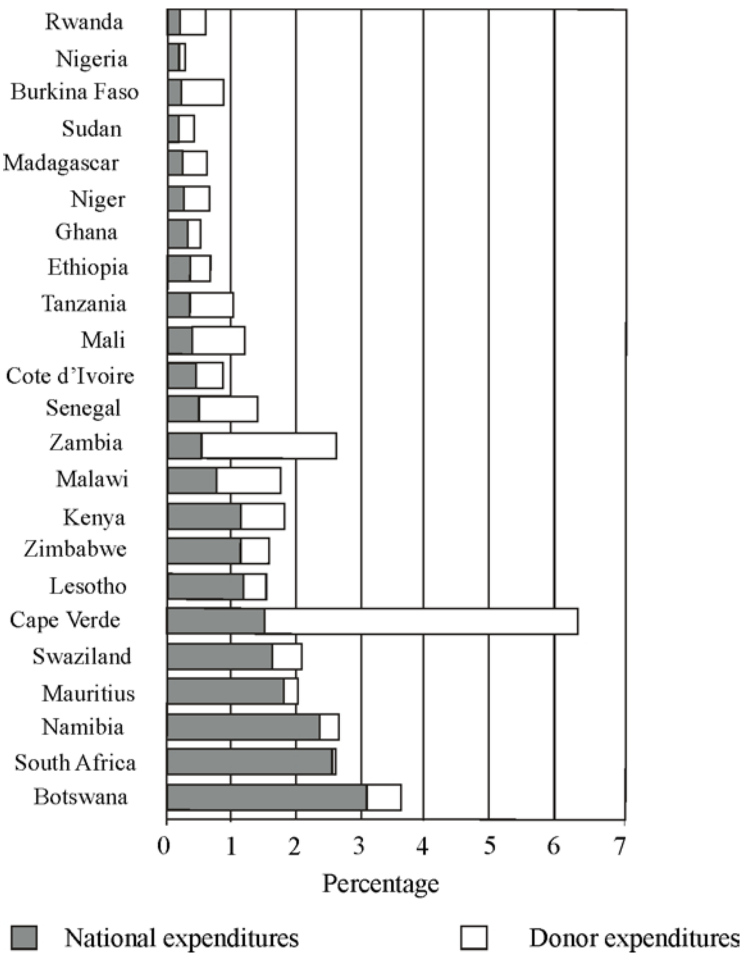

Figure 5.4: *Agricultural research expenditures by source of origin as a percentage of agricultural GDP, 1991*

5.5.4 *Government spending intensities*

Using a political economy framework to account for observed differences in government spending on agricultural R&D, Roe and Pardey (1991) looked at the share of total and agricultural spending by governments earmarked for agricultural R&D. Table 5.8 presents contemporary government spending shares for various African countries grouped by per capita income. Data for Nigeria and South Africa have been reported separately and they have been excluded from the respective middle and high-income classes whose averages they would dominate.

Table 5.8: *Agricultural research expenditures as a percentage of government expenditures*

Category[a]	1971	1981	1991
		(percentage)	
Low income (7)[b]	1.14	0.88	1.14
Middle income (5)	1.91	1.16	1.13
High income (4)	1.57	1.16	0.58
Subtotal (16)	1.57	1.06	1.06
Nigeria	1.50	0.84	0.27
South Africa	0.59	0.44	0.42
Total (18)	0.97	0.76	0.60

[a] Income classes were defined as follows: low, less than $750; middle, $750-1500; and high, greater than $1500 in terms of 1991 per capita income figures measured in terms of 1985 international dollars per capita in 1991.
[b] Number of countries in parentheses.

Whereas the conventional research intensity ratio (i.e., agricultural research spending as a share of agricultural output) in South Africa has been rising and consistently among the highest of all African countries since 1961, agricultural research expenditures have constituted a falling and relatively small share of total government spending. In 1991 South Africa spent only 0.42% of total government spending on agricultural R&D compared with 0.59% in 1971. This contrasts with the 16-country average whose share of R&D spending relative to total government spending was 2.5 times higher than the corresponding South African spending ratio. Aside from the exceptional case of Nigeria, poorer African countries currently commit much more of their public sector resources to agricultural R&D than Africa's richer countries. Governments in poorer and richer African countries alike, however, were giving less priority to agricultural R&D in 1991 than 1971.

5.6 *International R&D*

There are presently four international research centers of the Consultative Group on International Agricultural Research (CGIAR, or CG for short) headquartered in Africa: IITA, ILRI, WARDA, and ICRAF (table 5.9). There are a further 12 CG centers located throughout the world, many of whom maintain regional offices or, in some cases, significant research facilities in Africa, and most undertake research in the region, often in conjunction with local NARSs.

Table 5.9: *The CGIAR system in Africa*

Center	Date of: Joining CG	Date of: Foundation	Headquarters location	Main areas of focus	1995 Expenditures (million US$)
IITA, International Institute of Tropical Agriculture	1971	1967	Ibadan, Nigeria	Farming systems, rice, maize, cassava, cocoyams, soybeans	31.43
WARDA, West African Rice Development Association[a]	1975	1970	Bouaké, Côte d'Ivoire	Rice	9.70
ICRAF, International Centre for Research in Agroforestry	1991	1977	Nairobi, Kenya	Agroforestry, multi-purpose trees	16.90
ILRI, International Livestock Research Institute[b]	1995	1995	Nairobi, Kenya & Addis Ababa, Ethiopia	Livestock production and animal health	24.30

Source: Baum (1986), TAC/CGIAR (1987), and unpublished CG documents.
[a] Relocated from Monrovia, Liberia in 1989.
[b] ILRI became operational in January 1995 through a merger of the International Laboratory for Research and Animal Diseases (ILRAD) and the International Livestock Center for Africa (ILCA). ILRAD was established in 1973 as a CG center headquartered in Nairobi, Kenya. Its research focused on livestock diseases (world) and tick borne disease and trypanosomiasis (sub-Saharan Africa). ILCA was established in 1974 as CG center headquartered in Addis Ababa, Ethiopia and did research on animal feed and production systems for cattle, sheep and goats for sub-Saharan Africa.

The four African headquartered centers collectively spent $82.3 million in 1995, or about one-quarter of the CG total of $326.2 million. This misstates the size of the CG effort conducted in Africa – some of the work of these centers is conducted elsewhere, while other CG centers spend significant resources in the region. While it is possible, but difficult, to estimate the share of the CG's research undertaken in Africa, it is doubly difficult to meaningfully estimate the share of the system's effort directed toward Africa. This is because most of the international centers have global or commodity mandates; the results of their research are meant to spill broadly across various agroecologies that do not coincide with specific country or regional boundaries. Notwithstanding these difficulties, the CG centers estimate that about $127 million or 39% of total CG expenditures were directed toward Africa in 1994 (CGIAR 1995, p. 32); substantially higher than the 13% of overall developing country agricultural R&D expenditures spent by African NARSs in 1991.

5.7 *Conclusion*

Sub-Saharan African countries made some progress in developing their agricultural research systems during the past three decades. Particularly the development of research staff has been impressive in terms of numbers (a sixfold increase if South Africa is excluded), declining reliance on expatriates (from roughly 90% expatriates in 1961 to 11% in 1991), and improvements in education levels (65% of the researchers held a postgraduate degree in 1991). The indigenous capacity to train researchers also expanded, although the capacity to train at the MSc and PhD level is still limited.

Developments in agricultural research expenditures were considerably less positive. After reasonable growth during the 1960s and early 1970s, growth in expenditures basically stopped in the late 1970s. Although there is considerable variation around this trend, it brings back the notion that many African countries have lost ground with regard to financing their agricultural research. Donor support has clearly increased in importance. Its share in the financing of agricultural research increased from 34% in 1986 to 43% in 1991. While increased donor support somewhat compensated for declining government funding, it is unlikely that such high levels of support can continue indefinitely.

Many of the developments of the past decade in personnel, expenditures, and sources of support for public sector R&D in Africa are clearly not sustainable. The rapid buildup of research staff is not paralleled by an equal growth in financial resources. Spending per scientist has continuously declined during the past 30 years, but most dramatically during the 1980s. Richer and poorer African countries alike are giving lower priority to spending on agricultural R&D today than was the case two decades ago. Resources are spread increasingly thin over a growing group of researchers, which has negative effects on the efficiency and effectiveness of agricultural research. To turn this around is a complex undertaking but unless public and private funding for research is increased there is likely to be a painful and possibly wasteful reduction of research staff.

6. The transformation of the Dutch agricultural research system: An unfinished agenda

By Johannes Roseboom and Hans Rutten[1]

6.1 *Introduction*

The national agricultural research system (NARS) in the Netherlands has undergone a major transformation in many respects during the pas 25 years. This transformation has been influenced by changes in the structure of the agricultural sector (including agricultural markets), advancements in the (agricultural) sciences, as well as more general political and ideological changes. In this paper, we focus on these more general political and ideological changes and investigate how they have influenced the institutional context within which the system operates. We then compare the Dutch experiences with those in other developed-countries NARS. We conclude with an exploration of possible future developments in the Dutch NARS.

6.2 *The present structure of the Dutch agricultural research system*

A stylized overview of the present structure of the Dutch agricultural research system is presented in table 6.1. The term “system” is used here rather loosely to refer to the various agencies that deal with agricultural research in the Netherlands. The agricultural sector has been defined as including primary agricultural production, as well as agricultural input and processing industries.

The Dutch Ministry of Agriculture, Nature Management and Fisheries (MOA) is responsible for agricultural research and extension as well as education. Since 1995, policy formulation in these areas has been entrusted to a single directorate within the ministry, the Directorate of Science and Knowledge Transfer (DSKT). At the same time, the National Agricultural Research Council lost its coordination and planning functions and has been transformed into an advisory committee conducting foresight studies. Insofar as central planning and coordination of research is deemed necessary, these functions have been assumed by DSKT, which is the single most important funder for agricultural research in the country. DSKT funds or purchases research services at the Agricultural Research Department (known under its Dutch acronym DLO), the Organization for Applied Research in Agriculture (an organization which includes nine experiment stations), Wageningen Agricultural University (WAU), and, to a substantially lesser extent, the TNO-Nutrition and Food Research Institute (TNO-Food) and the Faculty of Veterinary Sciences of the University of Utrecht (FVS).

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[1] This chapter is a verbatim reproduction of an article that has been published earlier in *World Development* Vol. 26, No. 6 (June 1998): pp. 1113-1126. Not included are the summary and keywords. Headings and footnotes have been renumbered to match with this dissertation. All references have been included in the reference list of this dissertation. Final revision accepted, January 1998.

Table 6.1: *Present structure of the Dutch agricultural research system*

Organization	Description	Research budget (1995)
Directorate of Science and Knowledge Transfer (DSKT)	Created in 1995 and responsible for the agricultural research, extension and education policies of the Ministry of Agriculture, Nature Management and Fisheries (MOA)	Not applicable
National Council for Agricultural Research	Originally a coordinating and planning body but re-established in January 1995 as a ministerial advisory body in charge of conducting S&T foresight studies for the agricultural sector	Not applicable
Agricultural Research Department (DLO)	Executing branch of DSKT. Will be detached from MOA in 1998. Comprises 11 research institutes and a central publishing and documentation service center.[a] DLO institutes focus primarily on strategic and basic research.	Dfl 370 million [b]
Organization for Applied Research in Agriculture	Another executing branch of DSKT. Comprises 9 experiment stations. Each of them conducts applied agricultural research for a specific agricultural subsector.[c] Traditionally funding of these stations is shared between MOA and the farmers	Dfl 102 million
Nutrition and Food Processing Division of the Netherlands Organization for Applied Research (TNO-Food)	TNO-Food is a private, non-profit research organization and conducts research for both the public and the private sector. MOA is only one of its clients	Dfl 104 million
Wageningen Agricultural University (WAU)	Comes under the responsibility of DSKT of MOA. Has a primary role to play with regard to basic research, but also conducts some strategic and applied research	Dfl 319 million
Faculty of Veterinary Sciences (FVS), University of Utrecht	Comes under the responsibility of the Ministry of Education, Science and Culture. Conducts primarily basic research	Dfl 39 million
Private sector	Includes research departments of private companies as well as a few research institutes fully financed and managed by the industry, such as the Institute for Efficient Sugar Production and Netherlands Institute for Dairy Research	Dfl 745 million

Source: Roseboom and Rutten (1996), Roseboom and Rutten (1997) and CBS (1997).

[a] (1) Institute for Forestry and Nature Management (IBN-DLO); (2) Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO); (3) Agrotechnological Research Institute (ATO-DLO); (4) Centre for Plant Breeding and Reproduction Research (CPRO-DLO) (including the Centre for Genetic Resources); (5) Research Institute for Plant Protection (IPO-DLO); (6) Research Institute for Agrobiology and Soil Fertility (AB-DLO); (7) Institute for Animal Science and Health (ID-DLO); (8) Netherlands Institute for Fisheries Research (RIVO-DLO); (9) Agricultural Economics Research Institute (LEI-DLO); (10) Institute of Agricultural and Environmental Engineering (IMAG-DLO); (11) State Institute for Quality Control of Agricultural Products (RIKILT-DLO); and (12) Centre for Agricultural Publishing and Documentation (PUDOC-DLO).

[b] A Dutch guilder (Dfl) equaled 0.62 US dollar in 1995.

[c] (1) Arable crops and field vegetables; (2) fruits; (3) bulbs; (4) arboriculture; (5) floriculture and glasshouse vegetables; (6) mushrooms; (7) poultry; (8) pigs; and (9) cattle, sheep and horses.

With the creation of DSKT, the Ministry has adopted an agricultural knowledge system perspective in its policies. Instead of separate research, extension, and education policies, it now has one "knowledge policy" that is to operate for, and within, a knowledge system. Despite the recent integration at the policy level, the traditional cohesion between the different components of the knowledge system has been under considerable stress in recent years, because of major changes in the mandate, organization, and management of the various components of the system. Both extension and research have been detached from MOA and re-established as private, non-profit organizations in 1993 and 1998, respectively. Old bureaucratic links between the various actors have been cut-off, while new contractual arrangements have emerged. Both activities have to rely increasingly on the market for their funding and face – to some extent – market competition. For example, numerous private extension providers have emerged in recent years.

The decision to privatize the execution component of the Directorate of Agricultural Research was taken in 1986, but it took more than 10 years to implement it. During this period DLO completely restructured itself and established a corporate identity.

In recent years, the links between the DLO research institutes and Wageningen Agricultural University (as well as other universities) have also been strengthened by the establishment of so-called research schools and a further concentration of DLO research facilities in and around Wageningen. Most recently (in 1996), the Minister of Agriculture decided to merge DLO and WAU into a single organization – Knowledge Centre Wageningen (KCW). The boards of DLO and WAU have been merged and a new chairman was appointed in 1997. It is expected that some parts of the experiment stations will also be merged with KCW in the near future, while those parts not included in the merger will be handed over to the private sector (i.e. commodity boards or farmer organizations) or closed down. The only two entities not affected by this upcoming merger are TNO-Food and the Faculty of Veterinary Sciences.

With an estimated intramural research budget of Dfl 745 million (US$ 462 million) in 1995 (CBS 1997), the private sector is by far the largest component of the Dutch agricultural research system. This figure includes the intramural research expenditures by the private-business agriculture, forestry and fisheries industries (Dfl 89 million), food and drinks industries (Dfl 478 million), and an estimated 10%[2] of the research expenditures by the chemical and pharmaceutical industries (Dfl 178 million). In addition, in 1995 the private sector funded about Dfl 126 million of agricultural research executed by the public sector (in particular TNO-Food). This brings the balance between public and private funding of agricultural and agriculture-related research in the Netherlands to about 50:50.

[2] This percentage is a very rough estimate and requires further research.

6.3 *The policy dynamics behind the transformation of the agricultural research system*

It is evident that the Dutch NARS has undergone substantial transformation in recent years. Some of the basic political and ideological changes that have shaped this transformation are: the changing role of government in society; public administration reform; and changing agricultural policies. None of these changes has been unique to the Netherlands, but apply in varying degrees to most countries. We will, therefore, discuss each of these changes in generic terms and explore their theoretical underpinnings.

6.3.1 *The changing role of government in society*

The rapid expansion of the government sector in the OECD countries during the 1960s and 1970s,[3] was followed by a period in which further expansion of the government sector was considered undesirable and, above all, unfeasible because of rapidly growing government deficits and debts. This new consensus had its strongest advocates among neoliberal economists, who introduced (or revived) concepts such as "government failure" as opposed to "market failure" (the classic argument for government intervention), transaction costs, the dead-weight loss of economic activity due to taxation, and the distortionary effects of lobbying for government funds and interventions.

This change has introduced a more critical attitude toward government intervention, including public agricultural research.[4] Alston and Pardey (1996) argue that market failure in agricultural research is by no means a sufficient condition for government intervention. From a welfare economic point of view, an intervention is justified only if it improves the situation by reducing the social costs of market failure – the benefits of the intervention should be greater than the costs. The market provision of (agricultural) research usually fails when benefits spill largely beyond the research originator. Spillovers are particularly large in agriculture because of the structure of the sector (many small producers)[5] and the difficulty of excluding others from using the new technology or knowledge. Intellectual Property Protection (patents and plant variety rights) has solved the latter problem only to some extent. The presence of large spillovers provides an important economic rationale for government intervention.[6]

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[3] The average size of government expenditures in relation to nominal GDP in the OECD countries rose from 27 to 47% during 1960-82. This growth was due, to a large extent, to a very rapid growth of transfer payments in the form of subsidies, social security benefits, social assistance grants, and interest payments on government debt. But, even when such transfer payments are netted out, government final consumption rose in the OECD countries from 15 to 23% of GDP, and general government employment from 11 to 18% of total employment during 1960-82 (OECD 1985).

[4] For arguments in favor of government intervention in agricultural research see Thirtle (1986) and Alston *et al*. (1997).

[5] Since the structure of the agricultural sector is changing rapidly in the direction of a greater concentration of production capacity, this argument may have lost some of its relevance.

[6] Identifying the beneficiaries of those spillovers may help to shape such government intervention. Hussey (1996), for example, argues that spillovers beyond individual businesses, but within an industry, are a justification for within-industry arrangements to fund research such as industry taxes, while spillovers to the wider society are a justification for government intervention, including public funding of (agricultural)

The presence of market failure in the provision of agricultural research leaves unanswered, however, the question of whether it is amenable to government-initiated solutions. There is ample evidence that governments have often failed to correct a problem adequately, or even worsened the situation by their intervention. Moreover, government intervention can take various forms, which vary in intensity. For example, the government can support agricultural research through legislation and regulations to facilitate private market operation (e.g. intellectual property rights and plant variety rights), through direct or indirect funding (e.g. by providing tax breaks or matching funds for research), or by direct provision of research services. The latter form of intervention is considered the least desirable as it requires intensive and permanent government intervention.

Whatever government intervention is considered justifiable, it is important to determine *ex ante* whether the benefits of the intervention will outweigh the costs. The high rates of return usually reported for public agricultural research investments have been used frequently as an argument that there is underinvestment in (public) agricultural research (Ruttan 1982; Alston and Pardey 1996). Others are more skeptical and argue that those cost-benefit analyses ignore the transaction costs involved in collecting taxes and, more importantly, the distortions created in the markets being taxed, which cause dead-weight losses in economic activity. They claim that the social costs of these distortions are considerable.[7]

The new political economy provides another critical perspective on the role of government by highlighting the distortionary effects of (powerful) lobby groups on the distribution government subsidies and services.[8] For some, these distortions are a reason to oppose government intervention altogether, while others see the need to limit or regulate the influence of lobby groups on the distribution of government subsidies and services. Certainly, a better understanding is needed of the processes and mechanisms by which the public agricultural research agenda is set and the way lobby groups affect the outcome of that process.[9]

6.3.2 *Public administration reform*

The changed perspective on the role of government in society, as well as tight government budgets, have placed governments under increasing pressure to become more effective, efficient and accountable. This had led to some fundamental changes and innovations in the organization and management of government over the past two decades that are generally known as "new public administration". The most important

research. Similarly, spillovers beyond national boundaries can be a justification for regionally or internationally orchestrated interventions.

[7] This issue was first raised in relation to public agricultural research in the United States by Fox (1985).

[8] In most developed countries, the agricultural lobby has been quite effective in obtaining a disproportionate share of government subsidies and services.

[9] Examples of studies that have applied this perspective to agricultural research are de Janvry and Dethier (1985) and Roe and Pardey (1991).

characteristics of the new public administration approach include the following (Kaul 1997):[10]

– *Orientation toward the ultimate users of government services*: consumers of government services are no longer seen as passive recipients but as active clients. An orientation toward those clients has substantially affected the organizational and managerial culture of government agencies, and included a shift from an emphasis on inputs and procedures (the traditional bureaucratic concern) toward outputs and outcomes.

– *Separation between policy and operation*: the new public administration approach has introduced a strict separation between policy making and policy implementation in order to enhance transparency and accountability of government. Policy making is considered the core of government, while policy implementation can be contracted out to agencies within or outside the government. For both private and government providers, the same contractual arrangements, explicitly specifying the amount and quality of outputs to be delivered, can be used. The introduction of such contractual arrangements has been a major innovation within the government sector, and has replaced bureaucratic command structures with market-like relationships.

– *Separation between funding, purchasing and provision of services*: the separation between policy and operation has also led to a clearer distinction between the roles of government as funder, purchaser and provider of services, and has opened up a variety of ways of organizing and managing the provision of government services. For example, one way of making government services more responsive to the needs of clients is by giving clients greater control over what is purchased. Mechanisms available to government to empower clients include representation of client groups on research councils and boards of agricultural research agencies, or providing financial incentives by client group initiatives (e.g. matching funding schemes and tax breaks for R&D undertaken by client groups).

– *Competition between service providers*: competitive contracting of the delivery of services from other public or private providers puts pressure on current service providers to be efficient and effective. This requires the removal of monopoly protection for government providers, and the introduction of pricing systems that take into account the full resource costs of government-provided services. Eliminating monopoly protection may lead to complete privatization of a government service.

[10] See also Banks (1996), Mountfield (1997) and Wilson (1996) for discussions of the new public administration.

6.3.3 *Changing agricultural policies*

Increased public concern about the environment, the sustainability of agricultural production systems, food safety, animal welfare and land use has changed agricultural policies in developed countries substantially during the 1980s and 1990s. Most of these concerns came from outside the agricultural sector and often conflicted with traditional agricultural policies and beliefs, which focused exclusively on the production and productivity of the sector. Insofar as food security was concerned (a primary objective in the years directly after WWII), this fitted the production focus very well.

Integrating these new public concerns into existing agricultural policies has been, and continues to be, a difficult process, in which policy makers often have to choose between serving the commercial interests of the sector, and serving the interests of society at large. The traditional one-dimensional focus of agricultural policies on production and productivity, shared by both the agricultural sector and the government, no longer exists. It has been replaced, at least by the government, with a far more complex mandate. This shift in agricultural policies has been of particular importance to the public agricultural research system because it has created a far broader and more complex research agenda.

6.4 *The transformation of the Dutch agricultural research system*

The changing role of government, public administration reform, and adjustments in agricultural policy orientation, have induced major changes in the Dutch agricultural research system. We will highlight here the most significant institutional changes over the past 25 years with regard to: mandate; policy formulation and coordination; organization, structure and management; and financing.

6.4.1 *Mandate*

For many years, the principle objective of the Dutch Ministry of Agriculture was to raise the general level of welfare of the agricultural population and to assure food security for the population at large. In this context, public agricultural research and technology policy was straightforward and focused predominantly on increasing production and productivity. Measured in these terms, this policy has been very successful (van der Meer *et al.* 1991; Rutten 1992).

In the 1970s and 1980s this one-dimensional approach to agricultural production came increasingly under attack. Under pressure of public opinion, issues such as the environment, food safety, animal welfare and land use increased in importance and dominated the agricultural (research) policy agenda. The Dutch agricultural sector, and to a lesser extent the Ministry, were slow to recognize the growing importance of these issues; pressure to put them on the agenda came mainly from outside the sector. In the course of the 1980s, however, MOA adopted the concept of sustainable development as one of its core objectives, and changed its mission statement to "creating or improving the conditions for a competitive, safe and sustainable agriculture."

Despite this changed mission statement, the Ministry often finds itself caught between an agricultural sector that is reluctant to accept (or carry the financial burden of) stricter regulations with regard to pollution, food safety, or animal welfare and the rest of society, which insists on such regulations. In keeping with these new objectives, the Ministry has sought to reorient its research and technology policy accordingly, and has given greater priority to research on environmental, food-safety, animal-welfare and land use issues. This reorientation has been difficult as it came at a time when the budget of MOA for agricultural research was declining. In deciding what should be given up, the choice was made to reduce support to applied or near-market research because it supposedly has the lowest public-good content and, hence, could be privatized.

An important guiding principle adopted by the Ministry in recent years is that "farmers should take more responsibility for themselves in financing and organizing support services." MOA sees for itself a more limited role in the provision of services that accrue mainly to the agricultural sector itself, including agricultural research (MLNV 1996).

6.4.2 *Policy formulation and coordination*

During the 1970s and 1980s, great emphasis was given to policy formulation and coordination within the Dutch agricultural research system. The National Agricultural Research Council played an important role in this regard. From 1972 onward, the Council produced a long-term vision for agricultural research every 4 or 5 years. This central policy formulation and coordination was deemed important because of the fragmentation of the research system at that time. Over time, however, the Directorate of Agricultural Research grew in importance, and in 1981 assumed responsibility for all ministerial research organizations except for the experiment stations and farms. As a consequence, a considerable amount of duplication with regard to policy formulation and coordination arose between the Directorate and the Council.

The public administration reform embarked upon by the Dutch government in the early 1980s, led to the cabinet decision in 1986 to privatize the execution (but not necessarily the funding) of public agricultural research. This motivated DLO research institutes to develop a strong corporate identity and to orient themselves more toward their clients. Instead of meeting representatives of their clients in the Council, they now consult their clients directly and formulate their own strategies.

These developments undermined the position of the Council as a central entity for policy formulation and coordination, and finally culminated in the termination of the Council's policy coordination and formulation role in 1995. Since 1995, the focus of the Council has been on long-term strategies and priorities for the NARS. To the extent that policy coordination is still deemed necessary, this is now done by the Directorate of Science and Knowledge Transfer.

6.4.3 *Structure, organization and management*

During the 1950s and 1960s, public agricultural research in the Netherlands expanded rapidly, and numerous new agricultural research institutes and stations were established. This resulted in a patchwork of agricultural research agencies with overlapping mandates. The past 25 years, however, can be characterized as a continuous process of consolidation and rationalization of agricultural research capacity. This process gained momentum when funding became tight, particularly after 1980. For example, since 1981 the number of DLO research institutes has been reduced from 22 to 11. In place of the traditional geographical spread of agricultural research capacity, Wageningen, and to a lesser extent Lelystad, were selected as locations to concentrate the research infrastructure.

The responsibility for agricultural research within MOA has long been compartmentalized. Initially each subject-matter department had its own research capacity. A first step toward the consolidation of agricultural research into one agency was taken in 1962 with the establishment of a Directorate of Agricultural Research. Only the more upstream research institutes dealing with crop and livestock were transferred to this new directorate, while forestry, fisheries and veterinary research institutes, as well as the experiment stations and farms, remained within their subject-matter directorates.

A further step toward the consolidation of agricultural research within MOA was made in 1981. The number of directorates with administrative responsibility for one or more agricultural research entities was reduced from nine to three. Finally, with the establishment of the Directorate of Science and Knowledge Transfer in 1995, all research plus extension and education (including WAU) were brought together under one directorate.

The decision of the government to privatize the execution of public agricultural research (and, to some extent, the funding as well, by applying a stricter public-good argument) has significantly changed the organization and management of agricultural research. As a first move toward privatization, the Directorate of Agricultural Research was split into a Directorate of Science and Technology (DST) and an Agricultural Research Department (DLO) in 1989. In this new structure, DST (now DSKT) determines policy and controls the research budget of MOA, while DLO manages the research institutes. Between DST and DLO a client-provider relationship was instituted, while the traditional bureaucratic management style has been replaced by a more commercial, private sector one.

DLO will be formally privatized and detached from the Ministry in January 1998. Initially, the experiment stations were not affected by this privatization. After they were brought under the jurisdiction of DSKT in 1995, however, steps have been taken to organize and manage the experiment stations along the same lines as DLO. One of the consequences is the termination in 1998 of a long tradition of shared funding of the experiment stations between MOA and the farmers through commodity levies.[11]

A study on the future of the Dutch agricultural knowledge system, commissioned by the Ministry of Agriculture in 1995, concluded that there is considerable overlap and unnecessary competition in the Dutch agricultural research system (Peper 1996). One important recommendation in the report was to merge DLO and WAU – a rather revolutionary idea at the time. The Minister, however, adopted the recommendation right away and has made the integration of DLO and WAU one of his major policy objectives. The new organization – Knowledge Centre Wageningen (KCW) – will be one of the world's largest agricultural science conglomerates. As mentioned in section 6.2, the boards of DLO and WAU were merged and a new chairman appointed in 1997. Further details of the merger are currently being worked out. It is also expected that parts of the nine experiment stations will be merged into KCW and reorganized into one cluster of applied livestock research, and one cluster of applied crop research. However, the experimental farms and gardens (some 20 in total), which are currently attached to the experiment stations, will most likely be transferred to the regional farmer organizations and more closely linked to extension. This is in line with MOA's policy of devolving its responsibility for near-market research.

6.4.4 *Financing*

Over the past 25 years, important changes have taken place in the financing of public agricultural research with regard to its volume, source and the way it is provided. Figure 6.1 gives an overview of the trends in expenditures by the most important (semi-) public agricultural research agencies. The initial steady expansion of funding halted in 1978, stagnated for about a decade, and picked up somewhat after 1988. Of the five research entities, DLO and, to a lesser extent, the experiment stations were hardest hit in terms of real budget cuts. In contrast, TNO-Food, Wageningen Agricultural University and the Faculty of Veterinary Sciences of the University of Utrecht increased their relative share in the public agricultural research system.

The funding of public agricultural research has become increasingly diversified and complex over time. Figure 6.2 gives a stylized overview of the links between funding and executing agencies within the Dutch agricultural research system. The total budget of the system is estimated at Dfl 1679 million in 1995 (US$ 1041 million). Of the public sources of funding, MOA is by far the most important, but other ministries, the Netherlands Science Council and the European Union also provide substantial resources. Private sources of funding are: (i) the Agricultural Board and the commodity boards,[12]

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[11] The contributions from the agricultural producers are collected as levies by several commodity boards and the (now almost defunct) Agricultural Board.

[12] The Agricultural Board, which brought together the various interest groups within the sector and which had regulatory powers by law, collapsed in late 1995 over a labor dispute between farmers and the labor unions. The various tasks and responsibilities of the Agricultural Board (including the collection of levies for

which collects levies from farmers and agricultural business and pay about half of the costs of the experiment stations (MOA pays the other half); and (ii) the private business sector, which contracts out some research to public sector agencies but spends most of its R&D budget internally.

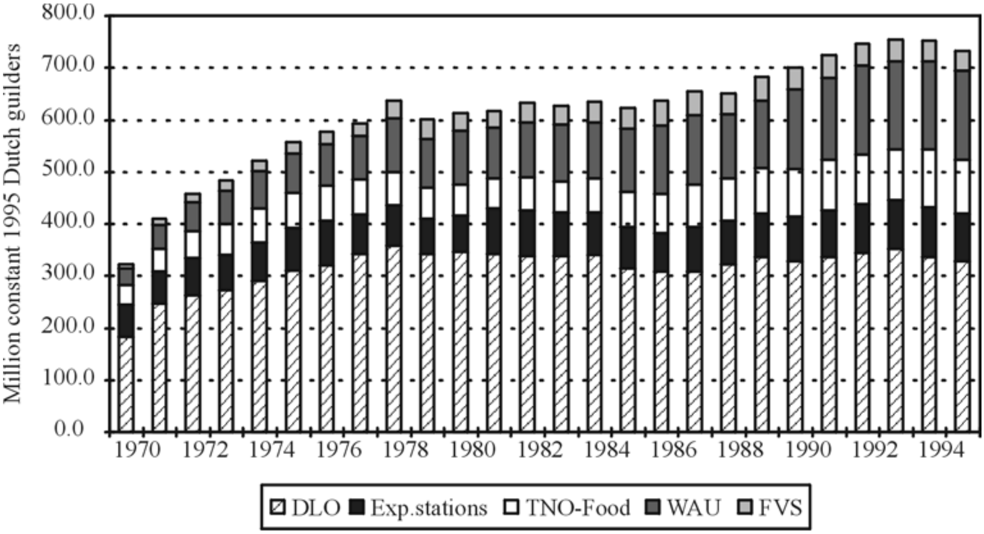

Figure 6.1: *Agricultural research expenditures by the public sector*

Source: Adapted from Roseboom and Rutten (1996).
Note: The time series data for DLO and the experiment stations do not include the costs of land and buildings, while the time series data for WAU only cover the agricultural sciences component of the university's research portfolio. In 1995, a Dutch guilder (Dfl) equaled US$ 0.62.

TNO-Food represents an interesting case, in that contracts with the private sector currently account for about two-thirds of its total budget. This not only reflects TNO-Food's close contacts with the Dutch food-processing and agrochemical industries, but also its rapidly expanding portfolio of research contracts with foreign clients, both public and private (approximately Dfl 12 million in 1995[13]). TNO-Food has an active policy to enter foreign research markets and has, in recent years, opened offices in Prague and Tokyo together with the other TNO institutes. In 1998, when DLO will be privatized, it is expected that the DLO institutes will also orient themselves more actively toward foreign markets.

research) are currently being split up. In recent years the various commodity boards, which cover the whole production column, have been merged into two: one for livestock production and one for crop production.
[13] Included here in the private sector contribution.

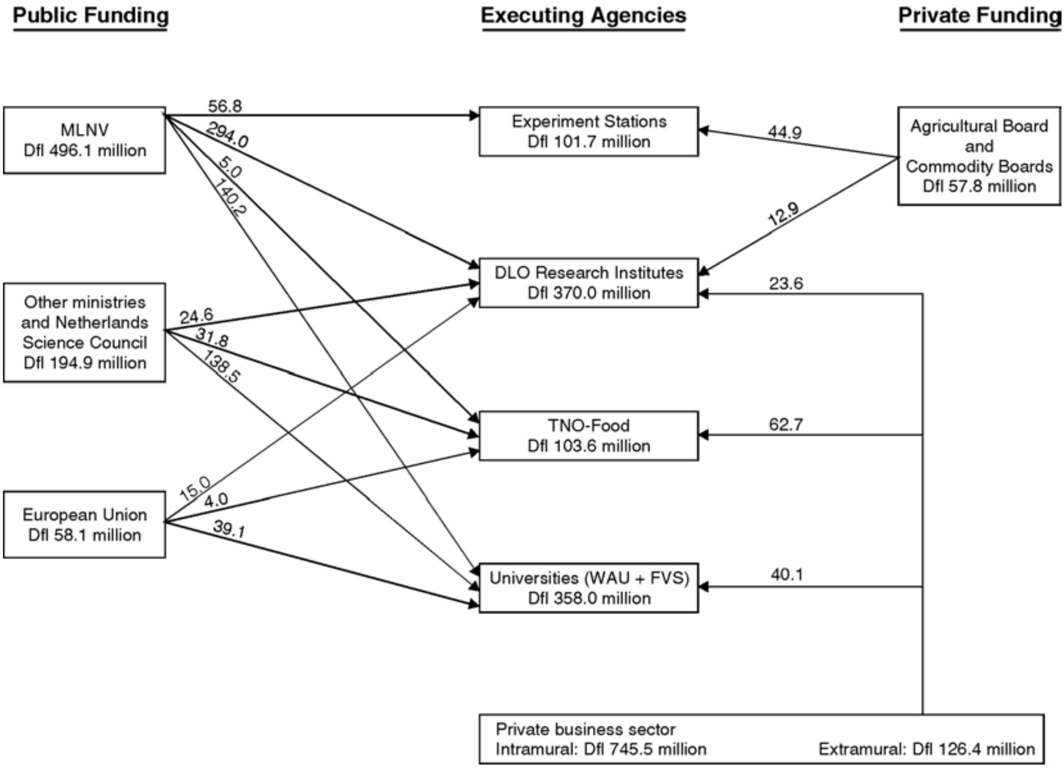

Figure 6.2: *Funding flows within the Dutch agricultural research system in 1995*

Note: In 1995 the Dutch guilder was equal to US$ 0.62.

Another recent development is the introduction of an R&D tax break for private businesses. This provision, introduced in 1994 to boost private sector R&D investments, subsidizes only personnel costs for R&D. Owing to an absolute limit on the total amount of tax reduction, the provision supports small- and medium-sized businesses more than large ones. The indirect subsidy provided by the tax break covers about 5-10% of total R&D costs.

The funding profiles of public agricultural research agencies have changed profoundly during the past 20 years (table 6.2). In line with a policy introduced in the early 1980s, and further articulated in the 1990s, that farmers should take more responsibility themselves for applied research, the Ministry has cut back most significantly on its contribution to the experiment stations. This was compensated for, in part, by an increase in funding provided by farmers through commodity boards and the (now defunct) Agricultural Board. The DLO institutes also experienced a major cut in their funding by MOA. They have generally had greater difficulty finding other sources of funding and have been forced to reduce staff. The current average of 25% funding from other sources varies quite substantially among the DLO institutes. Some institutes are still very dependent on MOA for their funding, while others obtain more than half of their funding from other sources.

Table 6.2: *Changes in sources of funding during 1978-95*

	Change in MOA's subsidy in real terms	Change in MOA's share in funding research	Other sources of funding
DLO research institutes	-19%	From 85% to 75%	Other ministries, private sector, European Union, Agricultural Board and commodity boards
Experiment stations	-33%	From 75% to 51%	Agricultural Board and commodity boards
Wageningen Agricultural University	-12% for the total university budget, but positive for research	From 74% to 46%	Netherlands Science Council, other ministries, European Union, private sector

Source: Roseboom and Rutten (1996, 1997)

Compared with other entities, Wageningen Agricultural University has fared relatively well. Despite the fact that MOA's subsidy to the university (covering both education and research) declined 12% in real terms during 1978 and 1995,[14] the number of full-time equivalent research positions paid by MOA increased from 223 to 361, while those paid by other sources (e.g. the Ministry of Development Cooperation, the Ministry of the Environment, the Netherlands Science Council, the European Union and the private sector) increased from 77 to 472. Of all the universities in the Netherlands, WAU has the highest proportion of external financing of research.

In addition to the change in composition of the financing sources, important changes have been introduced in the way financing is provided. Traditionally, most MOA funding was provided as a grant to an institute. For the DLO institutes, which operated within the bureaucratic structure of MOA, these grants narrowly specified the types of expenditures (some even made in kind, such as land and buildings) but were not specific with regard to expected outputs. Financial control by the Ministry focused on the input, rather than the output side. The ministerial grants to the experiment stations and Wageningen Agricultural University, both operating at some distance from the Ministry, had been less specific and had more the character of a lump-sum payment.

The new concept of public administration has led to a major change in the way MOA disburses its grants. Instead of providing open grants, the Ministry increasingly uses contracts that specify targets and outputs for the agreed-upon research programs, which are used to monitor and evaluate the research provider. With regard to the experiment stations, this has resulted in the decision by MOA to disentangle public and private interests, and end the arrangement for matching funding with the experiment stations as

[14] Largely because of a dramatic decline in the number of students in recent years.

of 1998. In the future, government grants will only be provided to the experiment stations for agreed-upon research programs that reflect the priorities of the Ministry of Agriculture (van Vloten-Doting 1997).

Not only has the Ministry introduced contract arrangements with the executing agencies, it has also tried to generate competition in the distribution of its research contracts by setting aside a small portion of its budget for competitive grants. Most of its research budget, however, is still spent in a rather closed system of consultation between DSKT and preferred providers (DLO, WAU, TNO-Food, etc.). This model of disbursing research funds is still far from a true "research market". The future merger of DLO and WAU will even further reduce whatever competition exists between the preferred providers. Competition, however, plays an important role in obtaining funding from other sources (e.g. the private sector, European Union, Netherlands Science Council and other ministries).

6.5 *Experiences in other developed countries*

The forces that have shaped the transformation of the Dutch agricultural research system over the past 25 years have not been unique to the Netherlands. In the majority of developed countries, the changing role of government, public administration reform, and shifts in agricultural policies have induced institutional changes in the national agricultural research systems.

In table 6.3 we have summarized in a stylized way the most important changes that have taken place over the past 25 years in five different NARS (Australia, England and Wales, Netherlands, New Zealand and the United States) with regard to mandate, policy formulation and coordination, organization and structure, management and financing.

In all five NARS, the mandate for public agricultural research has moved away from the traditional productivity focus toward issues of wider social interest, such as the environment, animal welfare and food safety. In the context of the new role seen for government, these latter issues are ranked higher with regard to their public-good content than productivity issues. In all NARS, greater emphasis has been placed on cost recovery or cost sharing for research that is of direct benefit to agricultural producers, or to the agricultural input and process industries.

Where governments still see a role for themselves in providing productivity-enhancing agricultural research, they have pushed for a better client orientation. In particular, public agricultural research systems of Australia, New Zealand, and England and Wales have been criticized in the past for being out of touch with their clients. In the course of the 1970s and 1980s, each of them introduced changes in order to improve client orientation and to reorient the agricultural research agenda toward applied research.

Table 6.3: *Institutional changes in some selected developed country NARS over the past two decades*

	Australia	England and Wales	Netherlands	New Zealand	U.S.A.
Mandate	Increased emphasis on both productivity and public concerns related to environment, animal welfare and food safety	Increased emphasis on public concerns related to the environment, animal welfare and food safety	Increased emphasis on public concerns related to the environment, animal welfare, food safety and land use	Increased emphasis on productivity and a relatively modest emphasis on environmental, animal-welfare and food-safety issues	Increased emphasis on public concerns related to the environment, animal welfare and food safety
Coordination and formulation of agricultural research policy	More market oriented and more decentralized through the introduction of Rural Industry R&D Corporations that now fund about 30% of all agricultural research in the public sector	Dual system of ministry and council responsibility. Since 1984 a Priorities Board with considerable industry representation sets the research priorities for both entities	From central coordination towards decentralized "research" markets	Responsibility for agricultural research transferred to the Ministry of Science and Technology, greater market orientation	Relatively decentralized, larger influence of Congress over federal funding through competitive and special grants
Structure and organization	Relatively few changes at the executing level, internal reorganization of CSIRO	Major restructuring, consolidation of capacity, in some instances sold to the private sector	Major restructuring, consolidation of capacity, privatization of executing agencies	Major restructuring, autonomous crown institutes established	Relatively few changes
Management	Adoption of private sector management principles	Adoption of private sector management principles, delegated management responsibility	Adoption of private sector management principles	Adoption of private sector management principles	Relatively few changes
Financing	Matching funding of farmer levies through Rural Industry R&D Corporations	Financing by MOA now output oriented and increasingly competitive; in contrast council funding is lump-sum and long-term; increase in private funding, establishment of levy boards	Switch from input to output financing, greater reliance on other (including private) sources of funding	Switch from input to output financing, increased reliance on private sources of funding	Decrease in formula fun-ding, increase in competitive and special grants, increase in other sources of funding (including private sector through cooperative R&D agreements)

Sources: *Australia*: Brennan and Davis (1996); Hussey (1996); Mullen *et al.* (1996); *England and Wales*: Jamieson (1989); Thirtle (1989); Thirtle *et al.* (1995); OECD (1995); *Netherlands*: Roseboom and Rutten (1995); Roseboom and Rutten (1996) and Roseboom and Rutten (1997); *New Zealand*: Brennan and Davis (1996); Jacobsen and Scobie (in press); Radford (1996);*USA*: Alston and Pardey (1996); Fuglie, *et al.* (1996), Just and Huffman (1992); Huffman and Just (1994).

This increased emphasis on client orientation has resulted in important changes in the role of research policy coordination and formulation within the NARS, particularly when clients are being given the opportunity to pull the financial strings (e.g. the introduction of the Priorities Board in England and Wales). This has forced public research agencies to be more demand oriented. Central planning of agricultural research seems to have lost its importance in most countries considered.

In three of the five countries, public research capacity has been significantly restructured over the past 10-15 years in order to improve efficiency. In all instances this has led to the consolidation of agricultural research into larger research entities. In addition, public administration reform has induced a separation of agricultural research policy formulation and execution in most countries, as well as more private sector-like management principles throughout the NARS. Our impression is that, at least at the macro level, the US agricultural research system has been affected the least by these public administration reforms.

In all five NARS, public funding of agricultural research has become more competitive. In part this has been the result of an increase in the importance of third-party funding, such as other ministries, agricultural producers, or private businesses. These funders shop around for research providers. The principal financing agencies also administer an increasing share of their funding on a competitive basis. Whether or not funding is provided through competition, research financing is increasingly tied to specified outputs. The traditional way of financing a research agency with a lump-sum grant on the basis of its mandate is in decline in most countries.

6.6 *Future challenges*

We have argued that the transformation of the Dutch agricultural research system is unique neither to the Netherlands nor to agricultural research as such. Structural changes within the agricultural sector, as well as broader political-economic developments, are the main driving forces behind these changes. The transformation, however, is far from complete. All actors involved (i.e. research institutes, policy makers and representatives from business and other interest groups) are still in the process of redefining and "re-finding" their roles. What are the perspectives for the next 10-15 years? Will a "new" agricultural research system be established and settled, and what features will it have?

A recent foresight study by the National Agricultural Research Council (NRLO 1996) tries to shed light on these questions by identifying three separate domains that affect the environment within which the agricultural research system operates: (a) the utility domain, (b) the scientific and technological domain, and (3) the managerial-institutional domain.

Two important conclusions can be derived from the expected trends in the utility and science and technology domains:

- agriculture, agribusiness and rural affairs (the utility domain) will become more integrated with other, nonagricultural and nonrural spheres;
- agricultural research will become more intertwined with other sciences and technologies.

Taken together, these two conclusions imply that agricultural research will lose much of its specificity and the distinction between agricultural and nonagricultural research will become increasingly blurred. The consequences for the agricultural research system are far-reaching. Much will depend on how managers and policy makers responsible for the present agricultural research system will *and can* react to these challenges. Should they try to guide this transition as smoothly as possible? Or should they strive for a new profile and organization of the NARS by redefining its core fields of interest? Or are both strategies called for? Within the Dutch agricultural research system there is not much support for pursuing the first strategy – which effectively would boil down to the NARS being absorbed into the national innovation system. The recent formation of Knowledge Centre Wageningen (KCW) is a clear choice for consolidating the NARS, rather than dissolving it. At the same time, however, the key to the success of KCW lies in whether it will be able to reposition itself effectively in a rapidly changing research market. This will depend very much on the organizational flexibility of KCW and on keeping the links open to science and technology developments elsewhere.

Future trends in the managerial-organizational domain are largely an extrapolation of the developments described here, and which were set in motion during the past decade. New public administration practices and stricter policies with regard to the funding of near-market research will have to be absorbed in the coming years. There are, however, still some crucial choices to be made by MOA with regard to its own position in the agricultural research market, namely: (i) will MOA reduce its role to that of a client only, or will it maintain a responsibility for the overall outcome of the "privatized" agricultural research market; and (ii) should MOA continue or even intensify its efforts to define its research needs in great detail, or should it adopt a more hands-off policy and return to a much broader definition of research needs?

Dutch agricultural research managers and policy makers see the internationalization of the agricultural research market as an important future challenge. It will open up new opportunities for Dutch agricultural research agencies, but also possible competition from abroad. In the private segment of the agricultural research market, national borders are hardly an issue. In the public segment, however, strong national borders still exist and it is unlikely that they will disappear overnight. The only hope in this regard is for a stronger and more centralized European policy on science and technology and a switch from predominantly national to European funding for agricultural research – not a very likely scenario. The private segment of the agricultural research market, however, is large and growing. The new private status of the DLO research institutes has given them much more flexibility to attract foreign clients than in the past. It is expected that at least some of the DLO research institutes (in particular, those that already derive much of their income from contracts with the private sector) will follow in the steps of TNO-Food and expand their research activities beyond national borders.

Part III: Underinvestment in Agricultural R&D Revisited

An implicit assumption in most of the descriptive analysis of agricultural R&D trends and patterns in part II is that there is "underinvestment" in agricultural R&D and that any slowdown in the growth or contraction of agricultural R&D investments is reason for serious concern. Support for this is quite widespread (Ruttan 1980; Pinstrup-Andersen 2001) and has been based on empirical evidence provided by a large number of studies that have estimated the rate of return (ROR) to agricultural R&D investment. The average rate that can be distilled from all these ROR studies is in the range of 40%-60% (Alston *et al.* 2000), which constitutes a more than excellent track record. This evidence has generally been interpreted as an indication of underinvestment in agricultural R&D – substantially more could have been invested profitably in agricultural R&D.

Nevertheless, the underinvestment hypothesis has been under attack from several quarters. Counter arguments that have circulated in the literature most prominently include the following:

(1) There are serious weaknesses in the ROR methodology, leading to systematic overestimation of the returns to (agricultural) R&D.
(2) There is a bias in the selection of ROR studies towards the better-performing R&D projects.
(3) It is not the rate of the average R&D project that determines the underinvestment gap, but the rate of the unobserved marginal R&D project.
(4) The gap is real, but it can be explained by factors such as budget rigidity, deadweight losses due to taxation, and risk and uncertainty.

The literature on measuring the economic impact of (agricultural) R&D is quite extensive and will therefore be discussed separately in chapter 7. An overview will be given of the most common approaches to *measuring* the relationship between (agricultural) R&D investment and productivity. The more important conceptual and technical details will be explored and summarized. The other three counter arguments will be taken up in chapter 8, which critically revisits the underinvestment hypothesis but takes the ROR evidence as it comes. By introducing a model of the distribution of R&D projects on an expected rate-of-return scale, the ROR evidence collected by Alston *et al.* (2000) will be interpreted in a new light. The proposed model provides a basis for estimating the under- or over-investment gap as well as for modeling the impact of possible explanations for the observed underinvestment gaps.

7. Measuring the economic impact of (agricultural) R&D

Rates of return (ROR) play a crucial role in the discussion of underinvestment in (agricultural) R&D. Therefore, this chapter sets out to review and discuss the standard methods used to quantitatively measure the economic impact of agricultural R&D. The two most common economic approaches in ex post evaluations of agricultural R&D are *the economic surplus approach* and *the production function approach*. Alston, Norton, and Pardey (1995) discuss both approaches in great detail.[1] This chapter provides only a brief summary of the principal characteristics of the two approaches (sections 7.1 and 7.2). A critical step in both approaches is the modeling of the relationship between R&D investment and measured R&D benefit (section 7.3). Section 7.4 discusses the various attribution problems encountered by R&D rate-of-return studies. Section 7.5 summarizes the conclusions.

7.1 *The economic surplus approach of measuring the impact of R&D*

The economic surplus approach uses a supply-and-demand model of a commodity market to estimate changes in consumer and producer benefits due to a research-induced shift in the supply curve. This is depicted graphically in figure 7.1 for a closed economy.

D represents the demand for a homogenous product and S_0 and S_1 represent, respectively, the supply of the product before and after a research-induced technical change. All curves are defined as flows per unit time, typically annually, as are the economic surplus measures. The initial equilibrium price and quantity are P_0 and Q_0; after the supply shift they are P_1 and Q_1.

Under these assumptions, the total annual benefit from a research-induced supply shift is equal to the area beneath the demand curve and between the two supply curves (ΔTS = *area* I_0abI_1). This area can be viewed, with linear supply and demand curves and a parallel shift of the supply curve, as the sum of two parts: (a) cost savings on the original quantity (the area between two supply curves to the left of Q_0 – area I_0acI_1) and (b) the economic surplus due to the increment to production and consumption (the triangular area *abc*). Alternatively, it is possible to partition the total benefit into a consumer surplus (ΔCS = area P_0abP_1) and a producer surplus (ΔPS = area P_1bcd).

[1] Alston, Norton, and Pardey (1995) mention a third, *nonparametric* approach to evaluating the impact of agricultural research. The advantage of this approach, which uses linear programming, is that by not imposing any functional form on the data, it avoids many of the pitfalls that come with the *parametric method* used in the production function approach. Chavas and Cox (1992) summarize the following advantages of a non-parametric approach relative to parametric approaches: (1) non a priori restriction on substitution possibilities among inputs, (2) allows joint estimation of the production technology, technical chance, and the effects of research on technical progress using very disaggregate inputs, (3) flexibility in the length and shape of the lag distribution between research and productivity, (4) permits an investigation of the separate effects of private and public research on technical progress, and (5) empirically tractable. To date, the nonparametric approach has been used only rather sparsely to evaluate the impact of agricultural research.

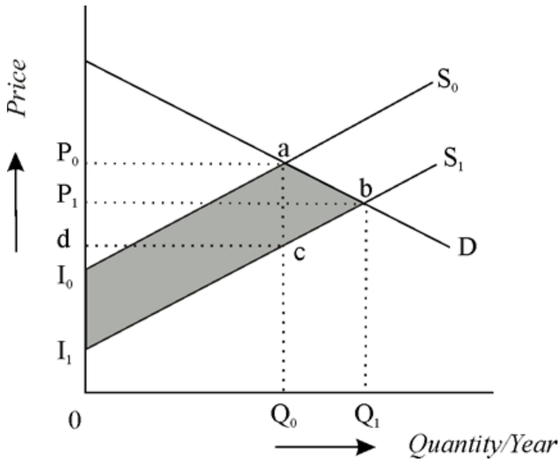

Figure 7.1: *Consumer and producer surplus measures*

The consumer and producer surplus measures can be expressed algebraically as follows:

$$\Delta CS = P_0Q_0\, Z\, (1{+}0.5Z\eta) \qquad [7.1]$$

$$\Delta PS = P_0Q_0\, (K{-}Z)\, (1{+}0.5Z\eta) \qquad [7.2]$$

$$\Delta TS = \Delta CS + \Delta PS = P_0Q_0\, K\, (1{+}0.5Z\eta) \qquad [7.3]$$

where *K* is the vertical shift of the supply function expressed as a proportion of the initial price [$(P_0\text{-}d)/P_0$], η is the absolute value of the elasticity of demand, ε is the elasticity of supply, and $Z = K\varepsilon / (\varepsilon+\eta)$ is the reduction in price relative to its initial value, due to the supply shift ($(P_0\text{-}P_1)/P_0$).

When *Z* or η are relatively small (reflecting a relatively small decline in price and relatively inelastic demand, respectively), it is reasonable to approximate the research-induced benefits as follows:

$$\Delta CS = P_0Q_0\, Z \qquad [7.4]$$

$$\Delta PS = P_0Q_0\, (K{-}Z) \qquad [7.5]$$

$$\Delta TS = \Delta CS + \Delta PS = P_0Q_0\, K \qquad [7.6]$$

Or, relating back to figure 7.1, when the decline in price is small or the demand rather inelastic (i.e., more vertical than depicted in figure 7.1), the benefits represented by triangle *abc* are negligible in comparison to the benefits represented by area P_0acd.

The latter approximation of the total economic surplus is frequently used in studies that use an implicit rather than explicit economic surplus model. The advantage of the implicit approach is that no estimations of the form and elasticity of the demand and supply curves are needed to estimate total benefits. While intuitively attractive, an implicit economic surplus model tends to obscure many of the underlying assumptions.

The basic economic surplus model presented above assumes linear supply-and-demand curves and a parallel shift of the supply curve. In the literature, quite a number of alternatives to this simple representation have been proposed and tried out, such as *divergent* and *convergent* shifts of linear supply curves as well as *parallel* and *proportional* (or *pivotal*) shifts in (quasi) *constant elasticity* supply-and-demand models (see figure 7.2).[2]

Depending on the model, the measure of estimated benefits can differ quite substantially. For example, given a linear supply curve function, total benefits from a parallel shift are almost twice the size of total benefits from a pivotal shift of equal size at the pre-research equilibrium (Alston, Norton, and Pardey 1995).

It is not only the elasticity of the supply curve that matters, but also that of the demand curve. The more inelastic the demand curve, the more likely producers will pass the benefits from a technical change on to consumers by means of lower prices. Also, if the supply elasticity is absolutely larger than the demand elasticity, consumers will tend to receive a larger share of the benefits than producers (Norton and Davis 1981). In the case of a pivotal supply shift and inelastic demand, however, farmers may actually be worse off than before the technical change.

After having reviewed all these different supply-shift forms, Alston, Norton, and Pardey (1995) conclude that, in the absence of the information required to choose a particular type of supply shift, the most practical solution is to assume a parallel research-induced supply shift and a local linear approximation of the supply-and-demand curve.[3]

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[2] See Norton and Davis (1981) and Alston, Norton, and Pardey (1995) for overviews.

[3] A side issue is whether the shift is expressed as vertical (in the price direction) or horizontal (in the quantity direction). Expressing a K percent yield increase (or cost saving) as either a K percent vertical shift or a K percent horizontal shift has different implications unless the supply elasticity is unitary. The equivalent horizontal supply shift, J, for a K percent vertical supply shift is given by using the definition that $dQ/Q=\varepsilon dP/P$ and therefore, $J = \varepsilon K$, where ε is the elasticity of supply (Alston, Norton, and Pardey 1995).

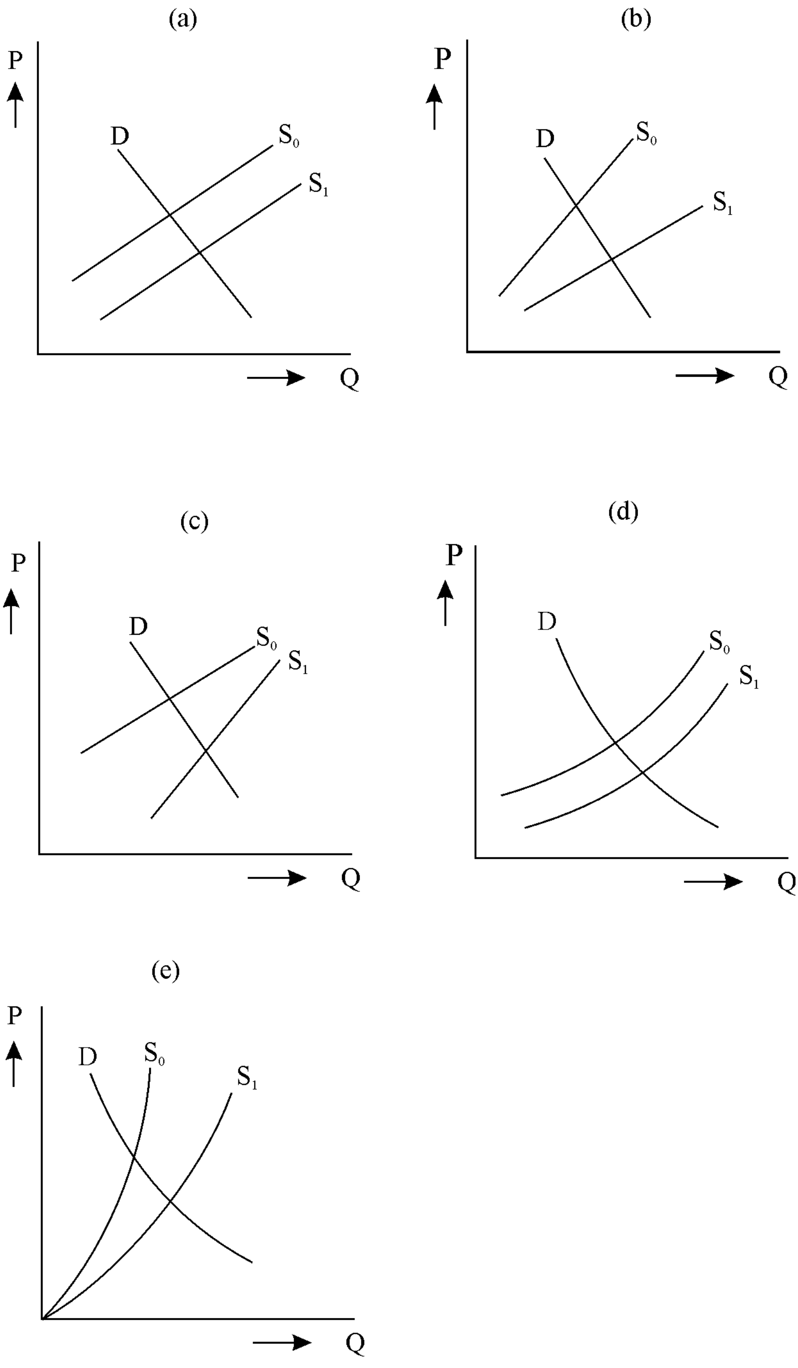

Figure 7.2: *Different supply-shift assumptions*

The basic economic surplus model deals with a single-commodity market in isolation – no interaction with the rest of the economy or world takes place. In chapter 4 of their book, Alston, Norton, and Pardey (1995) discuss a range of possible modifications and extensions to the basic model, which allow (1) disaggregation of economic-surplus effects across multiple markets horizontally (across geopolitical regions, socioeconomic groups, or commodities) and vertically (across stages of production or among factors of production), (2) the capture of the effects of interregional and international spillovers of research-induced price changes and research results, (3) incorporation of general-equilibrium feedback and economy-wide adjustments, (4) accommodation of market distortions and the effects of research on the creation (or amelioration) of market distortions caused by government intervention or production externalities, and (5) accounting for the costs of taxation to finance government spending. It is these modified and extended versions of the economic-surplus model in particular that have attracted many practitioners and have resulted in a blossoming of the literature on this topic.

Whatever the size of the measured R&D benefits, a critical consideration is how to link those benefits to past R&D investments. Or, in the case of an ex ante rate-of-return estimation, how to link an investment in R&D today to a benefit stream in the future. This issue will be taken up in more detail in section 7.3, as it is essential to both economic surplus as well as the production function approach.

In summary, the estimation of the benefits from a research-induced supply shift boils down to four critical determinants: (1) K, the percentage research-induced reduction in costs of production when the results are adopted, (2) P_0Q_0, the size of the industry affected, (3) the nature of the research-induced supply shift, and (4) the timing of the flows of benefits (the research lags) (Alston *et al.* 2000).

R&D investment evaluations using an economic surplus method either estimate the K-shift on the basis of information derived from (preferably) on-farm trials and observed adoption patterns (Maredia, Beyerlee, and Anderson 2000) or on the basis of historical time-series data of output and corresponding input use, using econometric techniques. In the latter instance, there is a close link between aggregate growth accounting, index number theory, and the economic surplus approach. Growth accounting involves compiling detailed accounts of inputs and outputs, aggregating them into input and output indices, and using these indices to calculate a total factor productivity (TFP) index or, as in the case of the economic surplus model, calculate the K-shift (which boils down to the question of what it would cost to produce Q_0 with today's technologies). The theory of index numbers shows that the method by which the raw data are combined into a manageable number of subaggregates, and in turn reaggregated, matters (Antle and Capalbo 1988). The preferred method is a chained index, such as the *Divisia* index, as it minimizes the impact of relative price changes on the aggregate quantity index. While the *Divisia* index proper requires continuous measurement of input prices and quantities and is therefore unattainable, several discrete approximations to the *Divisia* index are possible, such as the *Laspeyres*, *Paasche*, *Fisher ideal*, and *Tornqvist-Theil* approximations.[4] In particular, Diewert (1976, 1980, 1981) has contributed to a better understanding of the economic assumptions and the underlying aggregation functions that are implicit in the choice of an indexing procedure.[5] This understanding may help to match the right index with the right aggregator function. Growth accounting and index number theory are also of relevance to the production function approach discussed in the next section.

7.2 *The production function approach of measuring the impact of R&D*

The production function approach uses regression analysis to estimate an aggregate production (or productivity, cost, or profit) function model that can be used to evaluate the additional output (for given inputs) or the saving in inputs (for a given output) attributable to past investments in R&D.

The production function and productivity increases

A correct estimation of the production function is essential if one is to differentiate between various possible explanations for observed differences or increases in productivity correctly. Panel *a* in figure 7.3, adapted from Antle and Capalbo (1988), shows two single-output neoclassical production functions $F^1(X)$ and $F^2(X)$, which represent the technically efficient combinations of input X and output Q in period 1 and 2, respectively, using different technologies. X_1,Q_1 and X_2,Q_2 are the input-output combinations observed in period 1 and 2, respectively. The total factor productivity (TFP), measured as the average product of factor X, is greater in period 2 than in period 1. This measured productivity increase can be attributed to three distinctive phenomena:

(1) *Increase in (technical) efficiency:* Q_1 is below $F^1(X)$, indicating technical inefficiency; efficient production would have resulted in output Q_1*.
(2) *Scale of production:* Q_2 was produced with a greater input than was Q_1, so there is a difference in scale of production, which explains the difference between Q_1* and Q_2*.
(3) *Technical change*: Production function F^2 exhibits a higher total productivity than F^1, which explains the gap between Q_2* and Q_2.

A slightly more complicated version of the production function allowing for two inputs, $F^1(X_1, X_2)$, is depicted as isoquant Q_1 in panel *b* of figure 7.3. The isocost line (W_1) defines the economically efficient combination of inputs X_1, X_2 (point *A*). The observed input combination *B* to produce Q_1 is economically inefficient, which can be disaggregated into *technical* and *allocative* inefficiency. Technical inefficiency refers to failure to operate at the production function (*BC*), while allocative inefficiency refers to failure to minimize production costs (*CA*) while at the production function.

[4] See Alston, Norton, and Pardey (1995) for further details.
[5] The Divisia approximations of the Laspeyres and Paasche type imply either a linear production function in which all inputs are perfect substitutes or a *Leontief* production function in which all inputs are used in fixed proportions. Similarly, a geometric approximation is exact for a *Cobb-Douglas* production function, the *Fisher ideal* approximation is exact for quadratic aggregator functions, and the *Tornqvist-Theil* approximation is exact for a homogenous translog production function. Hence, the importance of index number theory lies in the linkage of the growth accounting approach to production theory (Antle and Capalbo 1988).

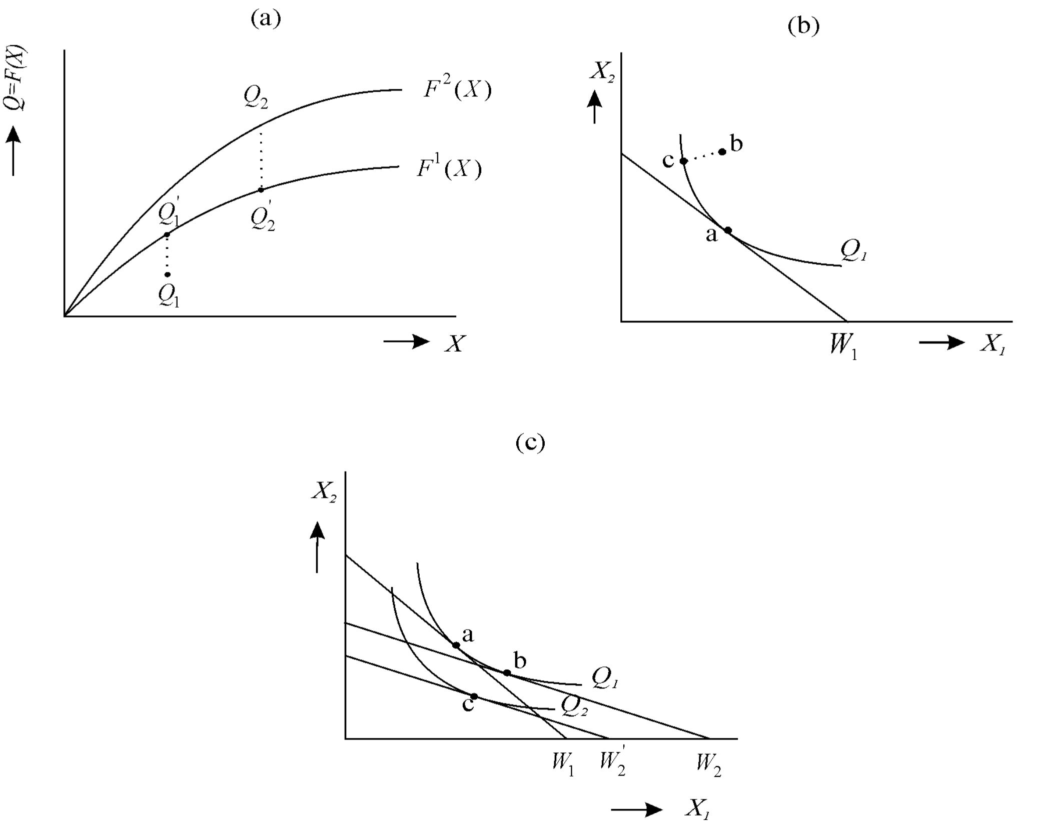

Figure 7.3: *Possible explanations of productivity increases*

Panel *c* in figure 7.3 depicts two production functions for periods 1 and 2. For given technology, a change in the relative prices of inputs X_1 and X_2 (depicted as a change in the angle of the isocost line from W_1 and W_2) shifts the economically efficient optimum from a to b. The situation becomes more complicated when, at the same time, there is a (neutral) productivity improvement so that the same amount of output can be produced with fewer measured inputs (isoquant Q_2). This would lead to a new optimum, point c. The difficulty in differentiating between these two phenomena is that points *a* and *c* can be observed, but point *b* can not.

Total factor productivity (TFP) can be defined as aggregate output (*Q*) divided by aggregate input (*X*). Hence, TFP growth is simply equal to the rate of growth of aggregate output minus the rate of growth of aggregate input for *Divisia* indices of aggregate output and input. While the basic principles of how to measure TFP growth properly are clear, some important choices about the extent to which inputs and outputs should be kept disaggregated in the construction of the indices still have to be resolved. Ideally, inputs and outputs should only be pre-aggregated when they are perfect substitutes or grow at the same rate (Alston, Norton, and Pardey 1995). If not, pre-aggregation of data may distort the measurement of TFP growth. Another, rather different measurement problem is that there is typically no explicit allowance for the reduction in the stock of environmental and natural resources associated with agricultural production in terms of land degradation, depletion of soil fertility, chemical pollution of air and groundwater, build-up of resistant pests and diseases, and so on. By ignoring the contribution of these inputs, TFP growth will be overestimated.[6] Putting aside these measurement problems, TFP growth can be attributed to technical and (although usually ignored) institutional change and, hence, to past investments in R&D.

The most straightforward approach to formally linking notions of technical change with measured rates of growth in productivity is to assume that an *index of the state of technology*, τ, can be incorporated directly into a production function such that

$$Q_t = \mathrm{F}(X_t,\ \tau_t) \qquad [7.7]$$

Hence, technological progress (i.e., $d\tau/dt > 0$) is perceived as an upward shift of the production function or, equivalently, as a downward shift of the production isoquant.[7] Rates of change in output over time can be partitioned into components due to changes in measured input use and those due to changes in the state of technology. Alston, Norton, and Pardey (1995) show that the *primal rate of technological change* can be expressed as the rate of change in output, minus a scale-adjusted index of the rate of change in input. Hence, under the assumption of constant returns to scale, input-output separability, efficient and optimizing producers, and disembodied technical change of the extended Hicks-neutral type, the primal rate of technological change equals the TFP growth rate mentioned above.[8]

In order to estimate the production function, several closely interlinked choices have to be made with regard to (1) the functional form for the empirical model, (2) the variables to be included, (3) possible proxy measures for those variables, and (4) the representation of technological change. The first three choices will be discussed only briefly here, followed by a more extensive discussion of the representation of technological change.

7.2.1 *Functional form of the empirical model*

Choices about functional form are dictated to a great extent by the availability of data and the purpose of the analysis. The functional form used most frequently in the literature on agricultural production is the Cobb-Douglas production function, although since the early 1960s, more flexible forms have also been explored, such as constant elasticity of

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[6] For attempts to correct for this error see for example Oskam (1991) and Barnes (2002).

[7] For a discussion of other approaches to modeling technical change see Alston, Norton, and Pardey (1995, p. 114-116).

[8] It is also possible to use the cost or profit function to derive a *dual rate of technological change* that is the counterpart of the primal rate. Alston, Norton, and Pardey (1995) show that under the assumption of constant returns to scale, the primal and dual rates are equal but opposite in sign. Because of scale effects, direct estimates of primal and dual rates of technological change generally differ.

substitution (CES), quadratic functions, and quadratic functions in logarithms (translog).[9] The translog production function, in particular, has been considered a good alternative to the more restrictive Cobb-Douglas production function. However, quadratic production functions, by their very nature, contain many variables that are intercorrelated, and therefore the estimated parameters suffer from low precision to the extent that they often do not make sense (Mundlak 2000).

The Cobb-Douglas production function can be written as follows:

$$\ln Q_t = \alpha_0 + \sum_{i=1}^{m} \alpha_i \ln X_{i,t} + \sum_{g=1}^{k} \beta_g \ln K_{g,t} + \sum_{h=1}^{l} \psi_h \ln Z_{h,t} + \mu_t \quad [7.8]$$

and the translog production function (suppressing the Z variables), as

$$\begin{aligned} \ln Q_t = {} & \alpha_0 + \sum_{i=1}^{m} \alpha_i \ln X_{i,t} + \sum_{g=1}^{k} \beta_g \ln K_{g,t} \\ & + \tfrac{1}{2} \sum_{i=1}^{m} \sum_{h=1}^{m} \alpha_{ih} \ln X_{i,t} \ln X_{h,t} + \tfrac{1}{2} \sum_{g=1}^{k} \sum_{h=1}^{k} \beta_{gh} \ln K_{g,t} \ln K_{h,t} \quad [7.9] \\ & + \tfrac{1}{2} \sum_{i=1}^{m} \sum_{g=1}^{k} \gamma_{ig} \ln X_{i,t} \ln K_{g,t} + \mu_t \end{aligned}$$

Where X, K, and Z respectively represent the quantities of conventional inputs, variables that determine the stock of knowledge in use (approximating the state of technology, τ), and various "fixed" institutional, infrastructural, and policy-related variables. As can be seen, the Cobb-Douglas production function is just a special case of the translog production function, one for which the parameters on all squared and interaction terms are assumed to be zero (Alston, Norton, and Pardey 1995).

A popular alternative to the primal or production function approach is that of the dual approach, which formulates production in terms of a cost or profit function. The advantage of dual functions is that they contain information about both optimal behavior and the structure of the underlying technology or preferences, whereas primal functions describe only the latter. Statistically, there is also the advantage of using factor prices (rather than their quantities) as explanatory variables, which may avoid problems of simultaneity that arise when input choices are jointly endogenous with output because factor (and product) prices are more likely to be behaviorally and, hence, statistically exogenous to a firm and even to an industry (Alston, Norton, and Pardey 1995). Mundlak (2000), however, seriously questions the use of dual functions. He argues that many of

[9] See Mundlak (2000) for a more detailed historical overview.

the properties of the dual estimators are derived for competitive firms and are not automatically applicable to aggregates that do not meet the underlying assumptions.

7.2.2 *Variables to be included and their possible proxies*

Variables usually included in a production function are conventional inputs such as land, labor, and capital, as well as some selected purchased inputs. To the extent that the available data do not differentiate inputs according to their intrinsic quality (e.g., reporting tractor hours rather than horsepower hours), indirect "quality" indices may be included to correct for such aggregation errors.[10] The labor and capital input variables require some additional careful handling, as available data usually represent labor and capital stock rather than their preferred service flow (e.g., tractors rather than tractor hours). In their seminal paper on the explanation of productivity change, Jorgenson and Griliches (1967) point out that all such measurement issues matter and that if quantities of output and input are measured accurately, growth in total output may be largely explained by growth in total input. Based on data for the private domestic economy in the US for the period 1945-65, their initial productivity growth of 1.6% annually (explaining 52.4% of the output growth) drops to only 0.1% annually (explaining only 3.3% of the output growth) after correcting for the following measurement distortions: (1) error of aggregation, (2) the prices of investment goods, and errors in (3) relative utilization, (4) aggregation of capital services, and (5) aggregation of labor services. While data for other periods and with different adjustments yielded less extreme differences, their principal argument remains valid – that the construction of output and input indices need careful attention as one may easily end up with spurious TFP growth results.[11]

In addition to the conventional inputs and their quality shifters, two sets of non-conventional inputs are usually included, namely, one set dealing with "fixed" factors outside the realm of the decision makers whose production decisions are being modeled (e.g., infrastructure, agricultural policies, and political stability) and one set dealing with the stock of knowledge in use as a proxy for technological change. Including "fixed" factors in the production function is rather arbitrary for two reasons: (1) it is not always clear whether the factor belongs in the model and (2) it is not always possible to know whether the proposed proxy is a close enough approximation to the actual phenomena that one assumes has an impact on agricultural production.

[10] One would prefer, however, that the input indices reflect changes in quality differences properly so that the real service flow provided by the input is measured. For commodities that have quality characteristics that are multi-dimensional, so-called "hedonic" price indices may be used to correct for "quality change."

[11] The fact that constructing correct price and product indices is not a minor issue is reflected in the findings of a recent study commissioned by the US Senate Finance Commission, which found that the US Consumer Price Index (CPI) overstates inflation by approximately 1.1% annually, of which 0.5 percentage points are due to index problems and 0.6 percentage points are due to new products and changes in quality (Nordhaus 1997). With an average CPI rate of 2%–3% annually, this upward bias is far from negligible. This finding has led to the introduction of new, corrected price indices in the US, resulting in lower inflation rates and higher TFP growth rates than had been the case with the traditional price index methods.

7.3 *Modeling the link between R&D investments and R&D benefits*

In the literature, a range of different approximations of technical change can be found. The most common one is to explain a change in TFP, or τ, by past investments in R&D. The questions then is: *R&D expenditures on what, where, when, and by whom?* Of these four questions, the *when* question is technically the most challenging, although the other three need careful consideration as well.

Defining *agricultural* R&D has its own pitfalls. One way is to differentiate R&D activities on the basis of the economic activity that is targeted *directly.* This establishes a one-to-one relationship between agricultural R&D and agricultural production. In this definition, R&D activities by non-agricultural industries, supplying as well as processing industries (e.g., chemical, machinery, and food processing industries), are thus excluded. To the extent that input indices pick up quality and price changes correctly, the (new) technology embodied in inputs has been taken care of, so R&D activities by these supplying industries should not play a role in explaining τ. However, when input indices fail to reflect quality and price changes properly, R&D activities by the supplying industries may explain some of the observed productivity changes in primary agriculture.[12]

By its very nature, basic research does not fit into an economic activity classification. Possible solutions are the following: ignore it, prorate it, or include it as a separate variable that explains τ. Each solution will affect the link between τ and R&D expenditures differently. In cases where the productivity analysis focuses on just one commodity or cluster of commodities, it is necessary not only to identify the R&D specific to that commodity or cluster of commodities, but also the generic (not-commodity-specific) agricultural R&D activities. The same solutions found for basic R&D are possible. Assuming that there is little difference in the timing of R&D benefits between commodity-specific and generic agricultural R&D, prorating the generic agricultural R&D activities is preferred.

Regarding the question of *where*, the answer is usually determined by the geographical location of the production considered, such as a state or province, country, or a particular region of the world. The basic assumption is that the R&D taking place in a particular geographical location primarily targets production in that location. This assumption holds reasonably well for public agricultural R&D, as it tends to be location-specific. In so far as the assumption of location does not hold, the concept of "technology spillovers" has been introduced to deal with this problem, at least conceptually.[13] For the R&D activities of the supplying industries, however, the location of where the research is done and

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[12] As will be shown in section 7.4, a substantial part of the benefits of R&D activities undertaken by supplying industries are captured by those industries. Hence, the relationship between R&D in a particular supplying industry and τ is different between industries as well as for R&D that targets agricultural production directly.

[13] Productivity studies that actually take the effects of technology spillover into account are very rare (Alston *et al.* 2000).

where it has an impact on agricultural production can differ significantly. In this instance, the one-to-one plus spillover assumption is of little use. Trade data (assuming technology gets embodied in products) may help to identify where the R&D of supplying industries has an impact (Roseboom 2000).

Who undertakes R&D or who finances it does not really matter when it comes to explaining TFP growth. However, some differentiation between R&D performers may be warranted when they specialize in certain types of R&D. For example, universities tend to focus more on strategic and basic research, while private companies focus more on applied research. Hence, the expected R&D benefit stream from university research in terms of lag, length, and form may differ from that of private companies (Griliches 1973). In the same way, the lag, length, and form of the R&D benefit stream of forestry research may be different from that of crop, livestock, or fisheries research, or R&D in other industries, for that matter. It is in establishing the link between the research activity and the benefit stream that differentiating by R&D performer may be relevant.

In order to link past research investments to today's changes in TFP (the *when* question), the concept of a *knowledge stock* is being introduced, which, similar to the concept of capital stock, allows a service flow measure of knowledge to be estimated. Such a service flow depends on the existing (but unobserved) knowledge stock as well as its *utilization* and approximates the state of technology, τ_t. The stock of useful knowledge (K) can be defined as follows:

$$K_t = K_{t-1} + I_t - D_t = (1-\delta)\, K_{t-1} + I_t \qquad [7.10]$$

Where I represents additions to the knowledge stock as a result of R&D and D depreciations of the knowledge stock as knowledge becomes obsolete or is replaced by better information. Assuming a constant rate of knowledge depreciation, δ, D can be expressed as δK_{t-1}. Through a repeated substitution for K_{t-1} in equation 7.10, it can be seen that the current knowledge stock, K_t, is defined by the entire history of changes in this knowledge stock, implying an infinite lag structure for research (Alston, Norton, and Pardey 1995). However, there is one exception and that is when $\delta = 1$, which means that the knowledge stock completely depreciates in one period and $K_t = I_t$. The opposite option is to assume that useful knowledge does not depreciate at all ($\delta = 0$), which implies that increments to knowledge in the past are just as effective today as the most recent increments to knowledge. Neither extreme is realistic. Alston, Craig, and Pardey (1998) cite several studies from the industrial R&D literature that have used knowledge depreciation rates ranging from 0% to 25%. However, most studies on the returns to agricultural R&D implicitly assume a depreciation rate of 100% (which means $\delta = 1$), so that $K_t = I_t$. Alston, Craig, and Pardey (1998) argue that this is true of all studies that model K_t (and hence, τ_t) as a function of a finite lag of research investments, $R_{t-GL-LL}$, such that

$$K_t = I_t = \mathrm{i}(R_{t-GL}, R_{t-GL-1}, \ldots\ldots, R_{t-GL-LL}, \varepsilon_t) \qquad [7.11]$$

where *GL* represents the gestation lag (the time it takes before research shows its first impact), *LL* is the total lag length (the period over which R&D is assumed to have an impact), and ε_t represents chance. Other possible explanatory variables, which have been suppressed here, are (1) various factors affecting the productivity of research, such as research orientation (in some areas, it is easier to make progress than in others) and improvements in the organization and management of research (with the same money, more innovation can be produced) and (2) spillovers of knowledge from research elsewhere or from other industries.[14]

The dynamics of the relationship between past investments in R&D, *R*, and increments in useful knowledge, *I*, are complicated and uncertain. There are at least four forces at work here, which are depicted in a stylized way in figure 7.4: (1) the lag between research investment and the actual invention of a new technique (a-b), (2) the lag between invention and the first economic application of the invention (b-c), (3) the lag between first use and complete diffusion (c-d), and (4) the disappearance of the technique due to depreciation (e.g., erosion of plant yields and chemical crop-protection techniques) or obsolescence (replacement by a better technique) (d-e). Based on the diffusion literature, an S-shaped diffusion pattern is being assumed as well as an adoption ceiling. The R&D benefit stream can be infinite, depreciate gradually (biological inventions tend to erode), or end abruptly as the technology is replaced by a better one (Schumpeter's creative destruction). Also, in the latter instance, a mirrored S-shaped phasing out of the technology can be expected, complementary to the diffusion of the new technology.

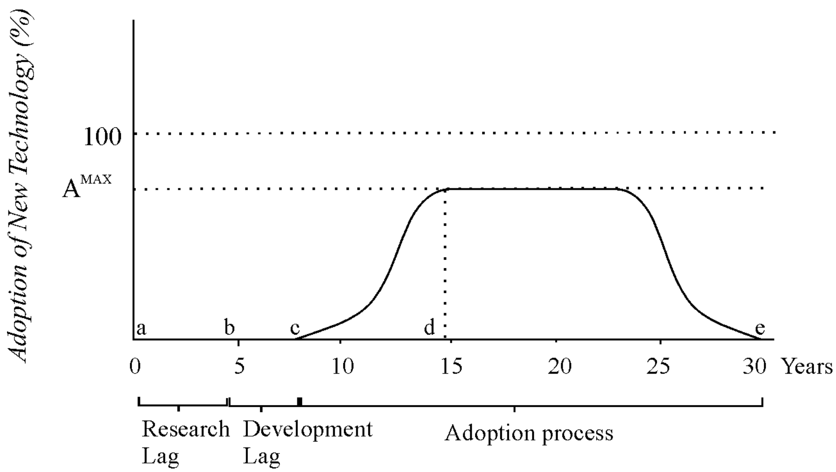

Figure 7.4: *Research, development and adoption lags*

Evenson (1968) was the first to investigate this question of research lag and length econometrically and found that an "inverted-V" distributed lag form fit his data best, with the peak influence coming with a lag of five to eight years and the total effect dying out

[14] Griliches (1979) provides a good introduction about how to model the effects of within-industry and within-economy knowledge spillover.

in about 10 to 16 years. In most ROR studies on agricultural R&D investments, however, rather than formal testing, a functional form has been imposed on the R&D expenditure data. This is usually done to avoid multicollinearity and degrees-of-freedom problems and not on the basis of some theoretically derived priors. Also, data availability often forces analysts to adopt short research lags. The functional forms most frequently used in empirical work are the inverted-V, polynomial, and trapezoidal lags.[15] Pardey and Craig (1989), using a free-form lag structure to model the relationship between agricultural research and public-sector agricultural research in the US, found evidence that the impact of research expenditures on agricultural output may last as long as 30 years, which was considerably longer than hitherto assumed. Chavas and Cox (1988, 1992) provided similar evidence using a nonparametric approach. But the questions of how much longer and what type of functional form to use remain unanswered.

Getting the lag structure correct is important because the implied internal ROR to agricultural research is quite sensitive to the (partial) research production coefficients derived from models estimated with inappropriate lag structures (Pardey 1986). Alston and Pardey (1996) further substantiated this argument by comparing R&D benefit streams with different lags, lengths, and profiles and found that the implied internal rates of return showed important differences. A further step in tackling the problem was made in a recent paper by Alston, Craig, and Pardey (1998). They assumed the following linear form between TFP, τ_t, and the useful knowledge stock, K_t:

$$\tau_t = \alpha + \beta K_t + \gamma W_t + u_t \qquad [7.12]$$

where W_t represents a single weather-related variable and u_t the usual random residual.[16] Quasi differencing this equation and using equation 7.12 gives[17]

$$\tau_t = \alpha\delta + \beta [K_t - (1-\delta) K_{t-1}] + \gamma [W_t - (1-\delta) W_{t-1}] + (1-\delta) \tau_{t-1} + u_t + (1-\delta) u_{t-1} \qquad [7.13]$$

Taking innovations in equation 7.11 to be a linear function of a finite lag of past logarithms of research investments,

$$I_t = \sum b_s \ln R_{t-s} \qquad [7.14]$$

the unobserved capital stock term in equation 7.13 can now be replaced by I_t (see equation 7.10) to yield

$$\tau_t = \alpha\delta + \beta \sum b_s \ln R_{t-s} + \gamma [W_t - (1-\delta) W_{t-1}] + (1-\delta) \tau_{t-1} + v_t \qquad [7.15]$$

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[15] See Alston, Norton, and Pardey (1995) pages 178-185, for a detailed description of these functional forms.
[16] Alston, Norton, and Pardey (1995) suggest a far more complicated relationship between τ and K, involving the stock of farmers' human capital, extension expenditures, and the relative prices of outputs and inputs.
[17] In this case, quasi differencing involves lagging equation 7.12 with one period, multiplying by 1-δ, subtracting the result from equation 7.12, and reducing terms to get equation 7.13.

This model nests the three depreciation alternatives discussed earlier: (1) the stock of knowledge never depreciates, δ=0, (2) the stock of useful knowledge vanishes in finite time, δ=1 (the implicit assumption in most models with a fixed cost-benefit structure), and (3) the intermediate case in which useful knowledge decays only gradually, $0<\delta<1$. Alston, Craig, and Pardey (1998) use this model to evaluate typical assumptions about the shape of the research lag, as well as implicit assumptions about knowledge depreciation associated with explicit assumptions about the research lag length. The findings of Alston, Craig, and Pardey's evaluation "reinforce the view that agricultural research affects productivity for much longer than most previous studies have allowed, possibly forever. A [polynomial] model consistent with infinite lags is statistically preferred over a more conventional [trapezoidal] model with finite lags. The results also suggest that many previous studies may have unduly restricted the shape of the research lag profile – often basing the entire distribution of lag coefficients on a single estimated parameter. The implications for reported rates of return are quite dramatic. The statistically preferred method indicated a real, marginal internal ROR to public agricultural research in the United States of 6.8 percent per annum whereas a more typical model, using a trapezoidal lag structure with shorter lags, indicates a more typical rate of 48 percent per annum" (Alston and Pardey 2000, p. 20.)

7.4 *Attribution imperfections affecting rate of return estimations*

It should be clear by now that ROR calculations of (agricultural) R&D investment are not without problems. There is a wide range of issues that affect the ultimate outcome of such calculations. And, given the average high rates of return reported by most studies, there is a general tendency to attribute this result, at least in part, to methodological flaws. Alston and Pardey (2000), for example, argue that rates of return on agricultural R&D investments tend to be overestimated because of attribution imperfections. They focus in particular on spill-ins of research results from parallel research programs and on the temporal aspects of the attribution of benefits (see above).

Another significant weakness in the ROR calculations is the treatment of purchased inputs. Usually only a limited number of the purchased inputs stemming from industries other than agriculture are included in the analysis. In most international comparisons, for example, only fertilizers and tractors are included as purchased industrial inputs and considered representative for all purchased industrial inputs (see, e.g., Hayami and Ruttan 1985).[18] This would to some extent be acceptable when the R&D activity and subsequent spillover across all input-suppliers would be more or less the same, but this assumption is highly questionable. Moreover, in the international comparisons, input quantities are used rather than values. This means that process innovations in the input industry leading to

[18] Mundlak (2000) and his colleagues at the World Bank made a major effort to better measure the capital input into agricultural production across 58 countries. This yielded quite significantly different results compared to earlier cross-country productivity analyses.

lower input prices are not accounted for. And, as Craig, Pardey, and Roseboom (1997) argue, such quantities are often not adjusted for quality differences and changes either.

But even when input prices are available, as in many national studies, the standard price indices tend to have some major shortcomings. One such shortcoming is the type of price index, as has been discussed in section 7.1. Another shortcoming is that price indices usually fail to capture the introduction phase of a new product or a new input correctly. As Nordhaus (1997) points out, the standard procedure is to "link" new goods and services into the price index rather than to re-price the basic category to take the quality change into account. In other words, the first bang that the introduction of a new product or a new input may give to economic growth is not measured.[19] Moreover, for many new products or inputs, the price often declines quite rapidly during the first few years after their introduction. The usually delayed inclusion of new goods and services in the price index is another factor that results in their contribution to economic growth being underestimated (Griliches 1979).

Overall, the way purchased inputs are treated in (agricultural) productivity analyses and ROR studies is rather unsatisfactory and constitutes a source of distortion. Only proper measurement of quality-adjusted inputs and prices can contain this problem and correctly capture the benefits stemming from input use in (agricultural) production and eliminate any unaccounted spill-ins related to their use.[20] Since this ideal approach may never be achieved, alternative approaches have been tried to measure technology spillovers (including those coming with purchased inputs) explicitly rather than eliminating them.

Griliches (1979) identified two main sources of potential externality generated by R&D activities: *rent spillovers* and *knowledge spillovers*. Rent spillovers originate exclusively from economic transactions and can therefore be traced by monitoring such transactions. Knowledge spillovers, however, arise when knowledge developed in one industry contributes to the innovation process of other industries. It is assumed that technology proximity rather than transaction intensity facilitates knowledge spillovers. Hence, the direction and intensity of rent and knowledge spillovers may differ greatly. In practice, however, it is difficult to empirically dissociate rent spillovers from knowledge spillovers, which creates quite some ambiguity in analyzing technology spillovers.

Figure 7.5, adapted from van Pottelsberghe (1997), provides a schematic overview of the potential rent and knowledge spillovers. Intermediate inputs, investment goods, patent

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[19] Nordhaus (1997) somewhat overshoots his argument when he compares horses with automobiles. The first automobiles were hardly more efficient than horses. It is only because of the steady improvement of automobiles that they became so much more superior. Nevertheless, despite all technological progress, the average speed of traffic in London was in the 1990s not much higher than in the 1890s.

[20] There is still another type of spillover that correct measurement of input use and prices does not account and that is the spillover of ideas and knowledge between industries.

flows, and technology proximity are the four channels by which technology spills over from one industry to the next.[21]

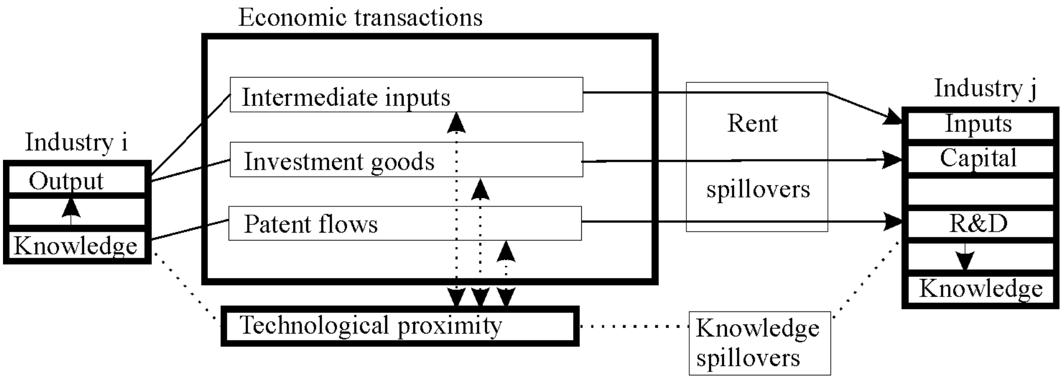

Figure 7.5: *Potential rent and knowledge spillovers from industry* i *to industry* j

Most studies on technology spillovers focus on just one type of spillover channel. Only a few have tried to compare the different approaches or capture the whole range in one model. Each spillover channel can be approximated by its own technology weighting matrix, resulting in the following four measures of external R&D capital stocks:

$$S_{m,j} = \sum_{i=1}^{n} \frac{M_{i,j}}{Q_i} R_i \,, \qquad i \neq j \qquad [7.16]$$

$$S_{k,j} = \sum_{i=1}^{n} \frac{I_{i,j}}{Q_i} R_i \,, \qquad i \neq j \qquad [7.17]$$

$$S_{p,j} = \sum_{i=1}^{n} \frac{P_{i,j}}{P_i} R_i \,, \qquad i \neq j \qquad [7.18]$$

$$S_{w,j} = \sum_{i=1}^{n} w_{i,j} R_i \,, \qquad i \neq j \qquad [7.19]$$

$M_{i,j}$ is industry j's intermediate input purchase from industry i, $I_{i,j}$ is industry j's investment good purchase from industry i, $P_{i,j}/P_i$ is the share of industry i's patents that are likely to be used by industry j,[22] $w_{i,j}$ is an indicator of industry j's proximity to

[21] See van Pottelsberghe (1997) for an overview of studies using the different weighting matrices. Early pioneers of technology weighting matrices are (1) Terleckyj (1974), using input-output matrix data for both intermediate inputs and investment goods, (2) Scherer (1982), using patent data to create a technology flow matrix, and (3) Jaffe (1986), pioneering various forms of technology proximity.

[22] Rather than measuring "potential" use of patents, it would be more appropriate to measure actual use of patents on the basis of royalty payments. Unfortunately, however, detailed data on royalty payments are not available.

industry *i,* and Q_i and R_i are industry *i*'s output and R&D capital, respectively (van Pottelsberghe 1997). While the external R&D capital stocks, $S_{m,j}$ and $S_{k,j}$, match the rent spillovers and $S_{w,j}$ with knowledge spillovers, the external R&D capital stock, $S_{p,j}$, takes a somewhat intermediate position, covering both types of spillovers. Comparing the different technology weighting matrices, van Pottelsberghe (1997) concludes that the technology flow matrix is closer to the input-output matrix than to the technology proximity matrix and, hence, matches the rent spillover better than the knowledge spill-over.

Roseboom (1999, 2000) provides an example of applying the input-output matrix approach to measure technology spill-ins into primary agricultural production. An approximation of $S_{m,j}$ and $S_{k,j}$ in itself is interesting (also because the study differentiates between local and imported inputs), but for the actual measure of technology spillover, two additional pieces of information are needed: (1) the success rate of R&D in each of the supplying industries, as this defines the total R&D benefit, and (2) how the R&D benefit is shared between the innovator and subsequent users. In most studies, the average success rate of R&D is usually assumed to be the same and is hence ignored. This may, however, not be a valid assumption. With regard to the second question, some strong opinions can be found in the literature. One such opinion is that multinationals manage to appropriate all or nearly all of the benefits from their R&D, and hence, farmers have nothing or very little to gain from buying inputs. Another popular opinion, formulated by Cochrane (1958), is that farmers are trapped in a technology treadmill and that most of the R&D benefits (either from within or outside the agricultural sector) are passed on to the processing industry or consumers by means of lower agricultural prices. Operating in a very fragmented and competitive industry means that farmers are in a weak position to appropriate much of the R&D benefits.

Looking from the perspective of the innovator, both the total benefits and the benefit distribution can be estimated by using an economic-surplus model. According to this model, the more inelastic the demand, the more the user rather than the producer (and innovator) of the new input will appropriate the R&D benefits. However, as discussed by Moschini and Lapan (1997), the economic-surplus model needs considerable modification when private innovators can protect their innovation with intellectual property rights and can legally exercise some monopoly power. Compared to the more conventional competitive version of the economic-surplus model, this will not only affect the overall size of the R&D benefits, but, more important, their distribution. In their study into the welfare effects of adopting Roundup Ready soybeans, Moschini, Lapan, and Sobolevsky (1999) estimated that about 44% of the R&D benefits accrue to Monsanto, 16% to farmers (but with a negative effect for non-adopting farmers), and 40% to consumers (nearly two-thirds of whom live in countries that have not adopted the technology). Falck-Zepeda, Traxler, and Nelson (1999) used a similar approach in their study on the benefit distribution of the use of Bt technology in cotton in the US.[23] They

[23] *Bacillus thuringiensis* (Bt) is the name of the bacteria from which a gene was taken and built into crops so that they are resistant to Roundup, Monsanto's best-selling insecticide.

estimated that about half the benefits from Bt cotton accrue to Monsanto and related seed companies, 40% to farmers, and 10% to consumers.

The other alternative is to look from the perspective of the user. The standard approach here is to explain the growth in total factor productivity (TFP) of an industry from its own R&D investments and from R&D investments by supplying industries, by industries that supply patents, or by industries that are close technologically. A selective list of ROR results from various studies using different approaches is presented in table 7.1. Including outside R&D in the ROR calculation of own R&D usually considerably reduces the ROR to own R&D. The ROR to external R&D could be interpreted as the "net" social ROR, i.e., the social rate minus the private rate to the innovator. Hence, the evidence suggests not only that the social rate exceeds the private rate by quite a margin (often more than double), but also that this margin differs significantly across industries and studies. Nevertheless, all these studies provide surprisingly consistent evidence for the existence of important technology spillovers (Griliches 1995).

The various approaches to measuring the spillovers and spill-ins of R&D benefits give results that are not easily comparable because essential information is often lacking. For example, in order to translate the difference between social and private ROR into a benefit distribution, it is necessary to know the cost-benefit structure of the underlying R&D project(s). Similarly, the benefit distribution by Moschini, Lapan, and Sobolevsky (1999) and Falck-Zapeda, Traxler, and Nelson (1999) cannot be translated into private or social ROR because the actual R&D expenditure by Monsanto and the seed companies is unknown. Nevertheless, there is good reason to believe that the distribution of R&D benefits between producer/innovator and user varies quite a bit across industries, and probably also over time and between different groups of users.

Table 7.1 *Selected estimates of returns to own and external R&D*

Type of study	*Author*	*ROR to own R&D*	*ROR to outside R&D*
Case studies	Mansfield, *et al.* (1977)	25	56
I-O weighted	Terleckyj (1974)	29	78
	Sveikauskas (1981)	10-23	50
	Goto and Suzuki (1989)	26	80
R&D weighted (patent flows)	Griliches and Lichtenberg (1984)	46-69	11-62
	Mohnen and Lepine (1988)	56	28
Proximity	Jaffe (1986)		30% of own R&D
Cost functions	Bernstein and Nadiri (1988, 1989)	9-27	10-160
	Bernstein and Nadiri (1991)	14-28	Median: 56% of own R&D

Source: Adapted from Griliches (1995).

7.5 *Conclusions*

Despite several decades of dedicated work by economists on ROR to (agricultural) R&D, the problems surrounding such studies are still huge. This chapter has provided an overview of the most common problems and issues in ROR studies. Three issues stand out in particular:

(1) The choice between economic surplus, production function (primal or dual), or a non-parametric approach. The answer to this question is and probably will remain inconclusive as each of them has its own strengths and weaknesses. In the end, the choice depends on the context within which an analysis takes place and the other issues (besides economic impact) that are relevant.

(2) The formal modeling of the link between increased productivity, or *K*-shift, and past R&D investments. Recent work by Alston, Craig, and Pardey (1998) has focused particularly on the lag structures that are usually assumed in ROR studies, as well as on the issue of knowledge stock depreciation. Some of their still somewhat experimental results suggest that lag structures are longer and more complex than usually assumed, resulting, in the case of the production function approach, in lower rates of return than hitherto estimated.

(3) The importance of measuring and aggregating inputs and outputs correctly cannot be stressed enough, but in practice, one hardly ever accomplishes this satisfactorily. Particularly disturbing is the poor coverage of purchased inputs in most agricultural ROR studies, which creates a significant risk of attributing increases in productivity to own R&D rather than to the use of inputs and the underlying R&D activities in supplying industries. This seriously limits whatever progress is made in the formal modeling of the relationship between R&D and production, and reduces the confidence one can have in the measured impact of R&D.

The fact that assessments of the impact of agricultural R&D are still surrounded by considerable uncertainty is a major handicap in convincing policymakers and taxpayers that public investment in agricultural R&D is really a profitable proposition and that more, rather than less, should be invested. The evidence may look impressive, but it is evidence that is not above all doubt. While the defenders of the underinvestment hypothesis share many of these concerns, they argue that the average ROR is so high that even after adjusting for the various uncertainties, the evidence will hold. In the next chapter, reported ROR results will be taken as they come but interpreted differently in a model that provides considerably more structure to the underinvestment hypothesis.

8. Modeling underinvestment in agricultural R&D

An implicit assumption made in chapters 3 through 6, as well as in the agricultural R&D literature in general, is that there is widespread "underinvestment" in agricultural R&D and that any slowdown in the growth or, even worse, contraction of agricultural R&D expenditures is reason for serious concern. Moreover, such underinvestment is more critical in countries with low intensity ratios for agricultural R&D than in countries with high intensity ratios.[1]

But what do we actually know about this underinvestment? How real is it? Is it higher in developing than in developed countries? Is it higher for some types of research than for others? And, how much more should have been invested in agricultural R&D? Studies on rates of return to (agricultural) R&D usually come up with rather high rates ex post, and the general conclusion is that it points to acute underinvestment in (agricultural) R&D. However, what matters is not the average of the rates of return ex post, but whether ex ante the expected rate of return (ERR) on the *marginal* R&D project is considerably higher than the social rate, or whatever other cutoff point is considered appropriate. This chapter aims to shed new light on the hypothesis of underinvestment in agricultural R&D by introducing in sections 8.1-8.4 a more solid analytical framework than has hitherto been used in the literature. After estimating how much more (or less) should have been spent on agricultural R&D, in section 8.5 we set out to see how the underinvestment gap could be explained. Perhaps, after all, decision makers behave more rationally than the proposed model would have us believe. Conclusions will be drawn in section 8.6.

8.1 *An economic model of the selection of R&D projects*

The ranked distribution of all possible R&D projects can be assumed to follow an exponential pattern, with the number of possible R&D projects increasing exponentially from high to low ERRs (figure 8.1).[2] Under the assumption of rational economic behavior and full information, the selection of R&D projects for implementation starts with the project with the highest ERR and continues with the next highest until the R&D budget has been exhausted or the ERR on the last (i.e., marginal) R&D project approaches the

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[1] Fox (1985) provides a brief survey of early statements on the underinvestment hypothesis. In particular, Ruttan's (1980) article "Bureaucratic Productivity: The Case of Agricultural Research" triggered some debate in the early 1980s. Although the debate was somewhat inconclusive, most leading agricultural economists support the underinvestment hypothesis.

[2] It is assumed that R&D projects are independent of each other. If they are not, they should be considered jointly. For example, when R&D projects target the same technical problem, only the project that has the highest ERR should enter the selection. However, when possible gains are high relative to the chance of R&D success, it may be worthwhile to select several R&D projects targeting the same problem simultaneously. In such an instance, the selected projects should be considered as a single joint R&D project.

social rate, whichever comes first.[3] When the highest ERR in the ranking does not exceed the social rate, no R&D projects should be implemented at all.

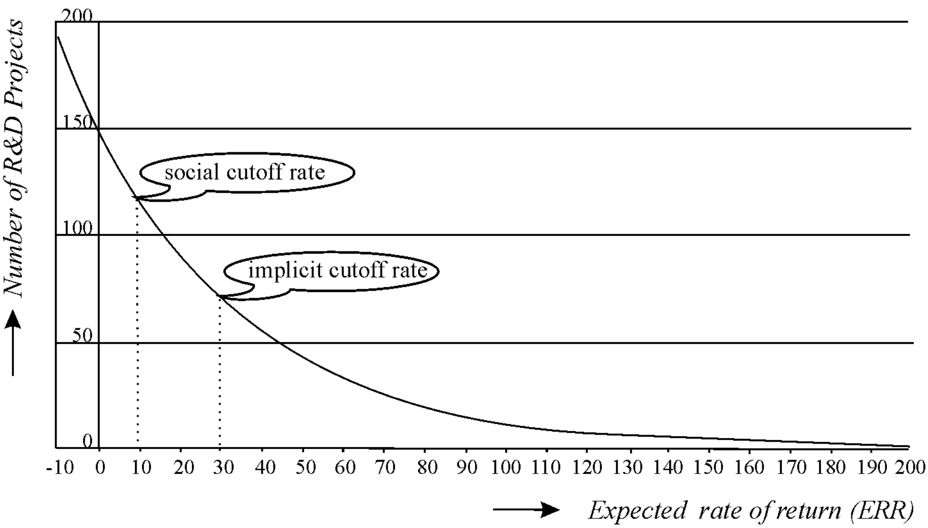

Figure 8.1: *A ranked distribution of R&D projects*

In a situation of abundant funding (i.e., where every project with an ERR equal to or higher than the social cutoff rate will be financed), the peak or mode of the ranked project distribution can be expected to be at the social rate.[4] In a tight funding situation, however, the downturn in research proposals takes place before the social rate is reached. Researchers expect only project proposals with a substantial margin above the social rate to be funded and adjust their behavior in regard to proposals accordingly. Moreover, selection committees and research managers will reinforce this behavior by only selecting the most promising R&D proposals.

As also plotted in figure 8.1, the number of imaginable R&D projects is also assumed to increase steadily after the cutoff rate has been passed. Negative rates of return indicate that the expected costs of the R&D project exceed the expected benefits.

Assume that the postulated distribution of R&D projects on an ERR scale can be thought of as taking the following semilog form:

$$Y = e^{\beta_0} e^{\beta_1 X} \qquad [8.1]$$

[3] The focus here is on the marginal R&D project, not on the marginal dollar spent on a project. Moreover, the private rate of return rather than the social rate is of relevance when considering private R&D rather than public R&D.

[4] Private R&D of course uses a private cutoff rate.

where Y stands for the number of R&D projects and X for the ERR. The coefficient β_1 has to be negative in order to get an asymptotic curve, as shown in figure 8.1. The closer the slope coefficient is to zero, the flatter the ranked distribution.

The cumulative number of R&D projects can be estimated by the following integral:

$$Y_r = \int_r^{\infty} e^{\beta_0} e^{\beta_1 X} dx = \left[\frac{1}{\beta_1} e^{\beta_0} e^{\beta_1 \infty} \right] - \left[\frac{1}{\beta_1} e^{\beta_0} e^{\beta_1 r} \right] = e^{\beta_0^*} e^{\beta_1 r} \qquad [8.2]$$

where Y_r stands for the number of R&D projects with a rate of return of r and higher. A simpler notation for the cumulative version of the ranked distribution is:

$$Y^* = e^{\beta_0^*} e^{\beta_1 X} \qquad [8.3]$$

where Y^* stands for the *cumulative* number of R&D projects at a certain value of X (the ERR). The slope coefficient β_1 is the same for both the cumulated (equation 8.3) and the non-cumulated (equation 8.1) version of the ranked distribution – only the constant β_0 differs.

The relative under- or overinvestment in (agricultural) R&D as a percentage of the original investment level can be estimated as follows:

$$\left[\frac{\int_s^{\infty} e^{\beta_0} e^{\beta_1 X} dx}{\int_r^{\infty} e^{\beta_0} e^{\beta_1 X} dx} - 1 \right] \times 100 = \left[\frac{\int_s^{\infty} e^{\beta_1 X} dx}{\int_r^{\infty} e^{\beta_1 X} dx} - 1 \right] \times 100 = (e^{\beta_1 \Delta X} - 1) \times 100 \qquad [8.4]$$

where s is the social rate and r the implicit cutoff rate and where ΔX represents the difference between r and s.

Based on this simple, stylized model, underinvestment in R&D can be captured in the following two propositions:

(1) *Assuming full information and a strict economic selection of R&D projects, under-investment in R&D manifests itself in a cutoff rate that is higher than the social or private rate.*

(2) *The size of the R&D underinvestment gap depends on three variables: (a) the relevant social or private rate, (b) the actual cutoff rate, and (c) the slope of the ranked distribution curve.*

To answer the question of whether there is underinvestment in R&D or not and, if so, how much, variables *b* and *c* need to be estimated and *a* set.

8.1.1 *Selecting the relevant social or private rate*

Underinvestment is a relative notion, so it is important to determine up-front the benchmark against which one wants to compare the actual level of investment. The relevant benchmark for private investments in R&D is the minimum private rate of return that a company has set for itself across all its activities. Such rates are usually in the range of 15%–20% real (that is adjusted for inflation) before taxes for companies in developed countries.

For public agricultural R&D investment, it is not the private rate but the social rate that is the relevant benchmark. By applying the same social rate across all government activities, governments try to identify those activities where underinvestment is most severe and where an additional dollar of investment will create the highest social pay-off.

Disagreements among economists and policymakers on the right conceptual basis for the social rate as well as on the selected value are quite prevalent. In the literature, various definitions of the social rate as well as guidelines on how the rate should be approximated can be found. For our purposes, the choice amounts to the following two definitions of the social rate: (1) the opportunity cost of capital and (2) the social time preference rate, which is the rate at which society is willing to trade present for future consumption.

The first definition is the most widely adopted and is used, for example, by the US Federal Government and the World Bank. According to the Revised Circular No. A-94 issued by the Office of Management and Budget of the White House in October 1992, the real discount rate to be used to evaluate US Federal Government programs is 7%. The document states that this rate approximates the marginal pretax rate of return on an average investment in the private sector in recent years. A comparable rate for developing countries is believed to be somewhere between 8% and 15% in real terms (Gittinger 1982). A common choice, also adopted by the World Bank, is 12%.

Zerbe and Devily (1994), however, make a strong and convincing plea for adopting the social time-preference rate definition and base the social rate on the after-tax, real rate of return on government bonds of the same length as the project in question. For the USA, these adjusted bond rates fluctuated between 2.5%–5.0% during the 1980s and early 1990s, with the ones close to 5% coming closest to the average length of an agricultural R&D project.[5] While statistics on the government bond market are readily available for developed countries, this is not the case in most developing countries. Often such markets

[5] Zerbe and Devily (1994) extensively discuss the problem of displacement of private capital but show that in most instances, this issue can be neglected or, if necessary, the borderline cases can be identified by a 10% adjustment in costs. It is only when government agencies are in direct competition with the private sector that the private-sector rate should be applied to both proposals.

are nonexistent or rather thin and volatile, and statistics are unavailable. An attempt to replicate Zerbe and Devily's estimate of the social rate for developing countries was not possible because of the lack of data; hence, the decision to fall back on the more traditional opportunity-cost-of-capital definition of the social rate and adopt 7% and 12% as the relevant social rates for developed and developing countries, respectively. These rates are probably also closer to political than economic reality. Nevertheless, one should keep in mind that there are good theoretical grounds to believe that the "economic" social rates are somewhat lower and that the underinvestment gaps may therefore be somewhat underestimated.

It is sometimes argued that the social rate should be topped up with a risk premium in order to capture the fact that agricultural R&D is a significantly riskier activity than the average government project. The White House circular, however, argues that any notion of risk specific to a project should be included in the ERR calculation rather than in the social rate.

8.1.2 *Estimating the implicit cutoff rate*

In the real world, most selection committees do not rank R&D projects on the basis of ERRs, nor do they have a concrete idea about the cutoff rate that they implicitly apply. However, the selection criteria actually used tend to underpin some kind of economic rationale. Since the selection is less than economically optimal, a number of R&D projects with ERRs less than the "optimal" cutoff rate will be selected at the expense of R&D projects with an ERR equal to or above the "optimal" cutoff rate. This results in an ex ante ranked distribution of R&D projects that takes the form of a bell-shaped distribution, although lopsided to the left (figure 8.2).[6]

Within reasonable limits, however, the assumption can be made that the modes of the *optimal* and *suboptimal* distributions more or less coincide. At first, this may seem a rather bold assumption, but the opposite assumption, namely that the two modes significantly differ, is considerably more unlikely. It all hinges on the selection procedure. When the selection is weak (i.e., deviating strongly, but not completely, from rational economic behavior), the mode of the suboptimal selection may be found to the right of the mode of the optimal selection. This requires a large number of R&D projects with ERRs at or higher than the cutoff rate not to be selected, while those with lower ERRs are. The latter results in a relatively long left-hand tail in the distribution. Although some suboptimality in the selection procedure is unavoidable because of imperfect information, etc., one wants to avoid mixing up an inefficient selection procedure with under-investment in agricultural R&D (i.e., a high cutoff rate). The relevant parameters of the distribution for checking for exceptional selection inefficiency are (a) the percentage of R&D projects with a rate lower than the mode of the distribution (the higher the percentage, the more imperfect the selection procedure) and (b) the position of the

[6] For the distribution to be lopsided to the left, the median of the distribution should be smaller than the mean.

median of the distribution (which should always be lower than the mean and preferably higher than the mode).

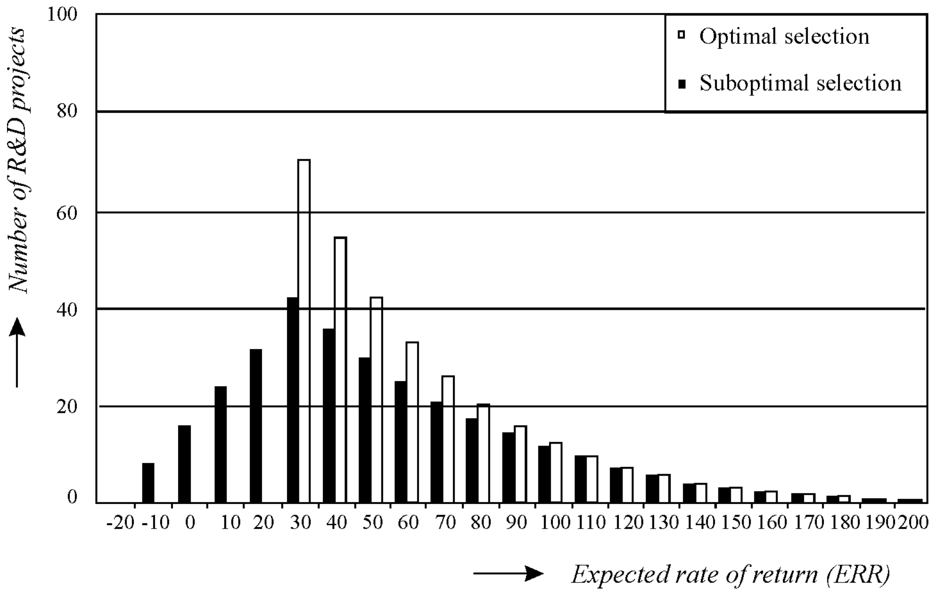

Figure 8.2: *Optimal versus suboptimal selection of R&D projects*

It is difficult to say at which level of selection inefficiency the assumption that the optimal and suboptimal modes fall together breaks down. And, what can be done to estimate the optimal mode, knowing only the suboptimal one. For now, it is assumed that with a moderate level of selection inefficiency, the two modes roughly fall together.

If the following hypothetical selection procedure is used, it is possible that the mode of the suboptimal selection could be found lower than the mode of the optimal selection. The selection committee makes a pre-selection of all R&D projects with an ERR above a certain cutoff rate that is lower than the "optimal" cutoff rate and subsequently funds projects at random until the R&D budget is used up. The mode of this suboptimal distribution will fall together with the cutoff rate used in the first step of the selection procedure. Although perhaps a plausible characterization of some selection procedures, its flaw lies in the fact that it assumes that information about the ERR of R&D projects is used in the first step of the selection procedure, but not in the second step. This is a rather implausible assumption. The importance of the first step in this hypothetical selection procedure is that without it, selected "suboptimal" R&D projects would spread out (creating a left-hand tail) rather than concentrating and creating a mode in the distribution. All in all, the chance of finding, ex ante, a suboptimal mode that is lower than the optimal mode seems unlikely.

The next step is to link the ex ante distribution with the ex post distribution. The two should be roughly identical if the following assumptions hold: (1) the differences between expected and actual rates of return of R&D projects are only stochastic and not systematic and (2) the outcome distributions of the ERRs are more or less symmetric. This latter assumption clearly does not hold when the success of an R&D project is considered discrete – it is either a full success or a complete failure. Although a common metaphor, it is more realistic to assume that the success of R&D (especially biological R&D) is relative rather than discrete and, hence, creates a continuous statistical distribution. Given the various parameters that enter an ERR calculation, each with its own probability distribution, the overall probability distribution of the ERR of an R&D project or program cannot be calculated easily. This is particularly true when the relationship between parameters and benefits is nonlinear. In such an instance, a Monte Carlo simulation can be used to estimate measures of the central tendency (e.g., mean or mode) and dispersion (e.g., variance and coefficient of variation) of the outcome distribution (Sprow 1967). To our knowledge, only a few studies (Greig 1979; Anderson 1991) have actually used this approach in an agricultural R&D setting. They reported probability distributions that were only slightly skewed.

Based on a rather strict, neoclassic interpretation of the R&D priority-setting process (i.e., that R&D investments are based on full information about profit opportunities and rational priority setting), the following proposition is suggested:

> *(3) Assuming that the evaluated R&D projects are selected at random and their ex post rates of return differ only stochastically and not systematically from the expected rates of return, the mode of the ex post distribution of R&D projects conveys some rough indication of the implicit cutoff rate used in the ex ante optimal selection procedure.*

8.1.3 *Estimating the slope coefficient*

The distance between the social rate and the implicit cutoff rate is not the only parameter that determines the magnitude of the underinvestment gap. The *slope* of the ex ante ranked distribution is also needed to estimate the optimal R&D budget by which all R&D projects with an ERR at or above the social or private rate are funded. Some strict assumptions have to be made in order to distill this information from the ex post rate-of-return results. Figure 8.3 sketches the problem that needs to be tackled.

Due to suboptimal selection, some of the projects with an ERR higher than the cutoff rate are not selected, while projects with an ERR lower than the cutoff rate are. It is assumed that all projects cost the same. If the selection were optimal, only R&D projects at or above the cutoff rate would have been selected. In order to reconstruct the ex ante *optimal* distribution, the right-hand side of the distribution has to be topped up with the number of R&D projects below the cutoff rate.

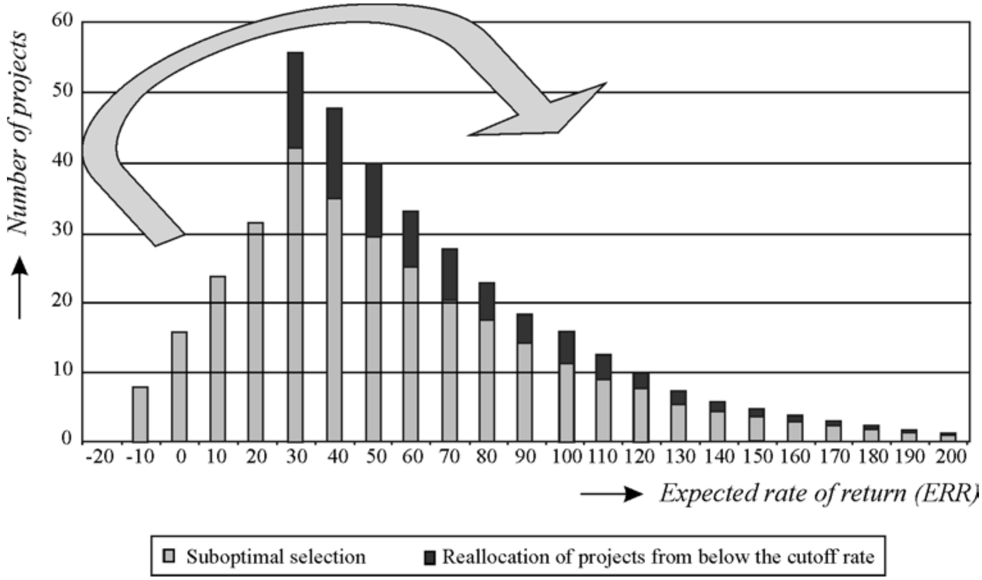

Figure 8.3: *Reconstruction of the optimal selection of R&D projects*

Of the various options available, distributing the suboptimal R&D projects proportionally seems to give a reasonable approximation and has the practical advantage that the adjusted and unadjusted right-hand side of the distribution has the same slope coefficient. However, a proportional distribution implies that the chance of not being selected is the same for all R&D projects above the cutoff rate. A more realistic assumption is that R&D projects close to the cutoff rate have a higher chance of not being selected than projects with higher ERRs. Such a differential in chance would lead to a steeper optimal slope and, hence, a bigger underinvestment gap. However, we lack empirical evidence on this chance distribution and have therefore adopted the second-best solution, namely, assuming equal chance and proportional distribution. Hence, the following proposition:

> *(4) The slope of the right-hand side of the ex post distribution of R&D projects is a reasonable but somewhat lower estimate of the slope of the optimal ex ante distribution.*

8.2 *Empirical evidence*

The (average) high rate-of-return results have been used frequently in the agricultural economics literature as an indication of underinvestment in agricultural R&D. The argument made here is that the *mode* of the ex post rate-of-return results provides substantially more information about relative underinvestment in agricultural R&D than the *mean*. Hence, it is necessary to give a new interpretation to the rate-of-return results, which have been compiled by several authors in the past (Evenson, Waggoner, and Ruttan 1979; Echeverría 1990; Alston and Pardey 1996).

The most recent compilation of rates of return to agricultural R&D has been published by IFPRI (Alston *et al*. 2000). The focus of the IFPRI study, which is a meta-analysis of more than 1800 agricultural R&D rate-of-return calculations, is to understand differences in rate-of-return results due to differences in methods, research focus, location, time, etc. For the purposes of the current study, however, a large number of the rate-of-return observations had to be eliminated, as they are not comparable. For example, all nominal (rather than real) rates of return were eliminated, as well as all rates of return pertaining to "all agricultural R&D," "crop & livestock R&D," or "all crop R&D." Such R&D programs are far too aggregate to provide meaningful information about the marginal R&D project.[7] Even after this correction, the set of rate-of-return results is still somewhat biased towards research programs rather than discrete research projects. The latter would be preferred in order to get as close a correspondence with the ex ante choice situation as possible.

Most rate-of-return studies provide multiple rates for the same R&D project or program, depending on the assumptions made, such as the time lag between R&D investment and impact. Rather than having four or five, or sometimes even 20, different rates for the same R&D project or program, the analysis proposed here requires only one observation per project or program, so multiple observations had to be reduced to only one. Since there is not yet a solid theoretical basis for preferring one method above the other, an average was calculated for each research project.[8] All in all, the more than 1800 observations in the IFPRI study boiled down to only 201 useful rate-of-return observations, of which 78 pertain to developed countries (mainly the USA) and 123 to developing countries.[9] It is assumed that these 201 rate-of-return observations represent a reasonable sample of all the agricultural R&D projects that have been undertaken worldwide. Although R&D projects with low or negative rates of return are underrepresented in the sample, this has fairly little effect on the two parameters that we want to estimate (the implicit cutoff rate and the slope coefficient) because, as will be documented below, the modes of the rate-of-return distributions stay far away from low or negative rates. Each observation is given the same weight, which implies that each R&D project is assumed to have cost the same.

Figure 8.4 plots the distribution of ex post rates of return for both developed and developing countries. As can be seen, the mode for developed countries (estimated at a rate of return of 20%) stands out more clearly than that for developing countries (estimated at a rate of return of 40%). Apparently, the assumption that the selection of R&D projects took place under more or less the same budget constraints (i.e., the same cutoff rate) and with more or less similar innovation opportunities holds less well for the

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[7] The ranked distribution of the aggregate studies has a higher mode and a lower standard deviation than the ranked distribution of the more specific R&D programs and projects.

[8] Alston *et al.* (2000) discuss in great detail the large variety of methods for calculating rates of return and provide some quantitative insight into how rate-of-return results can be affected by the choice of method. However, they do not provide a conclusive recommendation about which method should be preferred.

[9] Other observations that were eliminated are (a) observations that are not discrete, (b) private rates of return, and (c) rates pertaining to extension only.

developing countries as a group. This is confirmed by the quite different region-specific distributions and modes as reported in tables 8.1 to 8.3.

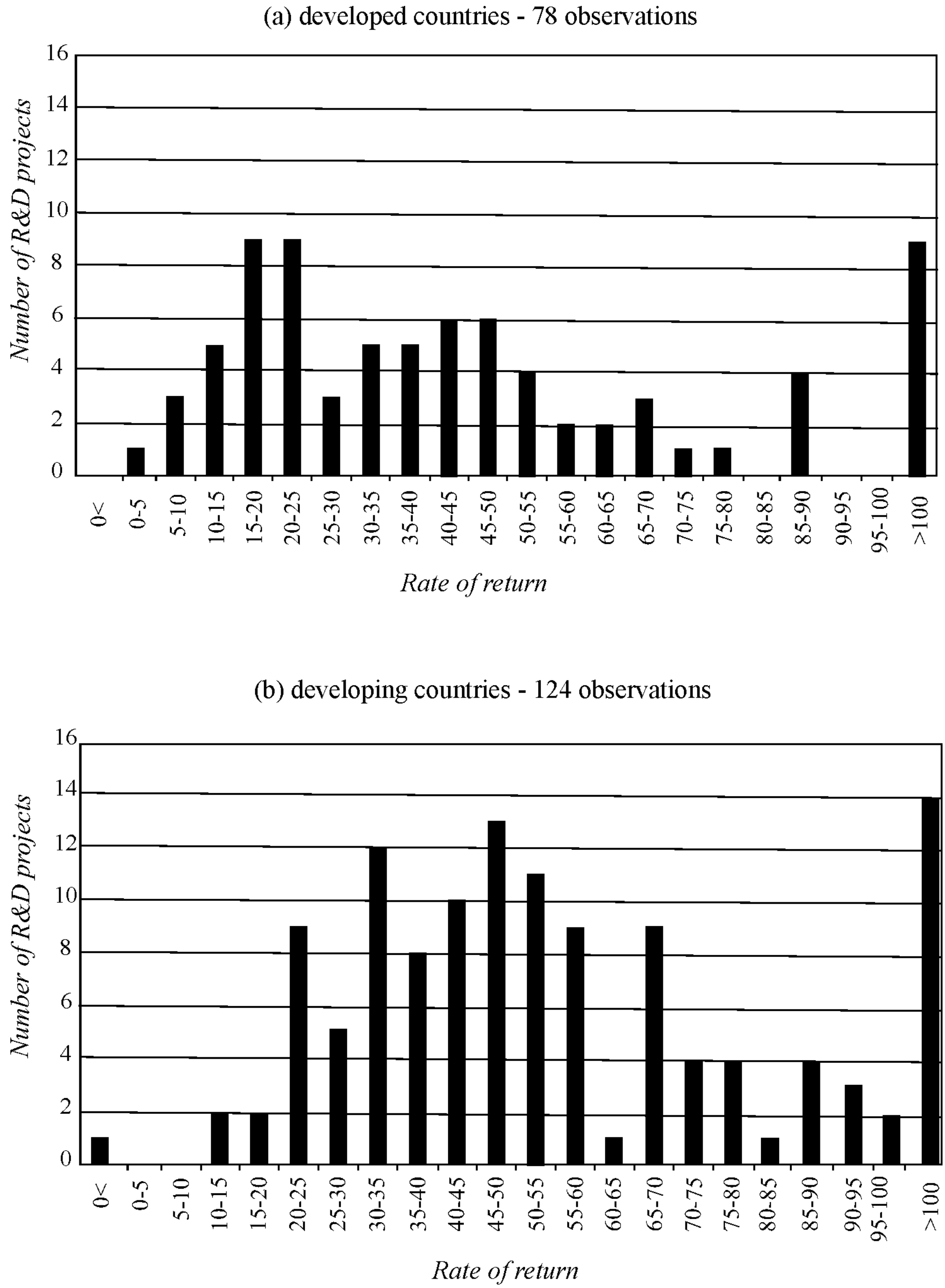

Figure 8.4: *Ranked distribution of ex post rate-of-return results*

Table 8.1 provides more detailed and differentiated information about the characteristics of the distributions. The differentiation between developing regions is somewhat speculative because of the rather small number of observations. Still, the distributions follow the expected pattern quite well. In all cases, the ranked distribution is lopsided to the left with a median lower than the mean, and an *estimated* mode lower than the median. The share of observations lower than the estimated mode ranges between 20% and 40%. When the distribution is perfectly representative (which unfortunately is not the case), this share would give an objective indication of selection performance.

Table 8.1: *Rates of return by geographical region and time period*

	Number of estimates	Rate of return				
		Estimated mode	Median	Mean	Standard deviation	% obs. < mode
	(count)	*(percentage)*				
Developed countries	78	20.0	38.8	65.8	119.7	23.1
Developing countries	123	40.0	50.0	58.9	37.9	31.7
Africa	25	30.0	36.1	46.4	27.2	20.0
Asia and Pacific	38	45.0	56.2	77.1	51.7	21.1
Latin America and Caribbean	56	40.0	47.9	51.9	26.7	36.4
Developed countries, 1985 ≤	31	20.0	41.3	79.6	152.6	22.6
Developed countries, >1985	47	20.0	34.0	56.7	92.6	23.4
Developing countries, 1985 ≤	33	40.0	47.8	55.3	32.3	39.4
Developing countries, >1985	90	40.0	51.4	60.3	39.9	28.9

Note: The grouping per time period is based on the publication date of the information.

The current sample includes a few very high rates of return (the highest is 855%), which causes rather high standard deviations for some distributions, and means that are biased upwards. Although one does not want to exclude very high rates of return a priori (although some healthy skepticism is warranted), statistically one expects them to be rare. However, the rate-of-return sample may not only have a blind spot for failed R&D projects, it may *be* biased toward the extreme success cases. Very successful R&D projects have a higher chance of being selected for an ex post evaluation than the average R&D project.

To estimate the underinvestment gap, it is not only relevant to know the implicit cutoff rate and the social rate, but also the slope coefficient β_1. The approach taken here is to estimate β_1 by regressing the rate-of-return observations on the right-hand side (those above the cutoff rate) of the ex post *cumulated* ranked distribution. Rates of return higher than 100% were excluded in order to eliminate their distorting effect on the estimation of the slope coefficient. As shown in table 8.2, this leads to a substantially better statistical fit of the exponential curve.

Table 8.2: *Regression results for estimating slope coefficient β_1*

	n	β_0	t-statistic	β_1	t-statistic	R^2
Developed countries – cutoff rate 20%						
All rates of return ≥ 20%	58	3.5859	43.45	-0.0054	-10.19	0.642
All rates of return ≥ 20% and ≤ 100%	51	4.6193	242.54	-0.0257	-66.68	0.989
All rates of return ≥ 15% and ≤ 100%	60	4.6340	315.62	-0.0259	-81.51	0.991
All rates of return ≥ 25% and ≤ 100%	43	4.6525	176.98	-0.0262	-53.38	0.986
All rates of return ≥ 20% and ≤ 100%, ≤1985	19	3.7143	51.51	-0.0242	-15.98	0.938
All rates of return ≥ 20% and ≤ 100%, >1985	32	4.1117	188.13	-0.0264	-61.08	0.992
Developing countries – cutoff rate 40%						
All rates of return ≥ 40%	84	5.1689	81.98	-0.0233	-30.34	0.918
All rates of return ≥ 40% and ≤ 100%	71	5.6659	264.60	-0.0308	-90.71	0.992
All rates of return ≥ 30% and ≤ 100%	92	5.6091	377.08	-0.0300	-116.53	0.993
All rates of return ≥ 50% and ≤ 100%	51	5.5628	196.02	-0.0295	-71.42	0.991
All rates of return ≥ 40% and ≤ 100%, ≤1985	18	4.3305	52.27	-0.0313	-25.20	0.975
All rates of return ≥ 40% and ≤ 100%, >1985	53	5.3658	176.03	-0.0305	-61.74	0.987
Africa: all rates of return ≥ 30% and ≤ 100%	16	3.9918	52.87	-0.0349	-23.34	0.971
Asia: all rates of return ≥ 45% and ≤ 100%	21	3.9940	62.36	-0.0162	-17.09	0.939
Latin America: all rates of return ≥ 40% and ≤ 100%	33	5.4419	80.66	-0.0442	-40.73	0.982

Varying the implicit cutoff rate with five percentage points for the developed countries and 10 percentage points for the developing countries affects the slope coefficients only marginally. Splitting the data sets into two time periods (before and after 1985) did not yield radically different slope coefficients either, nor did it suggest a notable change in the cutoff rate over time. However, the breakdown of developing countries by region led to a differentiation in implicit cutoff rates as well as slope coefficients. Given the relatively small number of observations, these latter results are statistically not very robust. Nevertheless, it partially explains why we did not find a very clear mode for the developing countries as a group.

To summarize, the estimated slope coefficients are a reasonable approximation of the slope coefficient of the ex ante optimal distribution of R&D projects if the following assumptions more or less hold:

(a) The semilog function is a good approximation of the ranked distribution of R&D projects.

(b) The ex ante selection of R&D projects has not been optimal, but is sufficiently vigorous economically.
(c) The chance not to be selected is equal for all R&D projects with an ERR above the implicit cutoff rate.
(d) Differences in the ex ante and ex post rates of return are merely stochastic and not systematic.
(e) The stochastic variation has a normal distribution.
(f) The sample of ex post rates of return is only biased at the extreme ends.
(g) The R&D projects in the sample are of equal size.

With estimates for the implicit cutoff rates as well as the slope coefficients and the social rate set at 7% for developed countries and 12% for developing countries, the underinvestment gaps can now be calculated using equation 8.4. The results of these calculations are presented in table 8.3 and indicate a considerably larger underinvestment gap for developing countries (137%) than for developed countries (40%). Differentiating the sample in studies from before and after 1985 hardly affects these results. Given the very approximate nature of the identified mode, extreme values for the mode were adopted, which resulted in lower and upper bounds of the underinvestment gap. Not surprisingly, the underinvestment gap is quite sensitive to the estimation of the mode. Grouping the rates of return of developing countries by region yields quite a bit of variation in both the cutoff rate and the slope coefficient and suggests that under-investment in agricultural R&D has been particularly high in Latin America.

Table 8.3: *Estimations of the underinvestment gap*

	Cutoff rate	Slope coefficient β_1	Underinvestment gap
Developed countries (social rate 7%)			
Baseline	20%	-0.0257	39.7%
Rates of return before 1986	20%	-0.0242	37.0%
Rates of return after 1985	20%	-0.0264	41.0%
5% points lower cutoff rate	15%	-0.0259	23.1%
5% points higher cutoff rate	25%	-0.0262	60.4%
Developing countries (social rate 12%)			
Baseline	40%	-0.0308	136.9%
Rates of return before 1986	40%	-0.0313	139.9%
Rates of return after 1985	40%	-0.0305	134.8%
10% points lower cutoff rate	30%	-0.0300	71.6%
10% points higher cutoff rate	50%	-0.0295	206.3%
Africa	30%	-0.0349	87.3%
Asia	45%	-0.0162	70.3%
Latin America	40%	-0.0442	244.5%

Adopting a social-time-preference definition as the basis for the social rate would lower the social rates by roughly two percentage points, i.e., from 7% to 5% and from 12% to 10%. This would increase the underinvestment gap for developed countries to 47% and for developing countries to 152%.

While there is considerable room for improvement in the statistical data used in the present analysis (both in coverage as well as the quality of the rate-of-return methods used), the ranked distribution model cuts quite nicely through what looked like a Gordian knot. It shows that the high *means* of the rate-of-return distributions as such are no evidence of underinvestment in agricultural R&D, nor are they indicative of the size of the underinvestment gap. The *modes* of the rate-of-return distributions are a substantially better indicator of underinvestment.

What is important to grasp is that under- or overinvestment in agricultural R&D is always relative to the portfolio of profitable innovation opportunities available and, hence, the importance of reconstructing the ex ante, ranked distribution of R&D projects. This is in essence what priority-setting methods also try to do. Even with relatively simple priority-setting tools, such as scoring methods, it is possible to identify quite adequately the R&D projects with very low or high rates of return. The real problem, however, lies close to the cutoff rate, where one can expect to find the majority of R&D projects and where rate-of-return differences between R&D projects are relatively small. Given the uncertainty surrounding the relative ranking of R&D projects, the advantage of a more sophisticated (and costly) economic-surplus method in priority setting is less clear than sometimes suggested. Reducing the issue of choice to those R&D projects close to the cutoff rate, the gains from a better ranking method is relatively modest. However, the economic-surplus approach has, in a different way, a clear advantage over scoring methods because it reveals ERR values. This is, as has been shown above, important information to judge whether there is under- or overinvestment in agricultural R&D. A scoring method only provides a relative ranking.[10]

Innovation needs should not be mistaken for innovation opportunities. Particularly in poor countries, innovation opportunities are far more limited than innovation needs. This is certainly unfortunate, but it is counterproductive to push for investment levels in agricultural R&D that would lead to funding R&D projects with very low or negative ERRs. In such instances, the emphasis should be placed on creating a better environment for innovations to prosper. This will enhance the portfolio of profitable R&D projects and, hence, pull more investment into R&D. In the next section, the focus is on the determinants of the ranked distribution of R&D projects and what the possible intervention points to increase the portfolio of profitable R&D projects could be.

[10] The highest-ranking R&D project may still have an ERR that is lower than the social rate and therefore should not be implemented, nor should any of the projects that rank below it.

8.3 *The position of the distribution of R&D projects on the ERR scale*

Our model of the selection of R&D projects suggests that the optimal level of investment in R&D depends on the position of the distribution of possible R&D projects on the ERR scale.

Differences in R&D intensity are quite large across countries, industries, companies, and over time. We want to understand why. Therefore, in this section, an attempt will be made to present and analyze the most likely underlying factors that shape the *economic* ranking of R&D projects and, hence, the relative position of the R&D portfolio on the ERR scale.

8.3.1 *Possible factors shaping the R&D portfolio*

The position of the portfolio of possible R&D projects on the ERR scale can be thought of as depending on the following six interacting factors: (a) technology, (b) scale, (c) the structure of the industry, (d) R&D efficiency and effectiveness, (e) adoption rate, and (f) risk and uncertainty.

The *technical* ranked distribution of all imaginable R&D projects is based only on the technical merits of the imagined innovations relative to the technology (and economic structure) in place and can be expressed in terms of a reduction in production cost per unit output. This technical ranked distribution is then multiplied with innovation-specific *scale* factors reflecting market potential or, in the case of public R&D, reflecting potential social impact.[11] This may change the original technical ranking quite substantially – promising technical improvements can turn out to have very low or negative ERRs because their potential use is limited, while small insignificant technical improvements can turn out to have high ERRs because of their wide application.

As discussed in chapter 2, the S&T literature frequently makes a distinction between major technological breakthroughs and small cumulative improvements. Major breakthroughs, such as a shift in the scientific frontier (Dosi 1982) or the introduction of a new design configuration (Metcalfe 1995), open up new R&D opportunities. Assuming that such new opportunities become available all at once, this would result in a new and very promising portfolio of possible R&D projects (i.e., reaching far to the right). Due to limited R&D capacity, however, not all R&D projects can be implemented at once. Instead, R&D projects are implemented over time, starting with the most promising ones first. As a result, the portfolio of possible R&D projects retracts to the left over time and the average of the rates of return declines steadily until the next major breakthrough.

A more realistic description is that only a small part of the R&D opportunities are immediately clear or sufficiently profitable at the time of the scientific breakthrough or the introduction of a new design configuration. Technological innovation is more an

[11] This difference in focus also leads to different ERRs – the first is private, the second is social.

incremental, cumulative, and path-dependent process, so R&D opportunities only open up gradually, resulting in a relatively stable R&D portfolio through time. Although major breakthroughs constitute a necessary condition for opening up new R&D opportunities, the rate at which these new opportunities open up may depend on quite different factors. Biotechnology, for example, is a scientific breakthrough that has created a wealth of new opportunities, most of which are still on hold, waiting for research costs to come down and uncertainties around safety and consumer acceptance to be resolved.

The *structure of an industry* also plays an important role in shaping the portfolio of possible R&D projects. A monopolist, for example, can be assumed to capture the whole potential market and, hence, appropriate all potential R&D benefits, while a small firm in a very fragmented market can only expect to capture a fraction of the market and the potential R&D benefits. In the latter case, the private incentive to invest in R&D will be quite small, leading to market failure in the provision of new technology. Patent rights may overcome this latter problem to some extent as they grant the inventor exclusive use of the technology for a restricted period of time (usually 15-20 years) on the condition that the technical details of the innovation are made public. This can help to avoid future duplication of R&D efforts, which is another disadvantage of very fragmented and competitive industries. In a monopolistic situation, however, the duplication of R&D effort is close to zero, while the potential portfolio of profitable R&D projects is the largest because of scale advantages. Nevertheless, a monopoly may not lead to the technologically most dynamic situation, as the competitive incentives to exploit potential opportunities for innovation are weak. Therefore, in the S&T literature, an industry with oligopolistic tendencies is considered to be the most conducive to technological innovation (Cohen 1995).

Primary agriculture is a classic example of a very fragmented industry where market failure prevails when it comes to generating new technology. The benefits individual farmers can appropriate from an invention are far too small to constitute much of an incentive to invest substantial sums in their own R&D. Joint action or government intervention is needed to overcome this market failure. Organizing and planning agricultural R&D as if the agricultural sector were just one big national farm brings important scale advantages to the provision of agricultural technology in the form of a far larger portfolio of profitable R&D projects. At the same time, duplication of R&D efforts can be minimized, at least nationally. However, whether this potential is actually exploited depends also on the competitive incentives (the monopolist dilemma) and the organizational capacity of governments or farmer and industry groups to do so. One could argue that autarkic economic policies provide fewer incentives to governments or farmer and industry groups to fully exploit innovation opportunities in agriculture than the open-trade policies advocated in more recent years.

R&D efficiency and effectiveness determine the ultimate costs and success of the R&D activity undertaken. These two performance indicators are assumed to affect all R&D projects within the same organization equally. They differ between R&D organizations, but more importantly between countries. Weak R&D performance usually reflects weak organizational capability in a society in general. Idachaba (1998), for example, documented how the late and very erratic release of government funding places a major constraint on the performance of agricultural research organizations in Nigeria. Overstaffing is another phenomenon that often negatively affects the performance of agricultural research organizations in developing countries (Pardey, Roseboom, Beintema, and Chan-Kang 1998). After all salaries have been paid, hardly any budget is left for operating expenses or capital investments.

Because of incomplete or slow *adoption,* not all potential benefits of an innovation may materialize. For example, a new maize variety could potentially be grown by 70% of the farmers, but past adoption rates indicate that only half of them will actually grow it. Hence, the technical ranked distribution of R&D projects must not only be corrected for scale, structure, and R&D efficiency and effectiveness, but also by a factor that reflects the adoption rate of the proposed innovation. Low adoption rates can be thought of as being caused by weak institutions and high transaction costs – problems that are particularly prevalent in developing countries.

As discussed in chapter 2, crucial to the adoption of new technology is how information about the new technology is packaged and transferred to farmers and how farmers assess the new technology in their own specific situation. Farmers may know about the new technology and be convinced about its superiority, but they may face other constraints, such as lack of capital or credit, lack of required inputs at the place and time needed, land tenure issues, and seasonal labor shortages, to name just a few, as listed by Pinstrup-Andersen (1982). Government policies targeting these constraints play an important role in improving rates of adoption and, hence, shifting the distribution of R&D projects to the right on the ERR scale.

The distinction between lack of scale and non-adoption can at times be difficult to establish. In the example given above, researchers could argue that the new variety is of relevance to only 35% of the farmers. In that instance, the scale factor subsumes the adoption factor. It is important, however, to keep the two factors separate as they may require different policy measures.

Being an inherently *risky and uncertain* activity, research is at odds with the risk-averse nature of humanity. Hence, private individuals and companies will, depending on how averse to risk they are, shy away from risky R&D projects and discount for statistical variance of the ERR when ranking R&D projects. A suggestion made by Freeman and Soete (1999) is that high ERRs are usually associated with high risks (i.e., higher variance). Therefore, risk-aversion effectively biases private R&D to the less uncertain, but usually also less rewarding, R&D projects. The risk-averse version of the ranked distribution of R&D projects can be thought of as positioned lower on the ERR scale than the risk-neutral version. This creates a divergence between the ex ante and ex post rate-of-return distributions, as the latter will more or less coincide with the risk-neutral version.

An alternative option for private companies is to think in terms of an R&D portfolio rather than separate R&D projects and to pool some of the risks. A few very promising and risky projects are selected in combination with a large number of less promising, but also less risky, projects. Pursuing a diversified R&D portfolio spreads the overall risk, and the larger the R&D portfolio, the more risk and uncertainty can be spread. Taken a step further, Arrow and Lindner (1970, 1972) argued that in a typical public-investment situation, governments could safely ignore risk as long as the investment is small relative to national income. Given that this is true for most public agricultural R&D projects, risk aversion should not play much of a role in the selection of public agricultural R&D projects or programs (Anderson 1991). In other words, public agricultural R&D projects or programs with the same ERR, but with one being riskier than the other (reflected by a higher statistical variance), should be treated the same. The weighted chance of a lower outcome is compensated by the weighted chance of a higher outcome. This does not mean that risk and uncertainty can be ignored altogether for public agricultural R&D. As shown by Anderson (1991), risk may play a role in accurately determining the mean project performance or ERR. The ERR obtained from taking every parameter at its most likely value will differ from the ERR derived from a Monte Carlo simulation if the distributions are asymmetric and the relationship between parameters and benefits are nonlinear (Alston, Norton, and Pardey 1995).

In theory, administrators of public research should be indifferent to risk and uncertainty when selecting R&D projects. Given the very limited use of probabilistic cost-benefit approaches in R&D selection processes, one would expect this to be true in practice, too. However, as Greig (1981) pointed out, public research administrators may very well be risk-averse and prefer a less profitable but also less risky R&D portfolio, so that demands for accountability can be answered by at least some positive results. Hence, even in the public-sector case, an R&D project with a high ERR but wide variance may be discriminated against in practice.

Risk and uncertainty are not static and may decline over time. R&D proposals that initially are turned down as being too risky may be selected at a later stage when critical variables can be predicted more accurately. For example, experience in a certain research field may increase the confidence in research effectiveness over time.

8.3.2 *Policies that could improve the portfolio of possible R&D projects*

The six underlying factors presented in the previous section are not necessarily exhaustive. Other factors may play a role as well. Moreover, the relative importance of each of the six factors differs across research fields. Market structure, for example, can be safely ignored when considering public (agricultural) R&D.[12] For other fields of research, however, this may constitute a highly relevant factor that affects the ERR of R&D projects and, hence, shapes the available R&D opportunities. Understanding which

[12] This does not mean that market structure is of no relevance when prioritizing agricultural R&D projects, but that research managers of public agricultural R&D can effectively assume that they hold a monopoly.

factors are the most critical is important when considering policies that could shift the portfolio of possible R&D projects higher up on the ERR scale.

Table 8.4 summarizes some of the government policies that could affect each of the six factors positively. Several of these policies are far broader than just R&D policy. These policies condition the extent to which R&D can contribute to the overall economy. In developing countries in particular, the profitability of R&D projects is (often severely) constrained by structural and institutional factors, such as infrastructure, education, and incomplete markets. One of the most constraining factors, however, is that of political instability – it disproportionately affects investments with a long time horizon, like R&D.

Table 8.4: *Policies that could affect R&D opportunities positively*

Factors affecting the ranked distribution	*Policies that could affect the position of the ranked distribution positively*
Technology	Investment in basic science, training of researchers, improved access to knowledge
Scale	Legislative and financial support for joint R&D activities in fragmented industries; supranational cooperation
Structure of the innovating industry	Effective anti-trust legislation to avoid monopolistic situations and patent legislation to provide incentives for private investment in R&D
R&D efficiency and effectiveness	Developing capacity to train researchers, improve management and organization of government research organizations
Adoption rate and speed	Markets, infrastructure, credit, education, etc.
Risk and uncertainty	Political stability; clear policies on IPR, ethical standards, and other regulatory measures

R&D can also be self-enforcing in the sense that past R&D results and experiences may have a positive influence on (some of) the underlying factors that shape the portfolio of possible R&D projects today. For example, becoming more experienced in conducting R&D increases the efficiency and effectiveness of R&D over time, and technology adoption may become easier once consumers and markets have become accustomed to rapid technical change. Risk and uncertainty may also be reduced by past R&D results.

The ranking of industries by R&D intensity stands out as rather stable in cross-country comparisons among developed countries (Freeman and Soete 1999). Despite substantially lower levels of investment in R&D in general, industries in developing countries also comply to roughly the same ranking (Roseboom 1999). So, across all countries, food-processing industries have relatively low R&D intensities and pharmaceutical industries have relatively high ones. This finding could be explained by assuming that some of the underlying factors are more industry-specific, such as technology and industry structure, while other factors are more country-specific, such as scale, R&D efficiency and effectiveness, and technology adoption. Risk and uncertainty could fit in either category. Hence, explanations for differences in agricultural R&D intensities across countries should be sought among the more country-specific factors.

This characterization of the ranked distribution of R&D projects provides a rough outline of the factors that shape the portfolio of innovation opportunities. Depending on the specific industry and country, a further detailing of these factors should provide a better understanding of the innovation opportunities within reach and also what could be done to enhance them.

8.4 *The R&D opportunity curve*

In the previous sections, agricultural R&D investments have been characterized without any reference to the actual amount invested. In this section, the analysis will be taken a step further by linking the characteristics of the reconstructed ex ante distribution of agricultural R&D projects (i.e., the implicit cutoff rate and slope coefficient β_1) with past agricultural R&D investment levels as reported in chapter 3. By cumulating the ranked distributions, a third dimension can be added to the picture, namely, that of R&D expenditure or intensity. The resulting R&D *opportunity curves* provide a comprehensive way of simultaneously illustrating the differences in R&D opportunities and the underinvestment issue (section 8.4.1). By assuming a standard cost-benefit structure across all R&D projects in the sample, the effect of changes in R&D benefits or costs on the R&D opportunity curve can be modeled and the R&D benefit or cost elasticity can be estimated (section 8.4.2).

8.4.1 *Comparing R&D opportunity curves*

By combining the characteristics derived from the rate-of-return samples (i.e., the implicit cutoff rate and the slope coefficient) with the corresponding levels of agricultural research expenditures (either in absolute or relative terms), R&D opportunity curves can be constructed as depicted in figure 8.5.[13] These curves represent the economically optimal R&D portfolios and are the relevant curves for assessing the characteristics of the underinvestment gap.

[13] Since a breakup of the sample into studies published before and after 1985 did not yield significantly different implicit cutoff rates or slope coefficients, the whole sample has been taken as approximate for the 1981–1985 R&D opportunity curve.

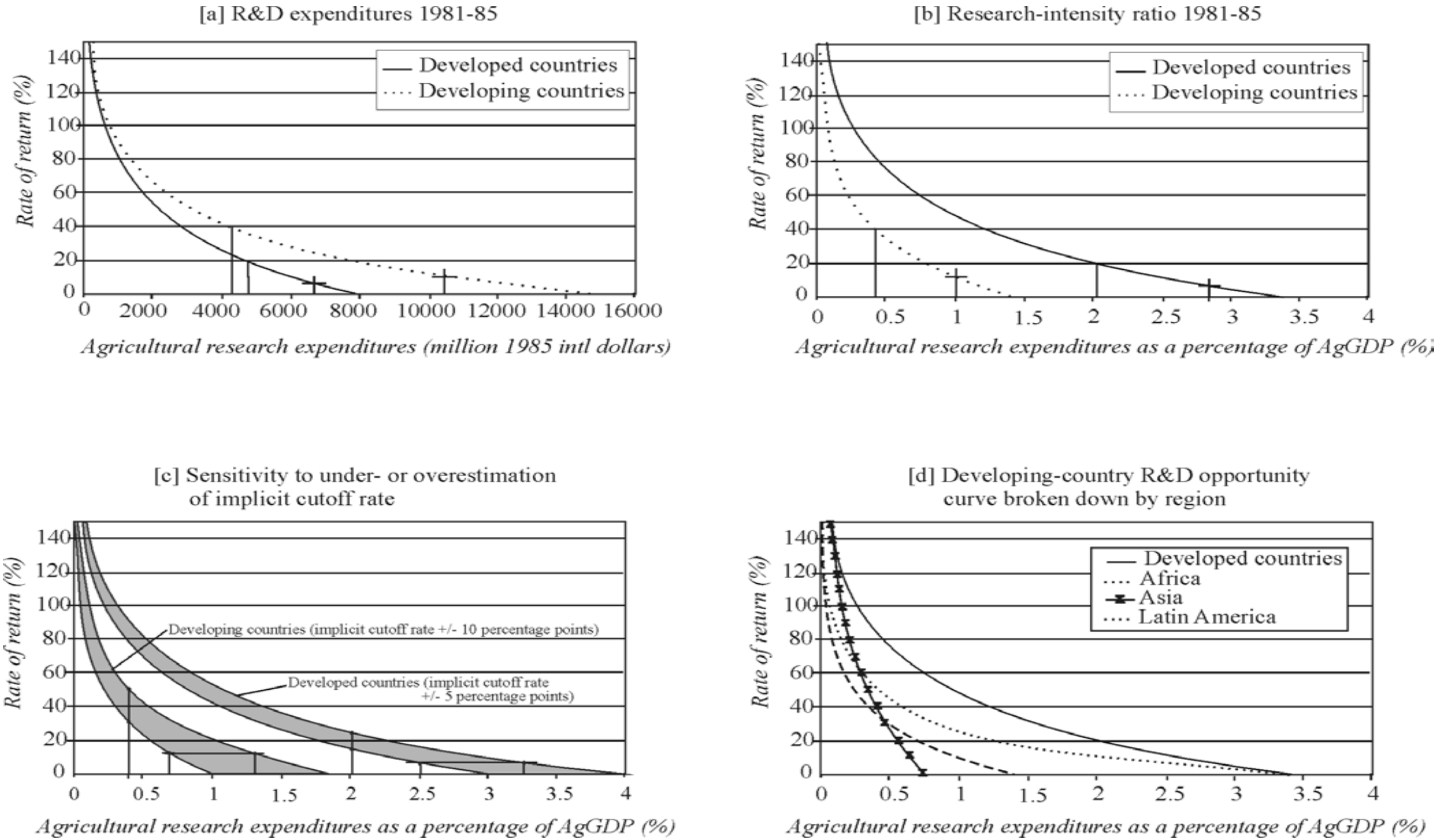

Figure 8.5: *R&D opportunity curves*

The positions and slopes of the R&D opportunity curves capture the differences in innovation opportunities between developed and developing countries in a nutshell. In retrospect, the optimal level of investment in agricultural R&D for developed countries can be estimated at $6.7 billion per annum rather than the actual $4.8 billion spent, by bringing the cutoff rate down from 20% to the social rate of 7%.[14] For developing countries, the difference is substantially larger – rather than the actual $4.4 billion, $10.4 billion could have been spent before reaching the social rate of 12% (figure 8.5a). In relative terms, however, the developed countries clearly stand out as having a far larger portfolio of profitable agricultural R&D investment opportunities than the developing countries have. Their optimal R&D intensity ratio stands at 2.8%, compared to 1.0% for developing countries (figure 8.5b).[15]

In figure 8.5c, the R&D opportunity curves are plotted assuming extreme values for the implicit cutoff rate. The implied lower- and upper-bound values for the optimal intensity ratios are 2.5% and 3.3% for developed countries and 0.7% and 1.3% for developing countries, respectively. This suggests that the R&D opportunity curves for both sets of countries are clearly distinctive. A further differentiation of the R&D opportunity curve for developing countries by region is presented in figure 8.5d. Although the actual R&D intensity for all three developing regions clusters around 0.5%, their estimated optimal R&D intensity ratios differ quite significantly: 0.9% for Africa, 0.6% for Asia, and 2.0% for Latin America. The robustness of these latter estimates is rather weak given the small number of rate-of-return observations per region. Nevertheless, it illustrates how, with sufficiently good rate-of-return data, some far-reaching conclusions regarding under-investment in agricultural R&D could be derived.

In figure 8.6, the R&D opportunity curves have been plotted for two different time periods. The results of the rate-of-return studies published in and before 1985 have been related to the expenditure level of 1961–65, while those published after 1985 are related to the expenditure level of 1981–85. The figure shows how, for both developed and developing countries, the R&D opportunity curve has shifted outward. If the R&D opportunity curve had remained unchanged, the increase in R&D spending would have reduced the implicit cutoff rate and, hence, the underinvestment gap. For developing countries, this would have brought the cutoff rate close to 25%, while for developed countries, the cutoff rate would have dropped below zero.

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[14] The expenditure data reported here are expressed in constant 1985 PPP dollars.
[15] Defined here as public agricultural research expenditures as a percentage of agricultural GDP.

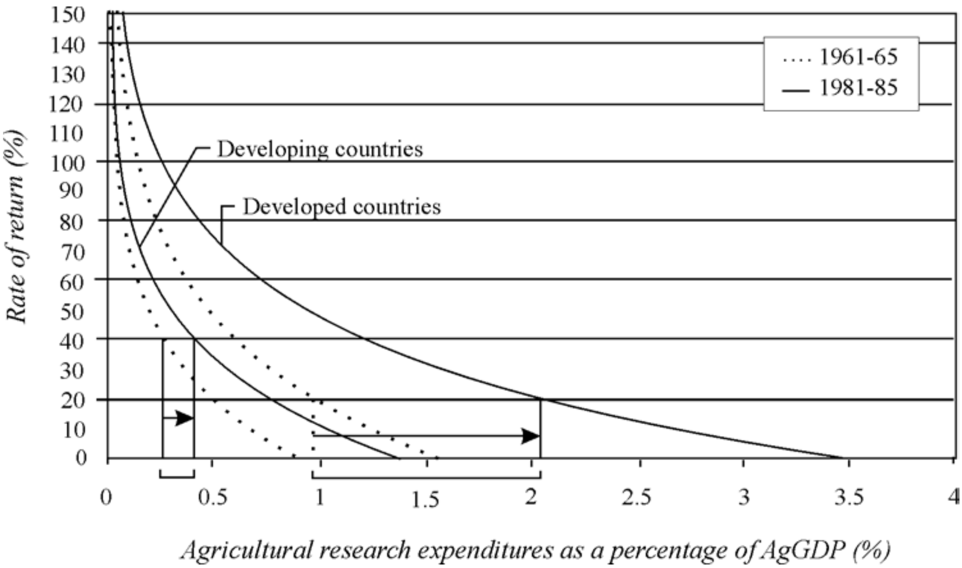

Figure 8.6: *The shift of the R&D opportunity curve over time*

An implicit assumption frequently made in the literature and also in policy advice is that there is one single R&D opportunity curve that is the same across countries and over time. For example, the recommendation made by the World Bank that developing countries should invest 2% of their AgGDP in agricultural R&D by 1990 (World Bank 1981) is based on this assumption.[16] The developed-country investment level of the early 1980s is taken as the target, and assuming that all countries are on the same curve, closing the underinvestment gap is a matter of moving along a fixed curve. If the advice had been followed, developing countries would have overinvested in agricultural R&D by quite a margin. The results of the current analysis suggest that for 1981–85, the optimal investment level for developing countries was about 1.0% (rather than the actual 0.4%) and that for developed countries, it was about 2.8% (rather than the actual 2.0%). It is important to realize that even at modest investment levels, overinvestment may very well take place if profitable innovation opportunities are scarce or nonexistent. Lack of scale in small countries, for example, may place many innovation opportunities out of reach economically. More generally, institutional constraints such as nonexistent or poorly functioning markets may hold back innovation opportunities and, hence, the level of R&D investment.

Developed countries invest far more in agricultural R&D per unit of value-added than developing countries for three reasons: (1) in relative terms, their portfolio of profitable R&D projects is far larger (that is, positioned more to the right), (2) their social rate or optimal cutoff rate is lower (7% against 12% in developing countries), and (3) their actual (implicit) cutoff rate is substantially lower (20% against 40% in developing countries).

[16] Even with just some feel for orders of magnitude, it should be quite clear that increasing the agricultural R&D capacity more than fivefold in just 10 years is physically quite impossible.

Moreover, their portfolio of profitable R&D projects has grown considerably faster than their AgGDP, which has resulted in more than a doubling of the agricultural research intensity ratio in 20 years' time. In contrast, the R&D opportunity curve for the developing countries has moved only slightly. This leads to the following proposition:

(5) Differences in research intensity across countries and industries and over time are due primarily to differences in the number of profitable innovation opportunities.

8.4.2. *R&D benefit or cost elasticity*

An improvement in the adoption rate of a particular technology or the price of the targeted commodity will lead to higher benefits and, hence, to an improvement in the relative ranking of an R&D project. In contrast, a price increase of all agricultural commodities enhances the profitability of all agricultural R&D projects and, assuming the same cost-benefit structure across all projects, shifts the whole R&D opportunity curve up, i.e., towards higher ERRs. With an overall price decrease, the opposite can be expected. Also, measures or factors that improve the efficiency or effectiveness of R&D or the adoption of technology in general, such as education, infrastructure, and markets, can help to improve the position of the R&D opportunity curve.

In reality, not all R&D projects have the same cost-benefit structure. As a consequence, the impact of a general price increase will differ across R&D projects and will cause changes in the relative ranking of R&D projects on the R&D opportunity curve. However, for reasons of simplification, the same cost-benefit structure has been assumed across all projects in order to model the effects of general R&D benefit or cost changes on the underinvestment gap. More precisely, a cost-benefit structure has been assumed of five years of costs followed by 16 years of benefits, as depicted in figure 8.7.

An asymmetric, inverted-V structure for R&D benefits has been selected as representative for the average agricultural R&D project.[17] The corresponding cost-benefit equation can be written as follows:

$$\overline{C}\sum_{t=0}^{t=4}(1+\hat{\rho})^{-t} = \overline{B}\sum_{t=5}^{t=11}(\frac{t-4}{7})(1+\hat{\rho})^{-t} + \overline{B}\sum_{12}^{20}(\frac{21-t}{10})(1+\hat{\rho})^{-t} \qquad [8.5]$$

where $\hat{\rho}$ represents the internal rate of return at which costs equal benefits.

[17] Other benefit distributions, such as trapezoidal and polynomial, are also frequently used (see Alston, Norton and Pardey 1995). While such benefit structures may yield different rate-of-return results, they do not yield significantly different responses to benefit or cost changes as long as the time periods are roughly the same.

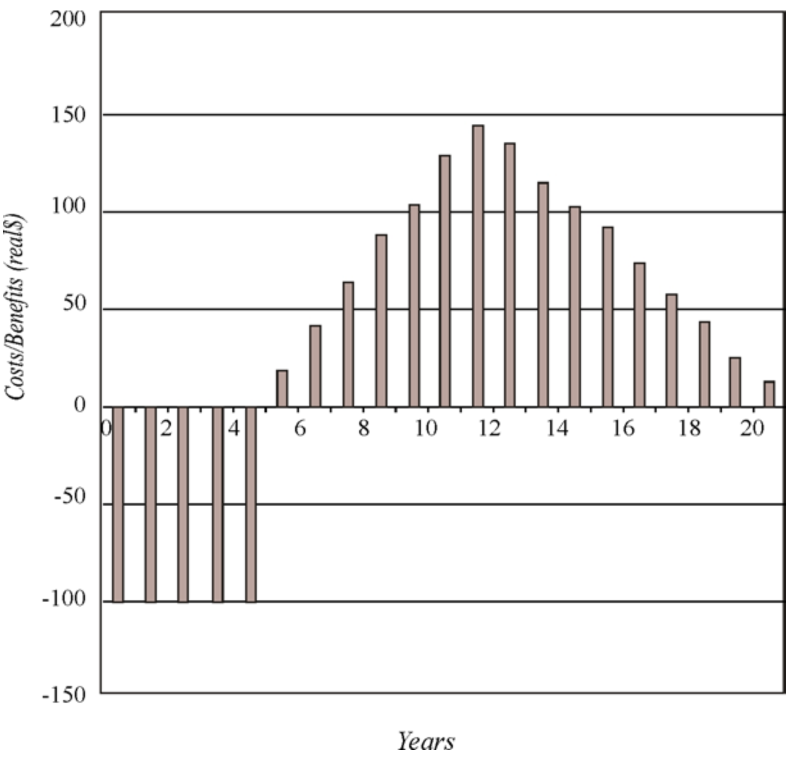

Figure 8.7: *Assumed cost-benefit structure of an average agricultural R&D project*

The effects on the ERR of changes in R&D costs or benefits can be estimated across all projects using equation 8.5, and the resulting shift in the R&D opportunity curve can be approximated by estimating new values for coefficients β_0 and β_1. Table 8.5 summarizes the reaction of the R&D opportunity curves to changes in R&D costs and benefits.

The elasticity of the optimal R&D portfolio to changes in R&D costs and benefits can be estimated by dividing the change in profitable R&D projects by the change in R&D costs or benefits (see table 8.5). Two important results stand out. One is that the *R&D benefit (or cost) elasticity* for developed countries is considerably lower than for developing countries. A 10% change in R&D costs or benefits leads to an increase or decrease in the optimal R&D portfolio in the order of 3.9% to 4.3% for developed countries and 8.7% to 9.8% for developing countries. In part, this is due to the steeper slope coefficient in the ranked distribution (a flatter slope for the R&D opportunity curve) for developing countries, but more important, it is because of the high implicit cutoff rate. Assuming an implicit cutoff rate and social rate

Table 8.5: *R&D benefit and cost elasticities*

Elasticity R&D opportunity curve – developed countries (marginal cutoff rate of 20%, social rate 7%)										
Change in R&D *benefits* (%)	-50	-25	-10	-1	0	1	10	25	50	100
Change in number of profitable R&D projects (%)	-27.5	-11.6	-4.3	-0.4		0.4	3.9	9.1	16.7	28.7
Underinvestment gap (%)	12.1	28.1	35.4	39.3	39.7	40.1	43.6	48.8	56.4	68.4
Elasticity	0.551	0.464	0.428	0.409	0.407	0.405	0.389	0.366	0.334	0.287
Slope coefficient	-0.0301	-0.0275	-0.0263	-0.0258	-0.0257	-0.0256	-0.0251	-0.0244	-0.0234	-0.0219
Change in R&D *costs* (%)	-50	-25	-10	-1	0	1	10	25	50	100
Change in number of profitable R&D projects (%)	28.7	11.8	4.3	0.4		-0.4	-3.9	-9.0	-16.3	-27.5
Underinvestment gap (%)	68.4	51.5	44.0	40.1	39.7	39.3	35.8	30.6	23.4	12.1
Elasticity	-0.574	-0.472	-0.430	-0.409	-0.407	-0.405	-0.387	-0.361	-0.326	-0.275
Slope coefficient	-0.0219	-0.0240	-0.0251	-0.0256	-0.0257	-0.0258	-0.0263	-0.0271	-0.0282	-0.0301
Elasticity R&D opportunity curve – developing countries (marginal cutoff rate of 40%, social rate 12%)										
Change in R&D *benefits* (%)	-50	-25	-10	-1	0	1	10	25	50	100
Change in number of profitable R&D projects (%)	-59.8	-25.8	-9.6	-0.9		0.9	8.8	20.9	38.4	67.1
Underinvestment gap (%)	77.1	111.1	127.3	136.0	136.9	137.8	145.7	157.7	175.3	204.0
Elasticity	1.195	1.031	0.959	0.922	0.918	0.914	0.882	0.834	0.769	0.671
Slope coefficient	-0.0361	-0.0329	-0.0316	-0.0309	-0.0308	-0.0307	-0.0301	-0.0293	-0.0280	-0.0262
Change in R&D *costs* (%)	-50	-25	-10	-1	0	1	10	25	50	100
Change in number of profitable R&D projects (%)	67.1	27.0	9.8	0.9		-0.9	-8.7	-20.1	-35.9	-59.8
Underinvestment gap (%)	204.0	163.9	146.6	137.8	136.9	136.0	128.2	116.8	101.0	77.1
Elasticity	-1.342	-1.081	-0.976	-0.924	-0.918	-0.913	-0.868	-0.804	-0.719	-0.598
Slope coefficient	-0.0262	-0.0288	-0.0301	-0.0307	-0.0308	-0.0309	-0.0315	-0.0324	-0.0338	-0.0361

similar to those of developed countries (i.e., 20% and 7%) would bring the R&D benefit elasticity for developing countries down to 0.522, which is substantially closer to that of developed countries (0.407). Hence, the following proposition:

(6) The R&D benefit or cost elasticity depends on (a) the assumed cost-benefit structure of R&D projects, (b) the slope coefficient of the R&D opportunity curve, and (c) the implicit cutoff rate.

8.5 *Possible explanations for the underinvestment gap*

While Ruttan's claim that there is substantial underinvestment in agricultural R&D has been generally accepted, it has not been completely undisputed. Pasour and Johnson, for example, argued in their critique of Ruttan's claim that (Pasour and Johnson 1982, p. 306):

> The only legitimate conclusion that can be drawn when the analyst's estimates do not coincide with those of his subjects' is that the analyst has incorrectly estimated the expected cost and benefits as perceived by decision makers.

This argument is of course also valid for the underinvestment gap as estimated by our model. In other words, "Are there rational explanations of why underinvestment gaps exist and why they are bigger in developing than in developed countries?" Such explanations may provide useful insights into how underinvestment gaps could be reduced. In addition to possible weaknesses in our model, three other possible explanations will be explored that have been suggested in the literature, namely, (a) deadweight losses due to taxation, (b) rigidities in budgeting, and (c) political bias in the selection of R&D projects.

8.5.1 *Possible weaknesses in the estimation of the R&D opportunity curves*

R&D opportunity curves are a stylized version of reality, based on several rather critical assumptions. However, not all of the assumptions may hold in reality, causing the R&D curve to be estimated wrongly. Four issues in particular stand out, which could explain (part of) the underinvestment gap: (1) a systematic overestimation of rates of return, (2) possible biases in the rate-of-return samples, (3) risk and uncertainty, and (4) weak priority setting.

The technical and more theoretical problems related to the measurement of R&D rates of return have been discussed in detail in chapter 7. With regard to a possible overestimation of rates of return to public agricultural R&D investment, two issues stand out in particular:

(1) The assumed cost-benefit structure. Alston and Pardey (2000) argue that in many instances, the assumed length of the R&D benefit stream is too short, which leads

approach and to an underestimation when using an economic-surplus approach. Given the fact that the first method is used more frequently in ex post evaluations, the net effect would be an overestimation of the average rate of return.

(2) A systematic underestimation of the contribution of purchased inputs from other industries to technological innovation in agriculture.

These two factors affect each R&D project differently but, in general, will bring the estimated rates of return downwards. This would result in a shift of the ranked distribution to the left and a reduction of the underinvestment gap. When real, such corrections should be applied, but one has to keep in mind the fact that the "apparent" underinvestment gap could also be explained by other factors. There is a danger in trying to explain away the underinvestment gap by focusing on only one aspect of it.

One of the assumptions in the model is that the sample of rate-of-return studies is perfectly random. However, it is very likely that there is a bias in the sample towards the more successful R&D projects, as there is usually little interest in knowing the rate of return of R&D projects that have failed. The distribution of the rate-of-return results seems to confirm this argument – only one out of 202 is negative. It is therefore reasonable to believe that the actual left-hand tail of the ranked distribution is considerably longer than observed.[18] However, as long as the implicit cutoff rate is relatively high, the right-hand side of the distribution and the estimated position of the implicit cutoff rate should not be affected by this bias. It is only the right-hand side of the ex post distribution that is used when estimating the underinvestment gap. The only possible effect of the bias in the sample could be a too optimistic assessment of the quality of the ex ante selection. In extreme cases, this may lead to an estimated implicit cutoff rate that is too high and therefore to an overestimation of the underinvestment gap. In such an instance, weak priority setting would mistakenly be interpreted as underinvestment.

As mentioned in section 8.3, risk and uncertainty may cause a divergence between ex ante and ex post rates of return when risk and uncertainty are discounted in the ex ante selection procedure. Although concrete examples of using probabilistic cost-benefit approaches are very scarce, some notion of probability of success most likely enters into selection procedures in rather informal ways. Assuming a strong and positive correlation between ERR and probability variance, the risk-averse version of the ex ante distribution can be thought of as positioned left of the risk-neutral version on an ERR scale and deviating more as the ERR increases. The ex post results should more or less coincide with the risk-neutral version of the distribution, which provides a possible explanation for the underinvestment gap observed ex post.

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[18] The relative share of negative rates of return also depends on the level of aggregation of the R&D "projects" or "programs" evaluated. Aggregated R&D programs yield a substantially smaller spread in rate-of-return results (and, hence, negative rate-of-return observations) than more disaggregated R&D projects. The same is true when such R&D projects are split into smaller sub-projects. At a higher level of aggregation, negative research results are compensated by positive research results and are hence less visible.

with the risk-neutral version of the distribution, which provides a possible explanation for the underinvestment gap observed ex post.
The estimated underinvestment gaps represent the optimal selection case. The fact that selection procedures are imperfect has deliberately been eliminated in order to get a better view of underinvestment. Hence, the model calculates what optimally could have been invested in agricultural R&D at a given social rate. Policymakers, however, may very well know that the selection of R&D projects is less than perfect and this negatively affects their assessment of what is an optimal level of investment in agricultural R&D. It is difficult to determine, however, to what extent weak priority setting could explain the observed underinvestment gap. Nevertheless, improved priority setting is often considered an important prerequisite for enhancing R&D budgets. The World Bank, for example, nearly always includes better priority setting as a condition in its loans for agricultural research capacity building.

8.5.2 *Deadweight losses due to taxation*

The argument of underinvestment in agricultural R&D has come under some considerable criticism as part of a broader discussion in the public-finance literature, which argues that the social opportunity cost of a dollar of government spending is larger than a dollar. There are direct costs to collecting taxes, but what is more important is that taxes introduce distortions in factor and product markets that create deadweight economic losses. It is particularly these latter losses that have drawn considerable attention in the public-finance literature. Ballard, Shoven, and Whalley (1985), for example, estimated the marginal welfare costs or excess burden for the USA in the range of \$0.17 to \$0.56 per US dollar of tax income.

Fox (1985) was the first to introduce the excess-burden argument in a paper discussing underinvestment in public agricultural R&D in the USA. He adopted the excess-burden rates as calculated by Ballard, Shoven, and Whalley (1985) and used a method of calculating a rate of return that assumes a very simple relationship between research costs and benefits: research costs (C) are all incurred in the first year, while the benefit stream comes in equal portions (B) over a period of 16 years. The internal rate of return ($\hat{\rho}$) of this hypothetical R&D project can be solved as follows:

$$C_0 = \overline{B}\sum_{t=0}^{T}\left(1+\hat{\rho}\right)^{-t} \qquad [8.6]$$

However, the true social cost of the project is (1+υ) C_0, where υ represents the marginal excess burden or welfare costs of taxation. The internal rate of return adjusted for taxation losses, $\hat{\rho}$, solves

$$C_0\left(1+\upsilon\right) = \overline{B}\sum_{t=0}^{T}\left(1+\hat{\rho}\right)^{-t} \qquad [8.7]$$

0.30 for the USA (about the mid-point of the range), he finds that the marginal rate of return for agricultural R&D that is adjusted for the excess burden of taxation is 26% rather than 37%. However, a major weakness of Fox's example is the assumed cost-benefit structure. It is not a good representation of the cost-benefit structure of a typical agricultural R&D project. All costs are assumed to take place in year 0, but most R&D projects take several years before they are completed and start to have an impact. Plant breeding projects, for example, take more than 10 years. Adopting a more "representative" cost-benefit structure, as presented in section 8.4.2, equation 8.7 should be modified as follows:

$$(1+\upsilon)\overline{C}\sum_{t=0}^{t=4}(1+\hat{\rho})^{-t} = \overline{B}\sum_{t=5}^{t=11}\left(\frac{t-4}{7}\right)(1+\hat{\rho})^{-t} + \overline{B}\sum_{12}^{20}\left(\frac{21-t}{10}\right)(1+\hat{\rho})^{-t} \qquad [8.8]$$

In this case, the downward adjustment of the marginal rate of return is considerably lower, namely, from 37% to 32% rather than the 37% to 26% reported by Fox. It is the longer cost period in particular that affects this result.

Most subsequent authors on investment in agricultural R&D agree in principle with the social opportunity-cost argument (e.g., Dalrymple 1990; Alston and Pardey 1996), but there has been some debate on the specifics. First, as pointed out by Ballard and Fullerton (1992), in certain situations the excess burden of taxation can be positive rather than negative, for example, in the case of a tax on pollution. While interesting for selecting the optimal tax instrument, it is more relevant for the current discussion to find out the marginal excess burden of the average taxation instrument, given that public agricultural R&D is usually paid out of general tax revenues.[19] Second, there is a difference between gross and net measures of marginal excess burden or welfare costs of taxation. The gross measure refers to the effect of a tax irrespective of its use, while the net measure takes the use of funds into account. If these are invested in, for example, infrastructure or productivity-enhancing R&D, then the net excess burden of taxation can be considerably lower (Dalrymple 1990). Third, measures of the marginal costs of funding as reported in the literature range from as high as \$4 (Browning 1987) to as low as \$0.62 (Fullerton and Henderson 1989). Which one to pick? Alston and Pardey (1996), citing a study by Fullerton (1991), suggest a considerably more modest range of \$1.07 to \$1.25 for the USA. More relevant perhaps is the decision in 1992 by the US Federal Government to use \$1.25, but allowing for lower rates to be used if the investment leads to cost savings for the Federal Government (Office of Management and Budget 1992).[20] Whether this is the "economically" correct excess-burden rate is not that relevant; it is the one that the US Government insists on using when evaluating government programs.

[19] Alston and Pardey (1996) argue that the marginal excess burden of a commodity-specific R&D tax is considerably lower than that for general taxes.

[20] To my knowledge, there are no real cases yet of agricultural R&D evaluations in the US that have used the excess-burden rate or, for that matter, a net excess-burden rate. There is no indication yet what would be the appropriate net excess-burden rate for agricultural R&D.

the "economically" correct excess-burden rate is not that relevant; it is the one that the US Government insists on using when evaluating government programs.

Whatever excess-burden rate of taxation is considered appropriate, the ranked distribution of R&D projects will shift to the left and will also become slightly steeper. Figure 8.8 shows how an excess-burden rate of $1.25 shifts the R&D opportunity curve to the left (assuming the same cost-benefit structure across all projects). Keeping the research intensity fixed, the underinvestment gap for developed countries is reduced from 40% to 31%, and for developing countries from 137% to 117%. Hence, the argument about the excess-burden rate of taxation can explain the underinvestment gap to some extent, but by no means the whole gap. Moreover, it has more impact on reducing the underinvestment gap for developed countries (-23%) than for developing countries (-15%).

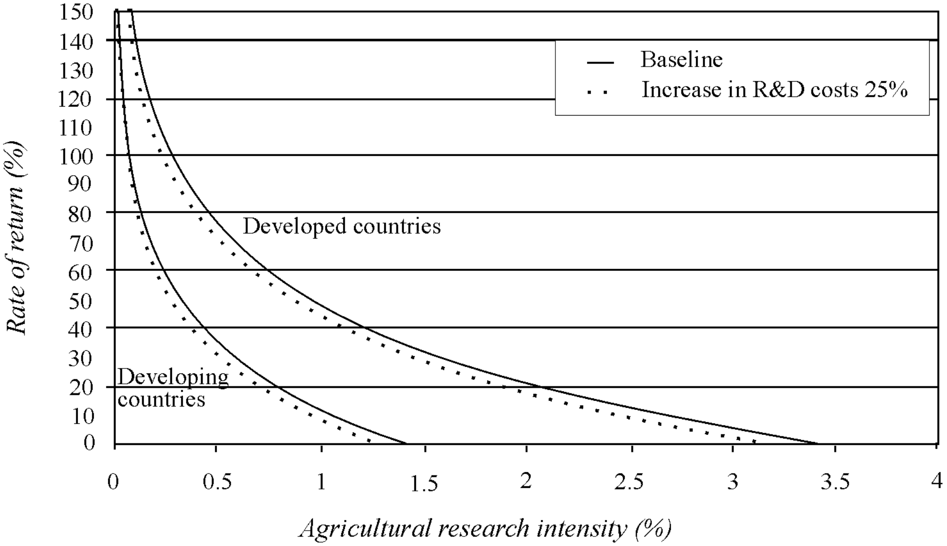

Figure 8.8: *Shift of the R&D opportunity curves due to a tax-burden rate of 25%*

Although often seen as a rather typical American, anti-government sentiment, the influence of the excess-burden literature on taxation policies has also outside the USA been quite significant. The recent trend in the OECD countries to lower high marginal tax rates is based on this literature. To my knowledge, however, there are no other countries that use an explicit excess-burden rate in their evaluations of government programs. Nevertheless, it does not mean that it is not a factor of importance in making a decision of whether or not to fund a government program. Politicians want to be re-elected (or, if it is not a matter of elections, to remain in a position of power), and they know that they do not make themselves popular by raising taxes unless they can show that the programs that are being funded bring significant (economic) benefits to society. One could argue that the excess-burden rate makes this economically rational resistance to taxation explicit, and it may explain why, when no provision is made for the excess-burden factor, Fox (1985) was certainly ahead of his time in applying an excess-burden rate to public agricultural R&D investments, but he considerably oversold his argument by suggesting a social rate of about 20% (nominally, this is more in the range of, say, 15-16% real terms) and an excess-burden rate of 1.30. The US Federal Government adopted a standard in 1992 that is considerable lower: a social rate of 7% (real, that is adjusted for inflation) and an excess burden rate of 1.25, which may be adjusted downward if the investment leads to cost savings for the Federal Government.

8.5.3 *Rigidities in the budget process*

Oehmke (1986) argued that rigidities in the budget process prevent an immediate response to new investment opportunities in agricultural R&D. Such new opportunities arise, for example, because of increases in product demand or research efficiency, which translates into respectively higher R&D benefits or lower R&D costs. Oehmke (1986) argues that these rigidities are rather permanent and lead to persistent underinvestment in agricultural R&D. He captures this fact in his model by basing R&D investment decisions on prices and quantities of period *T*-1 rather than period *T*, which results in an underestimation of the R&D benefits and an overestimation of R&D costs.

Assuming that the *T*-1 prices and quantities underestimate the actual benefits by 25% and overestimate the actual costs by 10% across all R&D projects, two R&D opportunity curves representing the developed-country case can be constructed as depicted in figure 8.9. Again, the same cost-benefit structure is assumed across all projects (see equation 8.5). The R&D opportunity curve based on *T*-1 prices and quantities is positioned to the left of the R&D opportunity curve based on *T* prices and quantities. Taking the social rate as the cutoff rate, optimal investments could have been 9.7% higher if *T* rather than *T*-1 prices and quantities had been used. For the developing countries, assuming the same price and quantity distortions, the underinvestment gap would yield 13.0%. Despite the quite substantial price and quantity distortions assumed, the estimated underinvestment gaps are relatively small in comparison with the ones actually observed. Therefore, budget rigidity can explain some of the underinvestment in agricultural R&D, but by no means all of it.

Budget rigidities, however, may also work in the opposite direction and cause over-investment in agricultural R&D. It is quite exceptional to find an R&D portfolio that only grows. A more realistic assumption is that some parts of the R&D portfolio grow and others shrink. One can expect that the speed by which such adjustments are implemented is less than optimal due to rigidities in the budget allocation process as well as in organization. Cutting back on a particular R&D activity may perhaps be even more difficult than trying to start a new one. Persistent overinvestment can be as much of a problem as persistent underinvestment.

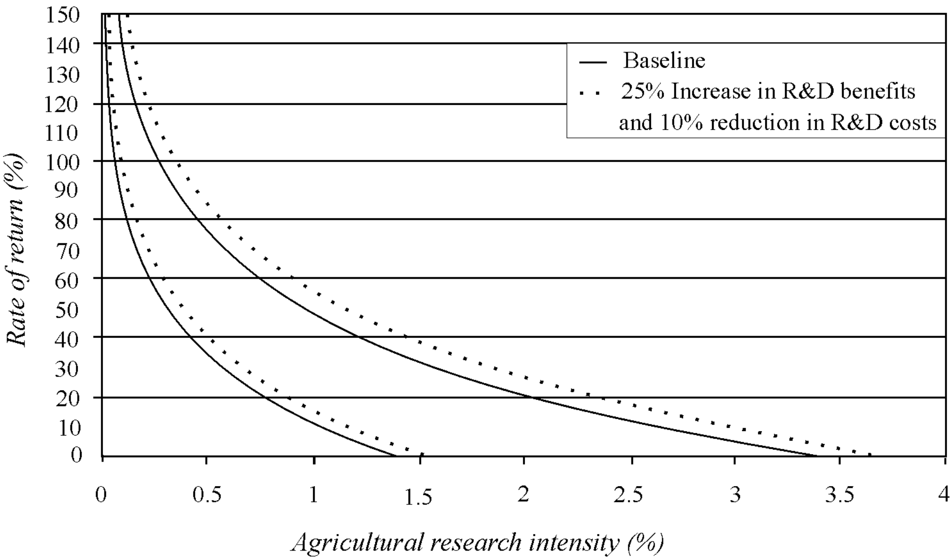

Figure 8.9: *Shift of the R&D opportunity curves due to budget rigidity*

8.5.4 *A political bias in the selection of R&D projects*

One of the criticisms of the rather strict neoclassical approach to the selection of R&D projects is that it is based exclusively on economic considerations. It is blind to the initial distribution of assets as well as to who ultimately benefits from the R&D projects selected and implemented. De Janvry, Sadoulet, and Fafchamps (1989) provide a more balanced perspective by introducing transaction costs and concepts of collective action into the debate.[21] They show that transaction costs differ across farmers due to differences in assets and that when this is taken into account, the ERR of a new technology to individual farmers becomes conditional on the distribution of assets.[22] Consequently, a single optimum R&D portfolio across all farms does not exist. It is this multiplicity of private optima that, in turn, makes collective action to influence choices in R&D so important.

If collective action by large commercial farmers is more effective than that by poor smallholders (as seems to be the case in Latin America), the selection of R&D projects will be biased towards those that benefit large commercial farmers most. In the terminology of the induced-innovation theory, the R&D portfolio will be biased towards labor-saving technology. However, de Janvry, Sadoulet, and Fafchamps (1989) argue that the bias is also affected by the size of the R&D budget. They find that with a sufficiently large R&D budget, the bias will converge to neutrality. This latter finding can be explained as

[21] Earlier versions of the ideas presented in de Janvry, Sadoulet, and Fafchamps (1989) can be found in de Janvry (1977) and de Janvry and Dethier (1985).

[22] Other factors may also play a role, such as geographical location (farmers close to the market face different transaction costs than farmers far away) and education.

particularly beneficial to them will be selected first, but such projects still have to exceed the social rate. In the most extreme case, all R&D projects preferred by large commercial farmers are selected first and only if there is funding left will R&D projects preferred by poor smallholders be selected. In reality, the distortion is probably less extreme, but it is still realistic to assume that there is some considerable distortion in the selection.[23]

Following this reasoning, the consequences of underinvestment in agricultural R&D are not neutral. Poor smallholders will be affected more than large commercial farmers. While acknowledging this bias, what should not be overlooked is that the portfolio of profitable R&D projects for large commercial farmers may be substantially larger than the portfolio for poor smallholders. A strictly balanced distribution of R&D resources may look politically correct but can be counterproductive economically. To illustrate this point, imagine a world government that could reallocate total agricultural R&D funding. It can do so by taking either an economic or a political perspective. The political perspective would argue for an allocation of R&D funding that is egalitarian. In other words, the distribution of R&D funding should be such that the R&D intensity across all countries is the same. Using the R&D opportunity curves as estimated in section 8.4, this would result in an intensity ratio of 0.7% and implicit cutoff rates of 22.6% (point c) and 61.4% (point d) for developing and developed countries, respectively (figure 8.10). In contrast, an economic perspective would argue for an allocation of R&D funding that would equalize the marginal rate of return of R&D projects between developing and developed countries. This would be the case at an implicit cutoff rate of 31.8% and intensity ratios of 0.53% (point e) and 1.50% (point f) for developing and developed countries, respectively.

The example given above can also be used to represent a dual-economy situation in which the developing countries represent poor smallholders and the developed countries the large commercial farmers. The initial asset distribution leads to quite distinctive innovation opportunities for the two groups and, hence, R&D opportunity curves as depicted in figure 8.11. However, in real life the positions and shapes of the R&D opportunity curves are generally not known. Instead, it is often assumed, usually implicitly, that both groups of farmers are on the same R&D opportunity curve. This leads to no other conclusion than that the R&D portfolio is very much biased in favor of the large commercial farmers and that this bias is economically suboptimal.

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[23] Hence, the difference between the optimal and suboptimal selection of R&D projects is not only a matter of weak priority setting but also the result of the lobbying activities of interest groups.

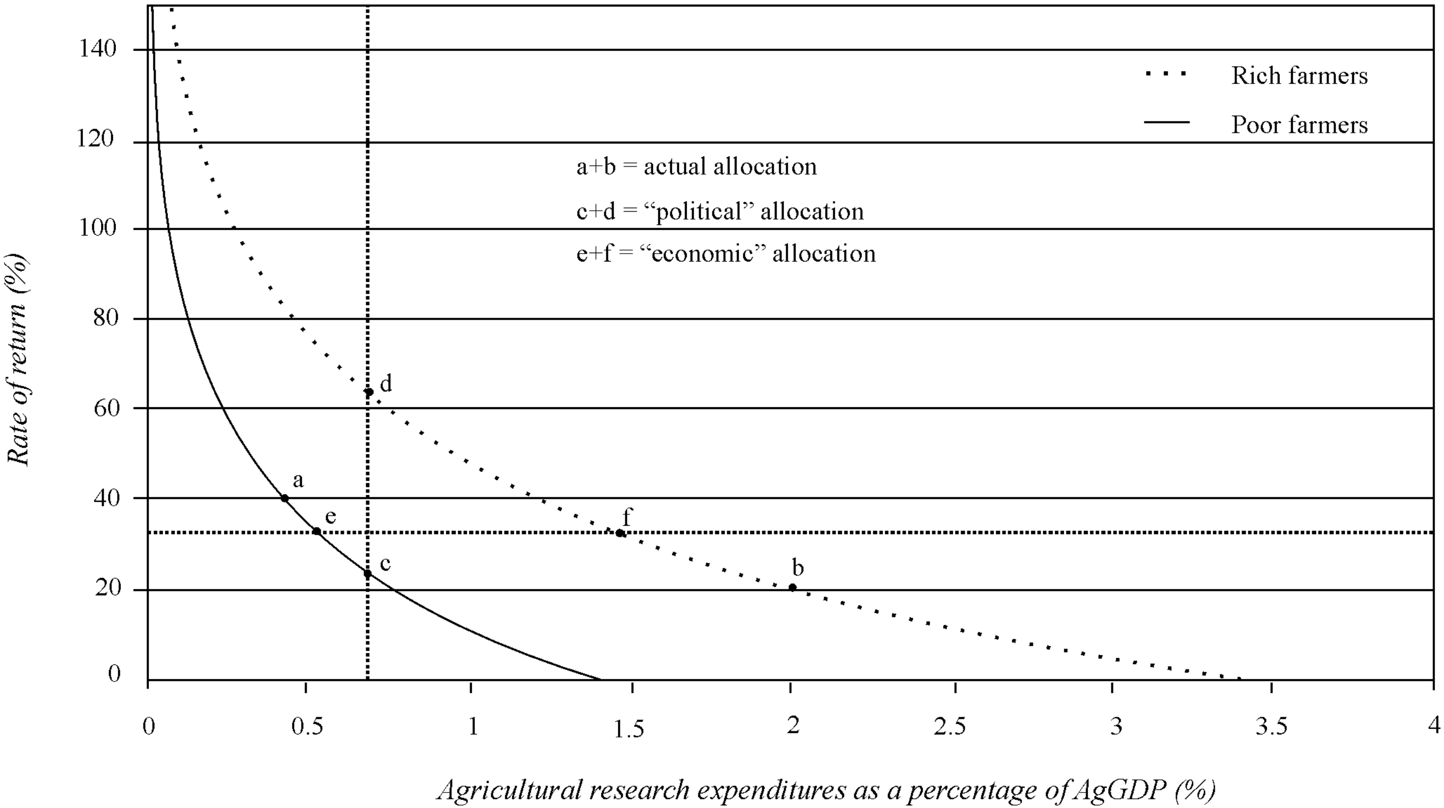

Figure 8.10: *The political versus economic equilibrium in the allocation of R&D resources*

Assuming two distinctive R&D opportunity curves leads to considerably different conclusions. A part of the bias in the R&D portfolio can still be attributed to overly strong lobbying by large commercial farmers that leads to an economically suboptimal outcome, but another (and in this example, larger) part of the bias in the R&D portfolio makes economic sense. The R&D investment opportunities are considerably better for large commercial farmers than for poor smallholders and, therefore, different R&D investment intensities are justified from an economic point of view. The model also reveals another fact, namely that strong lobbying by large commercial farmers should not be explained only in terms of better conditions for collective action (de Janvry, Sadoulet, and Fafchamps 1989) but also in terms of strong economic incentives. Settling on the more "democratic" proportional distribution of R&D resources would leave many very profitable R&D projects that target large commercial farmers unfunded (i.e., all R&D projects with an ERR lower than 61.4%). In contrast, the economic incentive for poor smallholders to lobby for (additional) R&D would be less as the cutoff rate of their preferred portfolio of R&D projects is considerably lower (i.e., 22.6%). In particular, farmers who are not integrated into the market have very little incentive to lobby for R&D as it only leads to untradable surpluses (de Janvry 1985).

This is rather sobering news for those of us who want to target R&D to the poorest of the poor and at the same time want to subscribe to economic rationality. Still, some things can be done to improve poverty targeting. One argument, for example, is that an extra dollar earned by a poor farmer should be valued higher than an extra dollar earned by a rich farmer. As shown in figure 8.11, the model can easily deal with such a correction under the assumption that the cost-benefit structure is the same across all R&D projects (i.e., five years of costs followed by 16 years of benefits). An additional premium of 25 cents for every additional dollar earned by a poor farmer shifts the R&D opportunity curve for poor smallholders up and to the right. With a fixed R&D budget, the new equilibrium for the marginal cutoff rate settles at 34.4% and the economically optimal agricultural research intensity ratios for poor smallholders and large commercial farmers settle at 0.55% (point g) and 1.40% (point h), respectively.

The effect of a poverty premium in this model is very modest – at higher poverty premiums as well, as shown in table 8.6. A one-dollar premium for every additional dollar earned by a poor farmer translates itself into a differentiated marginal cutoff rate of 28.1% for R&D projects targeting poor smallholders and 40.3% for R&D projects targeting large commercial farmers. The intrinsic limiting factor in the model is that the total number of profitable R&D projects for poor smallholders is, at least in relative terms, smaller than that for large commercial farmers. A poverty premium does not alter this fact.

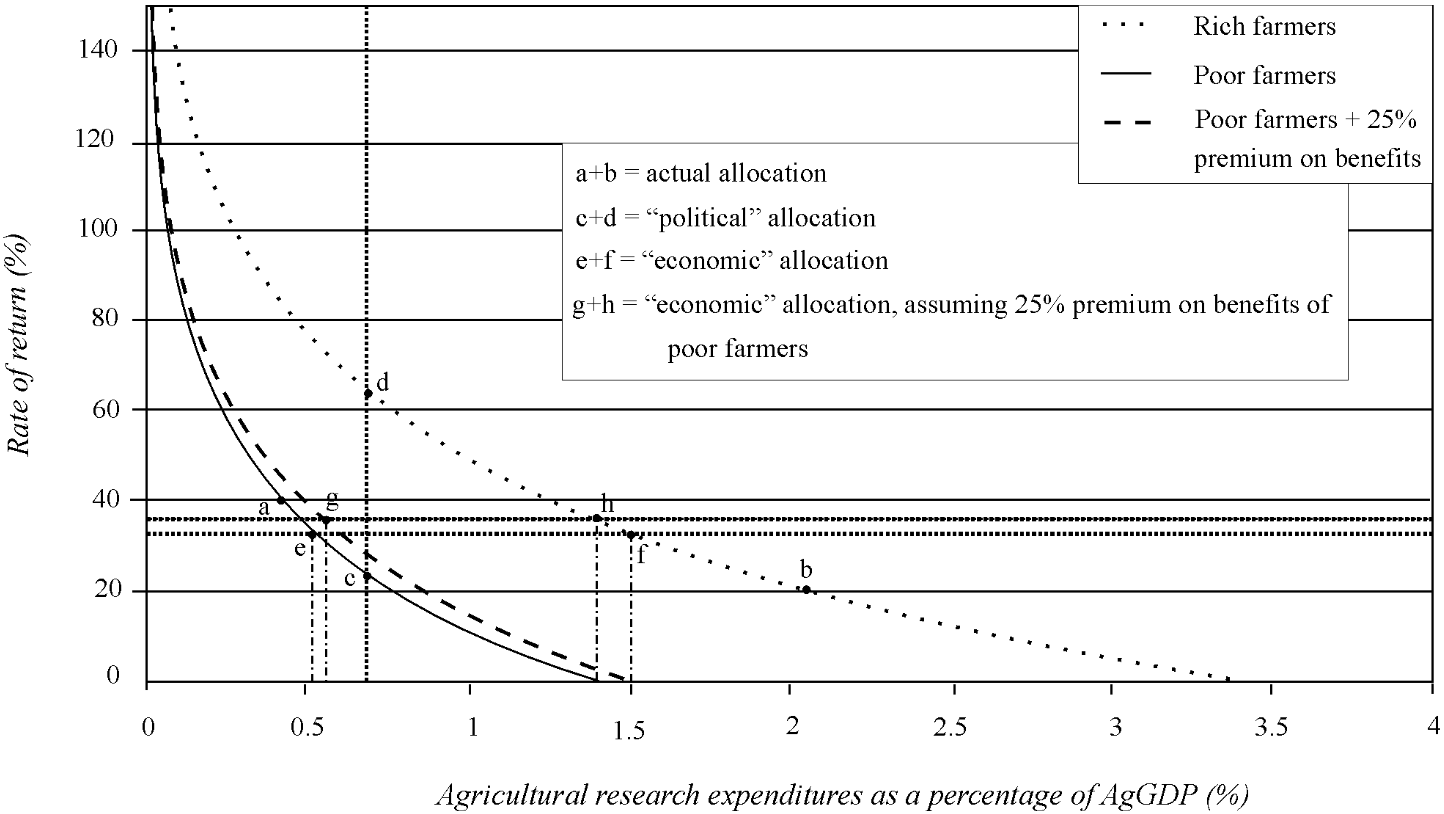

Figure 8.11: *The welfare effects of introducing a poverty premium on R&D targeting poor farmers*

Table 8.6: *Allocation of agricultural R&D funding under different assumptions*

	MDCs = large commercial farmers	LDCs = poor smallholders	All
AgGDP (million 1985 PPP$) [a]	237089	1075293	1312381
Actual allocation			
Agricultural R&D expenditures (million 1985 PPP$) [b]	4812.9	4408.7	9221.6
Agricultural research intensity ratio (%) {[b]/[a]}x100	2.03	0.41	0.70
Marginal rate of return (%)	20.0	40.0	
Average rate of return (%)[a] [c]	58.4	72.0	64.9
Net R&D benefits (million 1985 PPP$) {[b]x[c]}/100	2811.6	3172.9	5984.5
Economic equilibrium at optimal budget			
Agricultural R&D expenditures (million 1985 PPP$)	6223.0	11107.2	17330.3
Agricultural research intensity ratio (%)	2.65	0.98	1.32
Marginal rate of return (%)	10.0	10.0	
Average rate of return (%)[a]	48.4	42.0	44.3
Net R&D benefits (million 1985 PPP$)	3013.0	4661.6	7674.7
Economic equilibrium at fixed budget			
Agricultural R&D expenditures (million 1985 PPP$)	3551.4	5670.2	9221.6
Agricultural research intensity ratio (%)	1.50	0.53	0.70
Marginal rate of return (%)	31.8	31.8	
Average rate of return (%)[a]	70.2	63.8	66.3
Net R&D benefits (million 1985 PPP$)	2494.7	3617.6	6112.2
Adjusted economic equilibrium: 25% poverty premium			
Agricultural R&D expenditures (million 1985 PPP$)	3323.1	5898.5	9221.6
Agricultural research intensity ratio (%)	1.40	0.55	0.70
Marginal rate of return (%)	34.4	34.4	
Average rate of return (%)[a]	72.8	*62.5*	66.2
Net R&D benefits (million 1985 PPP$)	2420.2	3687.7	6108.0
Adjusted economic equilibrium: 50% poverty premium			
Agricultural R&D expenditures (million 1985 PPP$)	3138.8	6082.8	9221.6
Agricultural research intensity ratio (%)	1.32	0.57	0.70
Marginal rate of return (%)	36.6	36.6	
Average rate of return (%)[a]	75.1	*61.5*	66.1
Net R&D benefits (million 1985 PPP$)	2355.8	3742.0	6097.8
Adjusted economic equilibrium: 100% poverty premium			
Agricultural R&D expenditures (million 1985 PPP$)	2853.2	6368.3	9221.6
Agricultural research intensity ratio (%)	1.20	0.59	0.70
Marginal rate of return (%)	40.3	40.3	
Average rate of return (%)[a]	78.8	*60.0*	65.8
Net R&D benefits (million 1985 PPP$)	2247.4	3822.9	6070.2

Note: The figures in italics represent the values for the unadjusted R&D opportunity curves and are the relevant values against which to compare the effect of a poverty premium.

[a] Of R&D projects above the marginal rate of return.

Closing the estimated R&D underinvestment gap (i.e., increase R&D investment for both groups of farmers until the marginal rate hits 10%) requires an additional R&D investment of $8,109 million and creates a net benefit gain of $1,489 million for poor smallholders and $201 million for large commercial farmers.[24] The additional sums invested in agricultural R&D bring down the average rates of return quite significantly, particularly for the poor smallholders.

Reallocating R&D funding while the budget is fixed, as suggested by economic equilibrium, would create a net benefit gain of $128 million. Relative to the actual net benefits of $5,984 million, this is a rather minor improvement and, hence, the conclusion that, aside from the (probably substantial) losses due to poor priority setting, the allocation of R&D resources is not that far from the economic optimum. The distributional effect, however, is considerable: poor smallholders would gain $445 million, while large commercial farmers would lose $317 million.

Another finding is that poverty premiums of 25, 50, and 100 cents per dollar create net benefit losses of $4.3 million, $14.4 million, and $42.0 million, respectively. Again, relative to the total net benefits, these are minor distortions. The distributional effect is more significant: with poverty premiums of 25, 50, and 100 cents per dollar, poor smallholders would gain $70.2 million, $124.5 million, and $205.3 million, respectively, while large commercial farmers would respectively loose $74.4 million, $138.9 million, and $247.3 million.

The model assumes that R&D projects can be clearly differentiated between those that target poor smallholders and those that target large commercial farmers and that there are no negative externalities. This is of course an oversimplification. Poverty targeting is considerably more complicated when R&D projects have distributional effects that are less clearcut. For example, an R&D project may lead to a new technology that creates major benefits for large commercial farmers but, at the same time, has negative externalities for poor smallholders. As a consequence, each R&D project would be affected differently by a poverty premium. This makes it difficult not only to model the effects of a poverty premium but also to come to a general conclusion. It all depends on the (assumed) benefit distribution within a given R&D project.[25]

Rather than artificially shifting the R&D opportunity curve for poor smallholders, it is perhaps more useful to think about policies that could actually shift the R&D opportunity curve for poor smallholders outward. What are the factors that hold R&D investment opportunities for poor smallholders back vis-à-vis those for large commercial farmers? Without doubt, the distribution of assets plays a major role and land reform may lead to

[24] These benefit streams do not, of course, all end up with either the rich or poor farmers. A great deal is passed on to consumers in terms of lower prices.

[25] A classic example in the Green Revolution literature is that while richer farmers have tended to profit from Green Revolution technologies more than poor farmers, lower food prices have been particularly beneficial to poor consumers. Most authors therefore come to the conclusion that the net impact of Green Revolution technologies on poverty alleviation has been positive.

R&D opportunity curves that are closer to each other and with greater overlap. However, there are also many other factors, such as market structure, access to credit, transport facilities, education, and health, that all influence the adoption of a new technology positively and help to shift the R&D opportunity curve outward. Rather than pushing technology, it makes more sense to try to pull technology and R&D investment into smallholder agriculture by creating an environment in which innovation can prosper. In situations in which such an environment does not exist or is declining, investment in R&D can do very little.

8.6 *Conclusions*

Representing the ranked distribution of R&D projects by a semilog function has turned out to be a very fruitful way of structuring the underinvestment hypothesis. Rather than focusing on the average of the reported rates of return as is generally done in the literature, it shifts focus to the rate of return of the marginal R&D project funded. A great advantage of the model is that it defines underinvestment in agricultural R&D unambiguously. To estimate the underinvestment gap, only three parameters are needed: (a) the social cutoff rate, (b) the ex ante, implicit cutoff rate, and (c) the slope coefficient of the ranked distribution. The first parameter is set outside the model, but the latter two have to be estimated. By assuming certain values for the actual cutoff rate and the slope coefficient, the model can simulate various aspects of the underinvestment hypothesis.

With actual estimates for the implicit cutoff rate and the slope coefficient derived from a sample of ex post rate-of-return results, the model can produce actual estimates of past underinvestment in agricultural R&D. In order to do this, it is necessary to eliminate the suboptimality in the ex ante selection of R&D projects from the rate-of-return dataset. This factor obscures our sight of the optimal distribution of R&D projects. The actual rates of return produce a lopsided, bell-shaped distribution, not the expected asymptotic distribution. However, as is shown in this chapter, under some plausible assumptions, the latter can be derived from the former.

It is noteworthy that the estimates of underinvestment are made without any reference to the actual level of R&D investment. Bringing the two together substantially enriches the model and allows for the construction of R&D opportunity curves. These curves, based on the rule that the R&D project with the highest ERR is funded first, depict cumulated R&D expenditures against ERR. What is important conceptually is that these curves are not static; they differ across industries and countries and over time. An implicit assumption in much of the literature on investments in agricultural R&D is that the R&D opportunity curve is fixed. This is wrong. Allowing the R&D opportunity curve to change position over time and across countries (and within countries across regions, commodities, and farmer groups) provides a far better fit with the observed facts, as well as opportunities for policy measures.

The underinvestment gaps estimated by the model are less pronounced than often suggested on the basis of the average rate of return across a large number of R&D projects. The model shows that a high average rate of return in combination with a low marginal rate of return is very possible; hence, the conclusion that a high average rate provides no conclusive information about underinvestment.

Taking as a starting point the idea that R&D investment intensities are defined foremost by the innovation opportunities available gives a different perspective of the observed differences and changes in agricultural R&D intensities. Rather than pressing governments in countries with low or declining intensity ratios to invest more in agricultural R&D, it is more useful to stimulate those governments to adopt policies that improve opportunities for innovation. This would increase the profitability of agricultural R&D projects across the board and, in turn, pull additional R&D funding into agriculture. Such an approach also fits better with the suggestion that there may be perfectly rational explanations of why governments decide to stop funding agricultural R&D before the marginal rate of return is reached. Explanations that stand out most convincingly are the systematic overestimation of the rates of return, the distorted selection of R&D projects, and the excess burden of taxation.

Allowing the impact of R&D to be differentiated across different farmer groups significantly enriches the model. A highly uneven asset distribution among farmers translates into different paths of technological development. In addition, the uneven asset distribution leads to an uneven distribution of power among farmers in pursuing their preferred technology path. Hence, there is good reason to believe that the suboptimality in the selection of R&D projects is not random, but is affected by lobbying by the different interest groups. More concretely, such a political bias would express itself in a lower marginal cutoff rate for R&D projects preferred by the stronger lobby group. However, eliminating this political bias does not necessarily result in equal agricultural R&D intensity ratios. Differential intensity ratios may very well be warranted, as the innovation opportunities for one group of farmers may be considerably better than those for another group of farmers. In particular, the farmers with the better assets are more likely to have better innovation opportunities. Nevertheless, eliminating the political bias in the selection process can be achieved by adhering to a selection mechanism that is strictly economic. In that sense, poor smallholders, in particular, can gain from better priority setting.

A step further is to argue that an additional dollar earned by a poor farmer should be valued higher than an additional dollar earned by a rich farmer. Under the assumption that R&D projects can be clearly distinguished in terms of their impact on poverty alleviation, the model shows that the effect of a poverty premium is rather modest in terms of both welfare loss and the distributional income effect. The intrinsic problem is that the relative number of all profitable R&D projects is smaller for poor smallholders than it is for large commercial farmers. A poverty premium does not alter this, which reinforces the argument made earlier: to focus on policies that enhance innovation opportunities.

9. Discussion and conclusions

This dissertation has addressed the following three sets of questions:

1. Why do we invest in agricultural R&D? What, according to economic theory, drives investment in agricultural R&D, and what are the constraints?
2. How much do we invest in agricultural R&D? How have investment patterns changed over time? And, how do regions and countries at different stages of economic development differ in terms of agricultural R&D intensity?
3. Why, despite an impressive track record, have we not invested more in agricultural R&D? How much more could we have invested? And, are optimal levels of investment in agricultural R&D the same for all countries at all times?

Each of these three sets of questions has been dealt with in the three parts of this dissertation. Rather than just summarizing the answers to these questions, I will look at them in this chapter from a more objective point of view. The three sets of questions regarding agricultural R&D investment are important because they may give an answer to a far broader question: "Why is it that agriculture is so much more productive in one country than another, or more productive today than in the past?" It is an old question, but one that has not yet been answered satisfactorily.

Early answers from economists about this question of productivity focused on differences in natural and physical assets, but more recent explanations have added knowledge and institutions as important explanatory factors for differences in (agricultural) productivity. In a rather abstract way, economists capture these two factors in their macro-economic models as *human* and *social* capital. In contrast to natural and physical assets, knowledge and institutions are both nonrivalrous – using them does not necessarily exclude others from using them as well, nor does it deplete them. On the contrary, actively using knowledge and institutions only makes them better and stronger. In that sense, human or social capital depreciates not from being used, but from not being used and passed on.

Most strikingly, perhaps, is that in order to capture human and social capital in a traditional production-function approach, economists have had to give up the neoclassical paradigm of diminishing returns across all inputs and to assume that human and social capital yield increasing returns – making it possible to produce more output with the same inputs. As described in chapter 2, only quite recently has some progress been made by bringing knowledge and the creation of new knowledge into a growth-accounting framework under the banner of endogenous or new growth theory. However, economists still struggle with the concept of "social capital" and how to integrate it into an economic growth model. While substantial progress has been made in measuring technological innovation, no such counterpart for institutional innovation yet exists. At best, very rough proxies for differences in social capital are being used in modeling economic growth and production functions.

9.1 *The social capital dimension*

Despite being more qualitative than quantitative, the literature on social capital provides valid explanations of why agriculture is producing so much more today than in the past, or in one country compared to another. Some of those explanations relate to the wider economic context within which agriculture is embedded. The switch from subsistence to market-oriented agricultural production, for example, has only been possible because of the development of well-functioning markets. Society can only reap the benefits from specialization and a division of labor when it can rely on the market to facilitate the necessary exchanges smoothly. The social capital embodied in these markets cannot be easily overestimated. Looking more specifically at agricultural innovation, the establishment of the first agricultural experiment stations during the second half of the nineteenth century stands out as a major institutional innovation. This new "social capital" unleashed a stream of technological innovations that continues today and which created a watershed in the growth of agricultural productivity (Hayami and Ruttan 1985). During the 20th century (agricultural) innovation systems have greatly increased in size and complexity, and the recent rise of the concept of national innovation systems in the S&T policy literature reflects attempts to see how such systems can be further optimized (chapter 2). Institutional issues that have been featured on the agricultural research policy agenda in recent years (and which are discussed in various forms in chapters 3-6) include the following:

(1) How can the division of tasks between agricultural R&D agencies at the provincial, national, regional, and international levels be optimized?
(2) How can the mix between public and private and between basic, applied, and adaptive agricultural R&D be optimized?
(3) How can agricultural R&D be made more responsive to the diverse and sometimes conflicting needs of poor and rich farmers, consumers, and government?
(4) How can the internal organization and management of agricultural R&D agencies be improved?
(5) How can political and financial support for public agricultural R&D be mobilized and sustained?
(6) How can the full potential of the contribution of agricultural R&D to economic growth be exploited?

Answers to questions 1 to 4 may lead to more or better research output for the resources provided, while answers to questions 5 and 6 may help to optimize the volume of resources directed to agricultural R&D as such. Part III of this dissertation has focused in particular on the last question and has tried to identify the scale of underinvestment in agricultural R&D as well as the factors that could explain why it exists.

The (expected) rate of return of a research project not only depends on the innovation itself, but also on factors such as size and structure of the market, rate and speed of adoption, risk and uncertainty, and R&D efficiency and effectiveness. Some of these factors have strong social capital dimensions that are cumulative. For example, once farmers are used to buying new seeds regularly and seed markets are well established, the uptake of new varieties will be a lot smoother and faster. Similarly, risk and uncertainty surrounding R&D projects may decrease with the accumulation of experience with innovation. Also, the efficiency and effectiveness of agricultural R&D agencies depends on the organizational and managerial capability accumulated over many years. Therefore, differences in the optimal R&D portfolio across countries and over time depend, among other things, on the social capital accumulated in the broader economy as well as, more specifically, in the agricultural innovation system.

Social capital not only plays a role in defining the economic potential of R&D and, hence, the optimal R&D portfolio, but also in explaining why some countries manage to sustain investment levels in public agricultural R&D that are closer to (although still below) its optimal level when other countries don't. Such countries have not only a better capability to formulate, assess and select the right R&D projects, but also a better capability to mobilize political support and funding.

9.2 *The human capital dimension*

The financial resources and human talent that countries employ in public agricultural R&D have increased substantially since the early 1960s. As documented in chapters 3 and 4, the global agricultural research capacity roughly tripled between 1961 and 1991. Over time, however, the growth in investment in public agricultural R&D has slowed down quite significantly in both developed and developing countries. Economic and financial crises, which hit Africa and Latin America in particular during the 1980s and early 1990s, forced many governments to reduce their investment in agricultural R&D. This has at times led not only to a reduction of agricultural R&D capacity, but also to severe imbalances in staffing and operating budgets and a reduction in the efficiency of agricultural R&D.

The capacity to generate new agricultural knowledge is very unevenly distributed between developed and developing countries. Relative to agricultural GDP, developed countries invest about 4-5 times more in public agricultural R&D than developing countries. While the nonrivalrous character of knowledge would suggest that it does not matter who produces it (everybody will benefit from it), the location and situation-specificity of agricultural knowledge limits its application and, hence, spillover potential. For example, research into high-tech precision farming using the latest computer technology and satellites is of little direct use to resource-poor farmers in developing countries. Moreover, knowledge spillovers are neither automatic nor necessarily free. Investment in own R&D capacity is often crucial in gaining access to knowledge developed elsewhere. But factors such as climatic and economic similarity, geographic proximity, trade links, and language also influence patterns of knowledge and technology spillovers. In addition, a distinction needs to be made between the spread of knowledge and its application. Farmers may know of a new technology but may not be using it, or may only be using it partially. Other factors may form a binding constraint.[1]

All in all, the increasing returns attributed to human capital (or more specifically, to R&D labor) are probably more modest than suggested by some endogenous-growth theorists (Jones 1995). Nevertheless, the attribution of even modest increasing returns to human capital looks like a blank check for investments in education and R&D. Like all public goods, however, knowledge will be underproduced relative to the social optimum unless the individual or group responsible for its production can internalize the externality involved. This has been a strong rationale for governments all over the world to invest in public agricultural R&D. But do they invest enough? This issue has been taken up in part III of this dissertation, which revisited the agricultural R&D underinvestment hypothesis.

9.3 *Underinvestment in agricultural R&D revisited*

Starting with the early work by Griliches (1958) on hybrid corn, rate-of-return studies have become standard practice in documenting the economic impact of agricultural R&D. Although the estimated ex post rates vary substantially, the average is in a range of 40%–60% (Alston *et al.* 2000). Despite criticisms about the accuracy of these rates as well as on how representative the selected projects are, a widely shared believe is that the estimated rates are robust enough to accommodate such criticisms and still be in a range that is substantially above the social rate. Based on this evidence, Ruttan (1980) argued that there is serious underinvestment in public agricultural R&D. This argument has become a widely accepted opinion (if not fact) among agricultural economists. Hence, any slowdown in the growth or, even worse, contraction of public agricultural R&D expenditures is reason for serious concern.

But what do we actually know about this underinvestment? How real is it? Is it higher in developing countries than in developed countries? Is it higher for some types of research than others? Does it increase or decrease over time? And, how much more should have been invested in agricultural R&D? In order to answer these questions, the under-investment hypothesis had to be defined more clearly. Hence, the introduction in chapter 8 of a simple economic model that captures the ex ante selection of R&D projects.

The model assumes that the distribution of all possible R&D projects on an expected rate-of-return (ERR) scale can be thought of as declining asymptotically and can be approximated by a semilog function with a negative slope coefficient. Assuming full information and rational economic behavior, the R&D project with the highest ERR will be selected first, and this process will continue until the budget is finished or the last project hits the social rate. In strictly economic terms, the underinvestment gap can be

[1] Mundlak (2000), for example, argues that in many developing countries, the most limiting factor in the spread of new technology is not knowledge but capital.

defined as the difference between the ERR of the marginal R&D project (the actual rate) and the social rate. Only three variables need to be known to estimate the underinvestment gap: the social rate, the actual cutoff rate, and the slope coefficient of the distribution. Taking less than full information and economic rationality into account, the latter two can, under rather restrictive but plausible assumptions, be derived from a sufficiently large and representative sample of ex post rates of return on agricultural R&D.

The most important findings of the model are the following:

- Not the *mean* but the *mode* of the ex post rate-of-return distribution is the relevant variable for assessing underinvestment in agricultural R&D.
- Under the assumption of full information and economic rationality, developed countries could have invested about 40% more in public agricultural R&D and developing countries about 135% more. In terms of agricultural R&D intensity (i.e., expenditures as a percentage of agricultural GDP), developed countries could have invested 2.8% rather than 2.0%, and developing countries 1.0% rather than 0.4% in the period 1981–85.
- Low investment in public agricultural R&D in developing countries is caused first and foremost by a relatively smaller portfolio of profitable R&D projects to invest in. In looking at the difference in agricultural R&D intensity between developed and developing countries, underinvestment certainly plays a role (the gap is bigger for developing countries), but it explains only a modest part of this difference.
- While efforts to reduce the underinvestment gap should continue, more emphasis should be placed on designing policies that help to shift the portfolio of R&D projects higher up on the ERR scale, even at the risk of increasing the under-investment gap.

The presented model of the selection of R&D projects is purely neoclassical. By assuming full information and economic rationality, it takes the underinvestment argument to its extreme. The usefulness of the model is not that it is a good approximation of reality, but that it provides a benchmark against which reality can be compared. The estimated underinvestment gaps are not unconditional – they assume full information and economic rationality in the allocation of R&D resources. In reality, the ex ante selection of R&D projects is suboptimal and this obscures our sight of the under-investment gap ex post. It has to be eliminated in order to see the underinvestment gap more clearly and to be able to estimate its size. Ultimately, however, the model is useful not because it estimates past R&D underinvestment gaps, but because it helps to better understand why they exist. It is this understanding that may help us to create and better exploit the R&D investment opportunities of tomorrow.

One set of explanatory factors relates to the position and shape of the distribution of all potential R&D projects. There are important differences in innovation opportunities across companies, industries, countries, and over time. Besides pure technological opportunities (which may be enhanced by investing in basic R&D), other factors come into play, such as the size and structure of the market, the rate and speed of adoption, risk and uncertainty, and R&D effectiveness and efficiency. Each of these factors could, if improved, increase R&D benefits or reduce R&D costs and, hence, create a larger optimal R&D portfolio.

The other set of explanatory factors relates to why governments underinvest in public agricultural R&D. Possible explanations are a lack of information, suboptimal selection mechanisms, budget rigidity, excess burden due to taxation, and last but not least, a lack of political and organizational capacity in society. Improvements in each of these factors should bring the underinvestment gap down.

Both sets of factors have important social capital dimensions that tend to be cumulative. It is this social capital that makes it possible for rich countries to have not only a bigger portfolio of profitable agricultural R&D projects to choose from, but also a better capacity to identify, finance, and implement them. Hence, a prerequisite for poorer countries to catch up is that they develop the social capital that can bring innovation opportunities within reach.

9.4 *Some theoretical considerations regarding the R&D opportunity curve*

Chapter 2 explored the S&T literature for ideas and concepts concerning technical change and its link to investment in R&D. It turned out to be a very eclectic set of ideas and concepts, many of which had broken away from neoclassical assumptions such as diminishing returns, selection rationality, full information, and general equilibrium. They pushed the frontiers of neoclassical economics, or even went beyond.

Also, in this dissertation it was necessary to drop the assumptions of full information and selection rationality in order to make sense out of the observed facts, i.e., the distribution of agricultural R&D rates of return. It is only by assuming suboptimal selection of R&D projects that a more consistent story can be told and some link can be established between R&D investment and impact in the form of an R&D opportunity curve.

The R&D opportunity curve has strong parallels with Metcalfe's innovation opportunity frontier (section 2.2.1). However, there are also important differences. Using *rate of return* rather than *production cost reduction* as the dependent variable, the asymptotic form of the curve is not the result of a technological frontier that is imposed on the model. Moreover, the speed by which the research is implemented is optimized within each project. Another advantage of using a rate of return as the dependent variable is that research that does not lead to a cost reduction (e.g., maintenance research and research on product innovation) can be accommodated within the same model.

The S&T literature summarized in chapter 2 points to a wide range of factors that shape the position of the R&D opportunity curve. Technology, scale, market structure, diffusion, research efficiency, etc., all come together when estimating the rate of return to agricultural R&D. All hurdles between the inception of an R&D project and the ultimate stream of the R&D benefits realized are accounted for in a rate-of-return estimation. Many of these hurdles are project-specific, but there are also those that are more specific to technology, industry, country, or time. By differentiating the R&D rate-of-return distributions in these directions, one can start detecting how R&D opportunities differ.

It is interesting to note that the outward shift of the agricultural R&D opportunity curve through time is consistent with endogenous growth theory, which assumes increasing returns to knowledge. There are, however, many other factors that may have caused the outward shift as well. As discussed earlier, social capital may be one of them, but there are also other factors.

In the oil industry, for example, a major decline in R&D investment took place during the second half of the 1990s. This was largely due to low oil prices at that time, which negatively affected the expected private profitability of R&D projects across all oil companies. This resulted in an inward shift of the private R&D opportunity curve. Still, increasing returns to knowledge may have taken place but are now obscured by other factors.

9.5 *Suggestions for future research*

Important parts of this dissertation have remained broad and could benefit from further detail and filling in. In particular, the social capital factor in explaining differences in innovation opportunities and, hence, differences in productivity is for the most part unexplored. Why does innovation prosper more in one environment than another? And, what are relevant and measurable parameters that differentiate highly supportive from less supportive environments? Similarly, a better understanding is needed of what makes one country better in identifying, selecting, and funding (agricultural) R&D than another. What are the relevant policies and instruments that could help to reduce the underinvestment gap as well as the misallocation of resources?

With regard to human capital (restricted here to individuals who are formally involved in R&D) in particular, this dissertation has contributed to the measurement of human and financial inputs into agricultural R&D worldwide. Future research in this area should focus on a better coverage of research undertaken by universities and private businesses, as well as of new research themes that have recently been added to the agricultural R&D agenda, such as environment, food quality and safety, and biotechnology. Moreover, better data on the R&D activities undertaken in the industries involved in agricultural inputs and processing should provide a more complete picture of the contribution of R&D to increases in agricultural productivity.

As discussed in chapter 7, agricultural R&D rate-of-return calculations are surrounded by methodological uncertainties. Three issues that stand out in particular are (1) the assumed lag structures between R&D investment and impact on productivity, (2) the identification of technology spillovers from parallel research efforts, and (3) the identification of technology spillovers from R&D undertaken in supplying industries. Progress in each of these areas should help to improve confidence in the rate-of-return calculations.

The estimation of the implicit cutoff rate and the slope coefficient of the ranked distribution of R&D projects should be based on a representative sample of rate-of-return estimations for agricultural R&D. However, because they did not pass our minimum criteria of comparability, many of the available rate-of-return results had to be dropped from the analysis. This reflects the fact that most rate-of-return studies are conducted in isolation, without much attention to the question of comparability of the results with other studies. This very much limits the usefulness of such studies in a comparative framework. Future work in this area should pay more attention to standardization of approaches and methods, hence improving the comparability of rate-of-return results.

The limited number of comparable rate-of-return observations very much restricts the differentiation of the R&D opportunity curve over time, across regions, and by type of research focus. However, some of this differentiation may be possible in the future as more ex post rate-of-return calculations become available. It is a hopeful sign that the number of rate-of-return studies on agricultural R&D has been increasing steadily over the years.

As mentioned in the introduction, this dissertation builds on the work done by many researchers who have gone before. I have tried to stand on their shoulders (and I hope others will stand on mine) to look further than ever before and see glimpses of Bacon's lost Paradise – of food and peace for all.

References

Abernathy, W.J., and J.M. Utterback. "Patterns of Industrial Innovation." *Technology Review* Vol. 80, No. 7 (1978): 40–7.

Abramovitz, M. "Resources and Output Trends in the United States since 1870." *American Economic Review, Papers and Proceedings* Vol. XLVI (May 1956): 5–23.

Abramovitz, M. "Catching up, Forging ahead and Falling behind." *Journal of Economic History* Vol. 46 (June 1986): 385–406.

Adusei, E.O., and G.W. Norton. "The Magnitude of Agricultural Maintenance Research in the USA." *Journal of Production Agriculture* Vol. 3, No. 1 (January-March 1990): 1–6.

Aghion, P., and P. Howitt. "A Model of Growth through Creative Destruction." *Econometrica* Vol. 60 (March 1992): 323–51.

Ahmad, S. "On the Theory of Induced Innovation." *Economic Journal* Vol. 76, No. 302 (June 1966): 344–57.

Alston, J.M., and P.G. Pardey. "Distortions in Prices and Agricultural Research Investments." Chapter 4 in *Agricultural Technology: Current Policy Issues for the International Community and the World Bank*, edited by J.R. Anderson. Wallingford, UK: CAB International, 1994.

Alston, J.M., and P.G. Pardey. *Making Science Pay: The Economics of Agricultural R&D Policy.* Washington, DC: The AEI Press, 1996.

Alston, J.M., and P.G. Pardey. "The Economics of Agricultural R&D Policy." In *Paying for Agricultural Productivity*, edited by J.M. Alston, P.G. Pardey, and V. Smith. Baltimore and London: The Johns Hopkins University Press, 1999.

Alston, J.M., and P.G. Pardey. "Reassessing Research Returns: Attributions and Related Problems." Invited paper presented at the XXIV Conference of the International Association of Agricultural Economists, Berlin, 13–18 August 2000.

Alston, J.M., J.R. Anderson, and P.G. Pardey. "Perceived Productivity, Foregone Future Farm Fruitfulness, and Rural Research Resource Rationalization." In *Agricultural Competitiveness: Market Forces and Policy Choice*, edited by G.H. Peters and D.D. Hedley. Proceedings of the Twenty-Second International Conference of Agricultural Economists, Darmouth, Aldershot, 1995.

Alston, J.M., B. Craig, and P.G. Pardey. *Dynamics in the Creation and Depreciation of Knowledge, and the Returns to Research.* EPTD Discussion Paper No. 35. Washington, DC: International Food Policy Research Institute, August 1998.

Alston, J.M., G.W. Norton, and P.G. Pardey. *Science under Scarcity: Principles and Practice for Agricultural Research Evaluation and Priority Setting.* Ithaca and London: Cornell University Press, 1995.

Alston, J.M., P.G. Pardey, and J. Roseboom. “Financing Agricultural Research: International investment Patterns and Policy Perspectives.” Paper presented at the Conference of the International Association of Agricultural Economists, Sacramento, California, 1997.

Alston, J.M., P.G. Pardey, and J. Roseboom. “Financing Agricultural Research: International Investment Patterns and Policy Perspectives.” *World Development* Vol. 26, No. 6 (1998): 1057–1071.

Alston, J.M., P.G. Pardey, and V.H. Smith, eds. *Paying for Agricultural Productivity.* Baltimore and London: The Johns Hopkins University Press, 1999.

Alston, J.M., M.C. Marra, P.G. Pardey, and T.J. Wyatt. “Research Returns Redux: A Meta-Analysis of Agricultural R&D Evaluations.” Draft Research Report. International Food Policy Research Institute, Washington, DC, 1997.

Alston, J.M., C. Chan-Kang, M.C. Marra, P.G. Pardey, and T.J. Wyatt. *A Meta-Analysis of Rates of Return to Agricultural R&D.* IFPRI Research Report 113. Washington, DC: International Food Policy Research Institute, 2000.

Anderson, J.R. “Agricultural Research in a Variable and Unpredictable World.” Chapter 4 in *Agricultural Research Policy: International Quantitative Perspectives*, edited by P.G. Pardey, J. Roseboom, and J.R. Anderson. Cambridge, UK: Cambridge University Press, 1991.

Anderson, J.R. “Selected Policy Issues in International Agricultural Research: On Striving for International Public Goods in an Era of Donor Fatigue.” *World Development* Vol. 26, No.6 (1998): 1149–1161.

Anderson, J.R., R.W. Herdt, and G.M. Scobie. *Science and Food: The CGIAR and Its Partners*. Washington, DC: World Bank, 1988.

Anderson, J.R., P.G. Pardey and J. Roseboom, “Sustaining Growth in Agriculture: A Quantitative Review of Agricultural Research Investments.” *Agricultural Economics* Vol. 10, No. 1 (January 1994): 107–23.

Antle, J.M., and S.M. Capalbo. “An Introduction to Recent Developments in Production Theory and Productivity Measurement.” Chapter 2 in *Agricultural Productivity: Measurement and Explanation.* Washington, DC: Resources for the Future, 1988.

Arrow, K.J. “The Economic Implications of Learning by Doing.” *Review of Economic Studies* Vol. 28, No. 80 (June 1962): 155–73.

Arrow, K.J., and R.C. Lindner. “Uncertainty and the Evaluation of Public Investment Decisions.” *American Economic Review* Vol. 60, No. 3 (June 1970): 364–78.

Arrow, K.J., and R.C. Lindner. “Uncertainty and the Evaluation of Public Investment Decisions: Reply.” *American Economic Review* Vol. 61, No. 1 (March 1972): 171–72.

Arthur, W.B. “Competing Technologies, Increasing Returns, and Lock-in by Historical Events.” *The Economic Journal* Vol. 99 (1989): 116–31.

Atkinson, A.B., and J.E. Stiglitz. “A New View of Technological Change.” *Economic Journal* Vol. 79, No. 3 (1969): 573–78.

Ballard, C.L., and D. Fullerton. “Distortionary Taxes and the Provision of Public Goods.” *Journal of Economic Perspectives* Vol. 6, No. 3 (Summer 1992): 117–31.

Ballard, C.L., J.B. Shoven, and J. Whalley. “General Equilibrium Computations of the Marginal Welfare Costs of Taxes in the United States.” *American Economic Review* Vol. 75, No. 1 (March 1985): 128–38.

Banks, G. “Public Policy Principles for Agricultural R&D.” In *Conference Proceedings of the Global Agricultural Science Policy for the Twenty-First Century Conference.* Melbourne: Conference Secretariat, 1996.

Barnes, A.P. “Publicly-Funded UK Agricultural R&D and ‘Social’ Total Factor Productivity.” *Agricultural Economics* Vol. 27, No. 1 (2002): 65-74.

Barro, R.J., and X. Sala-i-Martin. *Economic Growth.* New York: McGraw-Hill, 1995.

Baum, W.C. *Partners Against Hunger: Consultative Group on International Agricultural Research.* Washington, DC: The World Bank, 1986.

Baumol, W.J., J.C. Panzar, and R.D. Willig. *Contestable Markets and the Theory of Industry Structure.* Revised Edition. San Diego, CA: Harcourt, 1988.

Beath, J., Y. Katsoulacos, and D. Ulph. “Game-Theoretic Approaches to the Modelling of Technological Change.” Chapter 5 in *Handbook of the Economics of Innovation and Technological Change*, edited by P. Stoneman. Oxford, UK and Malden, MA, USA: Blackwell Publishers Ltd, 1995.

Ben-Zion, U., and V.W. Ruttan. “Aggregate Demand and the Rate of Technical Change.” Chapter 9 *Induced Innovation: Technology, Institutions, and Development*, edited by H.P. Binswanger and V.W. Ruttan. Baltimore and London: The Johns Hopkins University Press, 1978.

Bernstein, J.I., and M.I. Nadiri. “Interindustry R&D Spillovers, Rates of Return and Production in High-Tech Industries.” *American Economic Review Paper and Proceedings* Vol. 78, No. 2 (1988): 429–34.

Bernstein, J.I., and M.I. Nadiri. “Research and Development and Intra-Industry Spillovers: An Empirical Application of Dynamic Duality.” *Review of Economic Studies* Vol. 56 (1989): 249–69.

Bernstein, J.I., and M.I. Nadiri. *Product Demand, Cost of Production, Spillovers and the Social Rate of Return to R&D.* NBER Working Paper No. 3625. Cambridge, MA, USA: National Bureau of Economic Research, 1991.

Beynon, J. “Financing of Agricultural Research and Extension for Smallholder Farmers in sub-Saharan Africa.” *ODI Natural Resource Perspectives* Vol. 15, No. 4 (1996).

Binswanger, H.P. “Induced Technical Change: Evolution of Thought.” Chapter 2 in *Induced Innovation: Technology, Institutions, and Development*, edited by H.P. Binswanger and V.W. Ruttan. Baltimore and London: The Johns Hopkins University Press, 1978a.

Binswanger, H.P. “The Microeconomics of Induced Technical Change.” Chapter 4 in *Induced Innovation: Technology, Institutions, and Development*, edited by H.P. Binswanger and V.W. Ruttan. Baltimore and London: The Johns Hopkins University Press, 1978b.

Binswanger, H.P., V.W. Ruttan, eds. *Induced Innovation: Technology, Institutions, and Development*. Baltimore and London: The Johns Hopkins University Press, 1978.

Boyce, J.C., and R.E. Evenson. *National and International Agricultural Research & Extension Programs.* New York: Agricultural Development Council, 1975.

Brennan, J.P., and J.S. Davis, eds. *Economic Evaluation of Agricultural Research in Australia and New Zealand*. ACIAR Monograph No. 39. Canberra: Australian Centre for International Agricultural Research, 1996.

Brennan, J.P. and P.N. Fox. *Impact of CIMMYT Wheats in Australia.* Economics Research Report 1/95. Wagga Wagga, Australia: NSW Agriculture, 1995.

Browning, E.K. “On the Marginal Welfare Cost of Taxation.” *American Economic Review* Vol. 77, No. 1 (March 1987): 11–23.

Byerlee, D. “Technology Transfer Systems for Improved Crop Management: Lessons for the Future.” Chapter 12 in *Agricultural Technology Policy: Issues for the International Community,* edited by J.R. Anderson. Wallingford, UK: CAB International, 1994.

Byerlee, D., and M. Morris. “Research for Marginal Environments: Are We Underinvested?” *Food Policy* Vol.18 (1993): 381–93.

Capalbo, S.M., and J.M. Antle, eds. *Agricultural Productivity: Measurement and Explanation.* Washington, DC: Resources for the Future, 1988.

CBS. *Kennis en Economie 1997*. Voorburg, The Netherlands: Centraal Bureau voor de Statistiek, 1997.

CGIAR. *Annual Report 1994–95.* Washington, DC: Consultative Group on International Agricultural Research, 1995.

Chambers, R.G. “The Incidence of Agricultural Policies.” *Journal of Public Economics* Vol. 57 (1995): 317–355.

Chavas, J.-P., and T.L. Cox. “A Nonparametric Analysis of Agricultural Technology.” *American Journal of Agricultural Economics* Vol. 70, No. 2 (May 1988): 303–10.

Chavas, J.-P., and T.L. Cox. “A Nonparametric Analysis of the Influence of Research on Agricultural Productivity.” *American Journal of Agricultural Economics* Vol. 74, No. 3 (August 1992): 583–91.

Cho, D., and S. Graham. "The Other Side of Conditional Convergence." *Economic Letters* Vol. 50 (1996): 285–90.

Clarck, J., and K. Guy. "Innovation and Competitiveness: A Review." *Technology Analysis & Strategic Managemen*t Vol. 10, No. 3 (1998): 363–95.

Cochrane, W.W. *Farm Prices, Myth and Reality*. Minneapolis, MN, USA: Uinversity of Minnesota Press, 1958.

Cohen, W. "Empirical Studies of Innovative Activity." Chapter 6 in *Handbook of the Economics of Innovation and Technological Change*, edited by P. Stoneman. Oxford, UK and Cambridge, MA, USA: Blackwell, 1995.

Coleman, J. "Social Capital in the Creation of Human Capital." *American Journal of Sociology* Vol. 94 (1988): s95–s120.

Corden, W.M. *Trade Policy and Economic Welfare*. Oxford: Oxford University Press, 1974.

Craig, B.J., P.G. Pardey, and J. Roseboom. "International Productivity Patterns: Accounting for Input Quality, Infrastructure, and Research." *American Journal of Agricultural Economics* Vol. 79 (November 1997): 1064–76.

Dalrymple, D.G. "The Excess Burden of Taxation and Public Agricultural Research." In *Methods for Diagnosing Research System Constraints and Assessing the Impact of Agricultural Research, Volume II – Assessing the Impact of Agricultural Research*, edited by R.G. Echeverría. The Hague: International Service for National Agricultural Research, 1990.

Dasgupta, P., and I, Serageldin, eds. *Social Capital: A Multifaceted Perspective*. Washington, DC: The World Bank, 2000.

Dasgupta, P., and J. Stiglitz. "Industrial Structure and the Nature of Innovative Activity." *The Economic Journal* Vol. 90 (June 1980): 266–93.

David, P.A. "Clio and the Economics of QWERTY." *American Economic Review* Vol. 75, No. 2 (1985): 332–37.

David, P.A. "Knowledge, Property, and the System Dynamics of Technological Change." In *Proceedings of the World Bank Annual Conference on Development Economics 1992*. Washington, DC: World Bank, 1993.

DeBresson, C, ed. *Economic Interdependency and Innovative Activity: An Input-Output Analysis.* Cheltenham, UK: Edward Elgar, 1996.

Diewert, W.E. "Exact and Superlative Index Numbers." *Journal of Econometrics* Vol. 4, No. 2 (May 1976): 114–45.

Diewert, W.E. "Capital and the Theory of Productivity Measurement." *American Economic Review* Vol. 70, No. 2 (1980): 260–67.

Diewert, W.E. "The Economic Theory of Index Numbers: A Survey." In *Essays on the Theory and Measurement of Consumer Behaviour in Honour of Sir Richard Stone*, edited by A. Deaton. London: Cambridge University Press, 1981.

Dosi, G. "Technological Paradigms and Technological Trajectories: A Suggested Interpretation of the Determinants and Directions of Technical Change." *Research Policy* Vol. 11, No. 3 (June 1982): 147–62.

Dosi, G. "Opportunities, Incentives and the Collective Patterns of Technological Change." *The Economic Journal* Vol. 107 (September 1997): 1530–47.

Dosi, G., C. Freeman, S. Fabiani, and R. Aversi. "The Diversity of Development Patterns: Catching up, Forging ahead and Falling behind" Chapter 7 in *Economic Growth and the Structure of Long-Term Development*, edited by L.L. Pasinetti and R.M. Solow. New York: St. Martin Press, 1994.

Dosi, G., C. Freeman, R. Nelson, G. Silverberg, and L. Soete eds. *Technical Change and Economic Theory*. London: Pinter Publishers, 1988.

Echeverría, R.G. "Assesing the Impact of Agricultural Research." In *Methods for Diagnosing Research System Constraints and Assessing the Impact of Agricultural Research: Volume II – Assessing the Impact of Agricultural Research,* edited by R.G. Echeverría. The Hague: International Service for National Agricultural Research, 1990.

Edquist, C., ed. *Systems of Innovation: Technologies, Institutions and Organizations*. London: Pinter Publishers, 1997.

Edquist, C., and B. Johnson. "Institutions and Organizations in Systems of Innovation." Chapter 2 in *Systems of Innovation: Technologies, Institutions and Organizations*, edited by C. Edquist. London: Pinter Publishers, 1997.

Eicher, C.K., "Building African Scientific Capacity for Agricultural Development." *Agricultural Economics* Vol. 4, No. 2 (June 1990): 117–14.

Eisemon, T. O., C.H. Davis, and E.M. Rathgeber. "Transplantation of Science to Anglophone and Francophone Africa." S*cience and Public Policy* Vol. 12, No. 4 (August 1985): 191–202.

Enos, J. "A Measure of the Rate of Technological Progress in the Petroleum Refining Industry." *Journal of Industrial Economics* (June 1958).

Evenson, R.E. "The Contribution of Agricultural Research and Extension to Agricultural Production." Unpublished Ph.D. Thesis, University of Chicago, Chicago, 1968.

Evenson, R.E. "Economic Impacts of Agricultural Research and Extension." Chapter 12 in *Handbook of Agricultural Economics*, edited by B.L. Gardner and G.C. Rausser. Amsterdam: North Holland/Elsevier, 2001.

Evenson, R.E. and Y. Kislev. “Investment in Agricultural Research and Extension: A Survey of International Data.” *Economic Development and Cultural Change* Vol. 23 (1975): 507–21.

Evenson, R.E., and Y. Kislev. “A Stochastic Model of Applied Research.” *Journal of Political Economy* Vol. 84, No.2 (1976): 265–82.

Evenson, R.E., P. Wagonner, and V.W. Ruttan. "Economic Benefits from Research: An Example from Agriculture." *Science* Vol. 205 (14 September 1979): 1101–07.

Fabricant, S. *Basic Facts on Productivity Change*. Occasional Paper No. 63. New York: National Bureau of Economic Research, 1959.

Falck-Zepeda, J.B., G. Traxler, and R.G. Nelson. *Rent Creation and Distribution from the First Three Years of Planting Bt Cotton*. ISAAA Briefs No.13. Ithaca, NY: International Service for the Acquisition of Agri-biotech Applications, 1999.

Falconi, C.A. *Public and Private-Sector Interactions in Agricultural Research in Less-Developed Countries: The Case of Ecuador.* ISNAR Discussion Paper 92–13. The Hague: International Service for National Agricultural Research, 1992.

Falconi, C.A. *Public and Private-Sector Interactions in Agricultural Research in Less-Developed Countries: The Case of Colombia*. ISNAR Discussion Paper 93–14. The Hague: International Service for National Agricultural Research, 1993.

Fan. S., and P.G. Pardey. *Agricultural Research in China: Its Institutional Development and Impact*. The Hague: International Service for National Agricultural Research, 1992.

FAO. AGROSTAT diskettes. Rome: Food and Agriculture Organization of the United Nations, 1997.

FAO. *Les Systèmes Nationaux de Recherche Agronomique dans les Pays de l’Afrique Occidentale et Centrale*. Rome: Food and Agriculture Organization of the United Nations, 1993.

FAO. *Funding Agricultural Research in sub-Saharan Africa.* Proceedings of an FAO/SPAAR/KARI Expert Consultation held at Nairobi, Kenya, July 6–8, 1993. Rome: Food and Agriculture Organization of the United Nations, 1994.

Fellner, W. “Empirical Support for the Theory of Induced Innovation.” *Quarterly Journal of Economics* Vol. 85 (1971): 580–604.

Findlay, C.C. and R.L. Jones. “The Marginal Cost of Australian Income Taxation.” *Economic Record* Vol. 58 (1982): 253–66.

Fox, G. “Is the United States Really Underinvesting in Agricultural Research?” *American Journal of Agricultural Economics* Vol. 67, No. 4 (November 1985): 806–12.

Freeman, C., and L. Soete. *The Economics of Industrial Innovation.* Third Edition. London and Washington, DC: Pinter, 1999.

Fuglie, K., N. Ballenger, K. Day, C. Klotz, M. Ollinger, J. Reilly, U. Vasavada, and J. Yee *Agricultural Research and Development: Public and Private Investments under Alternative Markets and Institutions*. Agricultural Economic Report No. 735. Washington, DC: Economic Research Service, US Department of Agriculture, 1996.

Fullerton, D. "Reconciling Recent Estimates of the Marginal Welfare Cost of Taxation." *American Economic Review* Vol. 81, No.1 (March 1991): 302–08.

Fullerton, D., and Y. Henderson. "The Marginal Excess Burden of Different Capital Tax Instruments." *Review of Economics and Statistics* (August 1989).

Gardner, B.L. *Price Supports and Optimal Spending on Agricultural Research*. Seminar Paper 89–02. Adelaide, Australia: Centre for International Economic Studies, University of Adelaide, 1990.

Geroski, P.A. "Models of Technology Diffusion." *Research Policy* Vol. 29, No. 4–5 (2000): 603–25.

Gittinger, J.P. *Economic Analysis of Agricultural Projects*. Second Edition. Baltimore and London: The Johns Hopkins University Press, 1982.

Gomulka, S. *The Theory of Technological Change and Economic Growth*. London and New York: Routledge, 1990.

Goto, A., and K. Suzuki. "R&D Capital, Rate of Return on R&D Investment and Spillover of R&D in Japanese Manufacturing Industries." *Review of Economics and Statistics* Vol. LXXI, No.4 (1989): 555–64.

Greig, I.D. *Research Management: Probabilistic Ex-Ante Evaluation of Two Broiler Research Proposals.* Agricultural Economics Bulletin No. 23. Armidale: University of New England, 1979.

Greig, I.D. "Agricultural Research Management and the Ex Ante Evaluation of Research Proposals: A Review." *Review of Marketing and Agricultural Economics* Vol. 49, No. 2 (August 1981): 73–94.

Griliches, Z. "Hybrid Corn: An Exploration in the Economics of Technical Change." *Econometrica* Vol. 48 (1957): 501–22.

Griliches, Z. "Research Costs and Social Returns: Hybrid Corn and Related Innovations." *Journal of Political Economy* Vol. LXVI (1958): 419–31.

Griliches, Z. "Research Expenditures and Growth Accounting." In *Science and Technology in Economic Growth*, edited by B.R. Williams. London: McMillan Press, 1973.

Griliches, Z. "Issues in Assessing the Contribution of Research and Development to Productivity Growth." *The Bell Journal of Economics* Vol. 10, No. 1 (Spring 1979): 92–116.

Griliches, Z. “R&D and Productivity: Econometric Results and Measurement Issues.” Chapter 3 in *Handbook of the Economics of Innovation and Technological Change*, edited by P. Stoneman. Oxford, UK and Cambridge, MA, USA: Blackwell, 1995.

Griliches, Z., and F. Lichtenberg. “Interindustry Technology Flows and Productivity Growth: A Re-Examination.” *Review of Economics and Statistics* Vol. 66, No. 2 (1984): 325–29.

Grootaert, C. *Social Capital: The Missing Link?* Social Capital Initiative Working Paper No. 3. Washington, DC: The World Bank, April 1998.

Grossman, G.M., and E. Helpman. *Innovation and Growth in the Global Economy.* Cambridge, MA, USA: MIT Press, 1991.

Gryseels, G., and J.R. Anderson. “International Agricultural Research. Chapter 9 in *Agricultural Research Policy: International Quantitative Perspectives*, edited by P.G. Pardey, J. Roseboom, and J.R. Anderson. Cambridge, UK: Cambridge University Press, 1991.

Hall, R.E., and C.I. Jones. *Why Do Some Countries Produce So Much More Output per Worker than Others?* Version 4.0. NBER Working Paper No.w6564, March 1998.

Hayami, Y., and V.W. Ruttan. *Agricultural Development: An International Perspective.* Baltimore and London: The Johns Hopkins University Press, 1971.

Hayami, Y., and V.W. Ruttan. *Agricultural Development: An International Perspective.* Revised Edition. Baltimore and London: The Johns Hopkins University Press, 1985.

Hazell, P.B.R., and C. Ramasamy. *The Green Revolution Reconsidered: The Impact of the High-Yielding Rice Varieties in South India*. Baltimore and London: The Johns Hopkins University Press, 1991.

Heston, A., R. Summers, D.A. Nuxoll, and B. Aten. *The Penn World Tables Mark 5.6 Electronic Dataset*. Philadelphia: University of Pennsylvania, 1995.

Hicks, J.R. *The Theory of Wages.* New York: McMillan, 1932.

Huffman, W.E., and R.E. Evenson. “Supply and Demand Functions for Multiproduct U.S. Cash Grain Farms: Biases Caused by Research and Other Policies.” *American Journal of Agricultural Economics* Vol. 71, No. 3 (August 1989): 761–73.

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

Huffman, W.E., and R.E. Just. “Funding, Structure, and Management of Public Agricultural Research in the United States.” *American Journal of Agricultural Economics* Vol. 76 (1994): 744–59.

Hussey, D. “Public Funding of Agricultural R&D – Policy Trends and Implications for Research Evaluation.” In *Economic Evaluation of Agricultural Research in Australia and New Zealand*, edited by J.P. Brennan and J.S. Davis. ACIAR

Monograph No. 39. Canberra: Australian Centre for International Agricultural Research, 1996.

Idachaba, F.S. *Instability of National Agricultural Research Systems in sub-Saharan Africa: Lessons from Nigeria*. ISNAR Research Report No. 13. The Hague: International Service for National Agricultural Research, 1998.

ILO. *International Standard Classification of Occupations: ISCO-88*. Geneva: International Labor Organization, 1990.

Jacobsen, V., and G.M. Scobie. "Agricultural R&D Policy in New Zealand." In *Paying for Agricultural Productivity: Financing Agricultural R&D in Rich Countries*, edited by J.M. Alston, P.G. Pardey, and V.H. Smith. Baltimore and London: The Johns Hopkins University Press, 1999.

Jaffe, A. "Technological Opportunity and Spillovers of R&D: Evidence from Firm's Patents, Profits and Market Value." *American Economic Review* Vol. 75, No. 6 (1986): 984–1002.

Jamieson, B.G. "Present Structures of the Agricultural and Food Research Council." *Journal of Agricultural Science, Cambridge* Vol.113 (1989): 127–30.

Janvry, A. de. "Inducement of Technological and Institutional Innovations: An Interpretative Framework." In *Resource Allocation and Productivity in National and International Agricultural Research*, edited by T.M. Arndt, D.G. Dalrymple, and V.W. Ruttan. Minneapolis: University of Minnesota Press, 1977.

Janvry, A. de, and J.J. Dethier. *Technological Innovation in Agriculture: The Political Economy of Its Rate and Bias*. CGIAR Study Paper No.1. Washington, DC: World Bank, 1985.

Janvry, A. de, E. Sadoulet, and M. Fafchamps. "Agrarian Structure, Technological Innovations, and the State." Chapter 18 in *The Economic Theory of Agrarian Institutions*, edited by P. Bardhan. Oxford, UK: Clarendon Press, 1989.

Johnson, B. "Systems of Innovation: An Overview and Basic Concepts." Introduction to Part I in *Systems of Innovation: Technologies, Institutions and Organizations*, edited by C. Edquist. London: Pinter Publishers, 1997.

Jones, C.I. "R&D-Based Models of Economic Growth." *Journal of Political Economy* Vol. 103 (1995): 759–84.

Jones, C.I. *Sources of U.S. Economic Growth in a World of Ideas.* SIEPR Discussion Paper No. 99–29. Stanford, CA, USA: Stanford University, July 2000.

Jorgenson, D.W., and Z. Griliches. "The Explanation of Productivity Change." *Review of Economic Studies* Vol. 34, No. 99 (1967): 249–83.

Judd, M.A., J.K. Boyce, and R.E. Evenson. *Investing in Agricultural Supply*. Economic Growth Center Discussion Paper No. 422. New Haven, CN, USA: Economic Growth Center, Yale University, 1983.

Judd, M.A., J.K. Boyce, and R.E. Evenson. "Investing in Agricultural Supply: The Determinants of Agricultural Research and Extension Investments." *Economic Development and Cultural Change* Vol. 35, No. 1 (October 1986): 77–113.

Just, R.E., and W.E. Huffman. "Economic Principles and Incentives: Structure, Management and Funding of Agricultural Research in the United States." *American Journal of Agricultural Economics* Vol. 74, No. 5 (1992): 1101–08.

Kassapu, S. *Les Dépenses de Recherche Agricole dans 34 Pays d'Afrique Tropicale*. Paris: Centre de Développement de l'OCDE, 1976.

Kaul, M. "The New Public Administration Management Innovations in Government." *Public Administration and Development* Vol. 17, No.1 (1997): 13–26.

Kendrick, J.W. *Productivity Trends in the United States*. Princeton, NJ, USA: Princeton University Press, 1961.

Kennedy, C. "Induced Bias in Innovation and the Theory of Distribution." *The Economic Journal* Vol. 74 (1966): 541–47.

Kravis, I.B., A. Heston, and R. Summers. *World Product and Income: International Comparisons of Real Gross Product.* United Nations International Comparisons Project: Phase II. Baltimore and London: The Johns Hopkins University Press, 1982.

Krugman, P. "What Economists Can Learn from Evolutionary Theorists." Talk given to the European Association for Evolutionary Political Economy, November 1996. <http:/web.mit.edu.krugman/www/evolute.html> [accessed 30/11/00]

Lele, U.J., B.H. Kinsay, and A.O. Obeya. "Building Agricultural Research Capacity in Africa: Policy Lessons for the MADIA Countries." Paper prepared for the joint TAC/CGIAR Centers Directors Meeting, Rome, June 1989. Mimeo.

Lipton, M.L., "The Place of Agricultural Research in the Development of sub-Saharan Africa." *World Development* Vol. 16, No. 10 (October 1988): 1231–57.

Lipton, M.L., and R. Longhurst. *New Seeds and Poor People*. Baltimore and London: The Johns Hopkins University Press, 1989.

Lucas, R.E. "On the Mechanics of Economic Development." *Journal of Monetary Economics* Vol. 22 (1988): 3–42.

Lundvall, B.-Å. *National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning.* London: Pinter Publishers, 1992.

Lundvall, B.-Å. "National Systems of Innovation and Input-Output Analysis." Chapter 23 in *Economic Interdependence and Innovative Activity,* edited by C. DeBresson. Cheltenham: Edward Elgar, 1996.

MacDonald, A.S. "Exchange Rates for National Expenditure on Research and Development." *Economic Journal* Vol. 83 (June 1973): 477–94.

Machlup, F. “The Supply of Inventors and Inventions.” In *The Rate and Direction of Inventive Activity: Economic and Social Factors*, edited by R.R. Nelson. Princeton, NJ, USA: NBER, Princeton University Press, 1962.

Mansfield, E., J. Rapoport, A. Romeo, S. Wagner, and G. Beardsley. “Social and Private Rates of Return from Industrial Innovations.” *Quarterly Journal of Economics* Vol. XCI (May 1977): 221–40.

Maredia, M.K., and D. Byerlee. “Determining the Efficiency of Research in the Presence of International Spillovers: Wheat Research in Developing Countries.” In *Efficiency of Investment in National and International Wheat Improvement Research*, edited by M. Maredia and D. Byerlee. Mexico City: Centro Internacional de Mejoramiento de Maíz y Trigo, 1997.

Maredia, M., D. Beyerlee, and J. Anderson. “Ex Post Evaluation of Economic Impacts of Agricultural Research Programs: A Tour of Good Practice.” Paper presented to the Workshop on The Future of Impact Assessment in the CGIAR: Needs, Constraints, and Options, Rome, May 2000.

Martin, B.R., and P. Nightingale, eds. *The Political Economy of Science, Technology and Innovation.* The International Library of Critical Writings in Economics No. 116. Cheltenham, UK: Edward Elgar Publishing Ltd, 2000.

Meer, C.L.J. van der, H.J. Rutten, and N.A. Dijkveld Stol. *Technologiebeleid in de Landbouw: Effecten in het Verleden en Beleidsoverwegingen voor de Toekomst*. The Hague: Wetenschappelijke Raad voor het Regeringsbeleid, 1991.

Mergen, F., R.E. Evenson, M.A. Judd, and J. Putnam. “Forestry Research: A Provisional Global Inventory.” *Economic Development and Cultural Change* Vol. 37 (1988): 149–71.

Metcalfe, S. “The Economic Foundations of Technology Policy: Equilibrium and Evolutionary Perspectives.” Chapter 11 in *Handbook of the Economics of Innovation and Technological Change*, edited by P. Stoneman. Oxford, UK and Cambridge, MA, USA: Blackwell, 1995.

Mills, F.C. *Productivity and Economic Progress*. Occasional Paper No. 38. New York: National Bureau of Economic Research, 1952.

Ministerie van Landbouw, Natuurbeheer, en Visserij. *LNV-Kennisbeleid tot 1999*. The Hague: Ministerie van Landbouw, Natuurbeheer, en Visserij, 1996.

Mohnen, P.A., and N. Lepine. *Payments for Technology as a Factor of Production*. Working Paper No. 8818. Montreal: University of Montreal, 1988.

Moschini, G., and H. Lapan. “Intellectual Property Rights and the Welfare Effects of Agricultural R&D.” *American Journal of Agricultural Economics* Vol. 79, No. 4 (November 1997): 1229–42.

Moschini, G., H. Lapan, and A. Sobolevsky. *Roundup Ready ® Soybeans and Welfare Effects in the Soybean Complex.* Staff Paper No. 324. Ames, IA, USA: Department of Economics, Iowa State University, September 1999.

Mountfield, R. "Organizational Reform within Government: Accountability and Policy Management." *Public Administration and Development* Vol. 17, No. 1 (1997): 71–76.

Mowery, D., and N. Rosenberg. "The Influence of Market Demand upon Innovation: A Critical Review of Some Recent Empirical Studies" *Research Policy* Vol. 8 (1979): 103–53.

Mullen, J.D., K. Lee, and S. Wrigley. "Financing Agricultural Research in Australia: 1953–1994." In *Economic Evaluation of Agricultural Research in Australia and New Zealand*, edited by J.P. Brennan and J.S. Davis. ACIAR Monograph No. 39, Canberra, Australia: Australian Centre for International Agricultural Research, 1996.

Mundlak, Y. *Agriculture and Economic Growth: Theory and Measurement.* Cambridge, MA, USA: Harvard University Press, 2000.

Nelson, R.R., ed. *National Innovation Systems: A Comparative Analysis*. Oxford, UK and New York: Oxford University Press, 1993.

Nelson, R.R., and B.N. Sampat. "Making Sense of Institutions as a Factor Shaping Economic Performance." *Journal of Economic Behavior & Organization* Vol. 22, No. 1 (2001): 31–54.

Nelson, R.R., and S.G. Winter. "Towards an Evolutionary Theory of Economic Capabilities." *American Economic Review* Vol. 63 (1973): 440–9.

Nelson, R.R., and S.G. Winter. *An Evolutionary Theory of Economic Change.* Cambridge, MA, USA and London: Harvard University Press, 1982.

Nordhaus, W. *Invention, Growth and Welfare.* Cambridge, MA, USA: MIT Press, 1969.

Nordhaus, W.D. "Traditional Productivity Estimates Are Asleep at the (Technological) Switch." *The Economic Journal* Vol. 107 (September 1997): 1548–59.

Norton, G.W., and J.S. Davis. "Evaluating Returns to Agricultural Research: A Review." *American Journal of Agricultural Economics* Vol. 63, No. 4 (November 1981): 685–99.

North, D.C., and R.P. Thomas. *The Rise of the Western World: A New Economic History*. Cambridge, UK: Cambridge University Press, 1973.

North, D.C. *Institutions, Institutional Change and Economic Performance*. Cambridge, UK: Cambridge University Press, 1990.

North, D.C., and J.J. Wallis. "Integrating Institutional Change and Technical Change in Economic History: A Transactions Cost Approach." *Journal of Institutional and Theoretical Economics* Vol. 150, No.4 (1994): 609–24.

NRLO. *Wageningen in Profiel – Landbouwwetenschappen in 2010: De Positie van de LUW.* The Hague/Amsterdam: National Council for Agricultural Research/Overleg Commissie Verkenningen (NRLO/OCV), 1996.

OECD. *Proposed Standard Practice for Surveys of Research and Experimental Development: "Frascati Manual 1980."* The Measurement of Scientific and Technical Activities Series. Paris: Organisation for Economic Co-operation and Development, 1981.

OECD. *The Role of the Public Sector.* OECD Economic Studies No. 4. Paris: Organisation for Economic Co-Operation and Development, 1985.

OECD. *Development Cooperation in the 1990s – Efforts and policies of the Members of the Development Assistance Committee*. Paris: Organisation for Economic Co-operation and Development, 1989.

OECD. *Proposed Standard Practice for Surveys of Research and Experimental Development: "Frascati Manual 1993."* The Measurement of Scientific and Technological Activities Series. Paris: Organisation for Economic Co-operation and Development, 1994.

OECD. "Country Note – England & Wales." Paper prepared for the Joint Conference of Directors and Representatives of the Agricultural Research, Agricultural Advisory Services and Higher Education in Agriculture, Organisation for Economic Co-operation and Development, Paris, 1995. Mimeo.

Oehmke, J.F. "Persistent Underinvestment in Public Agricultural Research." *Agricultural Economics* Vol. 1, No. 1 (1986): 53–65.

Office of Management and Budget. *Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs*. OMB Circular A-94, Revised (Transmittal Memo No. 64). Washington, DC: Office of Management and Budget, The White House, 1992. <http://www.whitehouse.gov/omb/circulars/a094/a094.html>

Olson, M. *The Rise and Decline of Nations.* New Haven, CN, USA: Yale University Press, 1982.

Olson, M. "Big Bills Left on the Sidewalk: Why Some Nations are Rich, and Others Poor." *Journal of Economic Perspectives* Vol. 10, No 2 (Spring 1996): 3–24.

Oram, P.A., and V. Bindlish. *Resource Allocations to National Agricultural Research: Trends in the 1970s.* The Hague: International Service for National Agricultural Research and Washington, DC: International Food Policy Research Institute, 1981.

Oskam, A. "Productivity Measurement, Incorporating Environmental Effects of Agricultural Production." In *Agricultural Economics and Policy: International Challenges for the Nineties*, edited by K. Burger *et al*. Amsterdam: Elsevier, 1991.

Pardey, P.G. "Public Sector Production in Agricultural Knowledge." PhD thesis, University of Minnesota, 1986.

Pardey, P.G., and B. Craig. "Causal Relationship between Public Sector Agricultural Research Expenditures and Output." *American Journal of Agricultural Economics* Vol. 71, No.1 (February 1989): 9–19.

Pardey, P.G., and J. Roseboom. *ISNAR Agricultural Research Indicator Series: A Global Database on National Agricultural Research Systems.* Cambridge, UK: Cambridge University Press, 1989.

Pardey, P.G., W.M. Eveleens, and M.L. Hallaway. *A Statistical History of US Agricultural Research: 1889 to 1991*. St. Paul, MN, USA: Center for International Food and Agricultural Policy, University of Minnesota, 1991.

Pardey, P.G., M.S. Kang, and H. Elliott. "Structure of Public Support for National Agricultural Research Systems: A Political Economy Perspective." *Agricultural Economics* Vol. 3, No. 4 (December 1989): 261–78.

Pardey, P.G., J. Roseboom, and J.R. Anderson, eds. *Agricultural Research Policy: International Quantitative Perspectives*. Cambridge, UK: Cambridge University Press, 1991a.

Pardey, P.G., J. Roseboom, and J.R. Anderson. "Regional Perspectives on National Agricultural Research." Chapter 7 in *Agricultural Research Policy: International Quantitative Perspectives,* edited by P.G. Pardey, J. Roseboom, and J.R. Anderson. Cambridge, UK: Cambridge University Press, 1991b.

Pardey, P.G., J. Roseboom, and J.R. Anderson. "Topical Perspectives on National Agricultural Research." Chapter 8 in *Agricultural Research Policy: International Quantitative Perspectives,* edited by P.G. Pardey, J. Roseboom, and J.R. Anderson. Cambridge, UK: Cambridge University Press, 1991c.

Pardey, P.G., J. Roseboom, and N.M. Beintema. *African Agricultural Research: Three Decades of Development*. ISNAR Briefing Paper No. 19. The Hague: International Service for National Agricultural Research, January 1995.

Pardey, P.G., J. Roseboom, and N.M. Beintema. "Investments in African Agricultural Research." *World Development* Vol. 25, No. 3 (March 1997): 409–23.

Pardey, P.G., J. Roseboom, and B.J. Craig. "A Yardstick for International Comparisons: An Application to National Agricultural Research Expenditures." *Economic Development and Cultural Change* Vol. 40, No. 2 (January 1992): 333–49.

Pardey, P.G., J. Roseboom, and B.J. Craig. "Agricultural R&D Investments and Impacts." In *Paying for Agricultural Productivity*, edited by J.M. Alston, P.G. Pardey, and V. Smith. Baltimore and London: The Johns Hopkins University Press, 1997.

Pardey, P.G., J.M. Alston, J.E. Christian, and S. Fan. *Hidden Harvest: US Benefits from International Research Aid*. Food Policy Report. Washington, DC: International Food Policy Research Institute, 1996.

Pardey, P.G., J.M. Alston, J.E. Christian, and S. Fan. "A Productive Partnership: The Benefits from US Participation in the CGIAR." Unpublished draft report. International Food Policy Research Institute, Washington, DC, 1997.

Pardey, P.G., J. Roseboom, N.M. Beintema, and C. Chan-Kang. *Cost Aspects of African Agricultural Research*. EPTD Discussion Paper No. 42. Washington, DC: International Food Policy Research Institute, 1998.

Pasour, E.C., Jr., and M.A. Johnson. "Bureaucratic Productivity: The Case of Agricultural Research Revisited." *Public Choice* Vol. 39 (1982): 301–17.

Peper, B. *Duurzame Kennis, Duurzame Landbouw; Een Advies aan de Minister van LNV over de Kennisinfrastructuur van de Landbouw in 2010*. The Hague: Ministerie van Landbouw, Natuurbeheer, and Visserij, 1996.

Persley, G.J. *Beyond Mendel's Garden: Biotechnology in the Service of World Agriculture*. Wallingford, UK: CAB International, 1990.

Piñeiro, M., and E. Trígo, eds. Cambio Técnico en al Agro Latino Americano – Situación y Perspectivas en la Década de 1980. San José: Instituto Interamericano de Cooperación para la Agricultura, 1983.

Pingali, P.L. "Technological Prospects for Reversing the Declining Trend in Asia's Rice Productivity." Chapter 21 in *Agricultural Technology Policy: Issues for the International Community*, edited by J.R. Anderson. Wallingford, UK: CAB International, 1994.

Pinstrup-Andersen, P. *Agricultural Research and Technology in Economic Development*. New York: Longman, 1982.

Pinstrup-Andersen, P. "Is Research a Global Public Good?" *Agriculture and Rural Development* Vol. 8, No.1 (2001): 3–5.

Pottelsberghe de la Potterie, B. van. "Issues in Assessing the Effect of Interindustry R&D Spillovers." *Economic Systems Research* Vol. 9, No. 4 (1997): 331–56.

Pray, C.E., and R.G. Echeverría. "Private-Sector Agricultural Research in Less-Developed Countries." Chapter 10 in *Agricultural Research Policy: International Quantitative Perspectives*, edited by P.G. Pardey, J. Roseboom and J.R. Anderson. Cambridge, UK: Cambridge University Press, 1991.

Pray, C.E., and C.F. Neumeyer. "Impact of Technology Policy on Research in the Agricultural Input Industries." Paper presented at the American Agricultural Economics Association Meetings, Baton Rouge, Los Angeles, 1989.

Pray, C.E., and D. Umali-Deininger. "Private Agricultural Research: Will It Fill the gap?" *World Development* Vol. 26, No. 6 (1998): 1127–48.

Putnam, R. "The Prosperous Community: Social Capital and Public Life." *American Prospect* Vol. 13 (1993): 35–42.

Radner, R. "A Behavioral Model of Cost Reduction." *The Bell Journal of Economics* Vol. 6, No.1 (Spring 1975): 196–215.

Radford, J. "Research Evaluation in New Zealand." In *Economic Evaluation of Agricultural Research in Australia ad New Zealand*, edited by J.P. Brennan and J.S. Davis. ACIAR Monograph No. 39. Canberra, Australia: Australian Centre for International Agricultural Research, 1996.

Robinson, D. "Civil Service Remuneration in Africa." *International Labour Review* Vol. 129, No. 3 (1990): 371–86.

Roe, T.L., and P.G. Pardey. "Economic Policy and Investment in Rural Public Goods: A Political Economy Perspective." Chapter 1 in *Agricultural Research Policy: International Quantitative Perspective*, edited by P.G. Pardey, J. Roseboom, and J.R. Anderson. Cambridge, UK: Cambridge University Press, 1991.

Romer, P.M. "Increasing Returns and Long-Run Growth." *Journal of Political Economy* Vol. 91, No.5 (1986): 1002–37.

Romer, P.M. "Endogenous Technological Change." *Journal of Political Economy* Vol. 98, No. 5 (October 1990): S71–S102.

Romer, P. "It's All in Your Head." *Outlook Magazine* (June 1998).

Roseboom, J. *Sources of Technological Innovation in Brazilian Agriculture.* ISNAR Discussion Paper No. 99–12. The Hague: International Service for National Agricultural Research, December 1999.

Roseboom, J. "Technological Innovation in Agriculture: The Contribution of Agricultural Input Industries." Poster presentation at the International Association of Agricultural Economists conference in Berlin, 13–18 August 2000.

Roseboom J., and H. Rutten. "Financing Agricultural Research in the Netherlands: The Changing Role of Government." Paper prepared for the Office of Technology Assessment, Washington, DC, 1995.

Roseboom, J., and H. Rutten. "Financing Agricultural Research in the Netherlands: The Changing Role of Government. In *Conference Proceedings of the Global Agricultural Science Policy for the Twenty-First Century Conference.* Melbourne: Conference Secretariat, 1996.

Roseboom, J., and H. Rutten. "The Transformation of the Dutch Agricultural Research System: An Unfinished Agenda. Paper presented at the 51st EAAE Seminar on Innovation for Innovation, the Organization of Innovation Processes in Agriculture, Zandvoort, The Netherlands, 1997.

Roseboom, J., and H. Rutten. "The Transformation of the Dutch Agricultural Research System: An Unfinished Agenda." *World Development* Vol. 26, No. 6 (June 1998): 1113–126.

Rosenberg, N. *Inside the Black Box: Technology and Economics.* Cambridge, UK: Cambridge University Press, 1982.

Ruttan, V.W. “Induced Institutional Change.” Chapter 12 in *Induced Innovation: Technology, Institutions and Development*, edited by H.P. Binswanger and V.W. Ruttan. Baltimore and London: The Johns Hopkins University Press, 1978.

Ruttan, V.W. “Bureaucratic Productivity: The Case of Agricultural Research.” *Public Choice* Vol. 35 (1980): 529–47.

Ruttan, V.W. “Bureaucratic Productivity: The Case of Agricultural Research – A Rejoinder.” *Public Choice* Vol. 39 (1982): 319–29.

Ruttan, V.W. “Induced Innovation, Evolutionary Theory and Path Dependence: Sources of Technical Change.” *The Economic Journal* Vol. 107 (September 1997): 1520–29.

Ruttan, V.W. *Technology, Growth, and Development: An Induced Innovation Perspective*. New York and Oxford: Oxford University Press, 2001.

Rutten, H. *Productivity Growth of Dutch Agriculture*, 1949–1989. Mededeling 470. The Hague: Landbouw-Economisch Instituut, 1992.

Scherer, F.M. “Inter-Industry Technology Flows in the United States.” *Research Policy* Vol. 11, No. 4 (1982): 227–45.

Schmookler, J. “The Changing Efficiency of the American Economy, 1869–1938.” *Review of Economics and Statistics* Vol. 34, No. 3 (August 1952): 214–31.

Schumpeter, J. “The Instability of Capitalism.” *Economic Journal* Vol. XXXVIII, No. 151 (September 1928): 361–86.

Schumpeter, J.A. *The Theory of Economic Development.* Cambridge, MA, USA: Harvard University Press, 1934.

Schumpeter, J.A. *Capitalism, Socialism and Democracy*. New York: Harper & Brothers, 1942.

Shapiro, C. “Patent Licensing and R&D Rivalry.” *American Economic Review* Vol. 75 (1985): 25–30.

Solow, R.M. “A Contribution to the Theory of Economic Growth.” *Quarterly Journal of Economics* Vol. 70 (February 1956): 65–94.

Solow, R.M. “Technical Change and the Aggregate Production Function.” *Review of Economics and Statistics* Vol. 39 (August 1957): 312–20.

Solow, R.M. “Technical Progress, Capital Formation, and Economic Growth.” *American Economic Review* Vol. 52, No. 2 (1962): 76–86.

Sprow, F.B. “Evaluation of Research Expenditures Using Triangular Distribution Functions and Monte Carlo Methods.” *Industrial and Engineering Chemistry* Vol. 59, No. 7 (July 1967): 35–38.

Stoneman, P., ed. *Handbook of the Economics of Innovation and Technological Change.* Oxford, UK and Cambridge, MA, USA: Blackwell, 1995.

Summers, R., and A. Heston. "A New Set of International Comparisons of Real Product and Price Levels Estimates for 130 Countries, 1950–1985." *Review of Income and Wealth* Series 34, No. 1 (March 1988): 1–25.

Summers, R., and A. Heston. "The Penn World Table (Mark 5): An Expanded Set of International Comparisons, 1950–1988." *Quarterly Journal of Economics* Vol. 106, No. 2 (May 1991): 327–68.

Sveikauskas, L. *The Impact of R&D on Productivity Growth.* BLS Bulletin No. 2331. Washington, DC: Government Publishing Office, 1981.

Swan, T.W. "Economic Growth and Capital Accumulation." *Economic Record* Vol. 32, No. 2 (1956): 334–61.

TAC/Center Directors Working Group. *The Ecoregional Approach to Research in the CGIAR.* Rome: TAC Secretariat, Food and Agriculture Organization of the United Nations, 1993.

Taylor, A., G. Boukambou, M. Dahniya, B. Ouayogode, R. Ayling, M.A. Noor, and M. Tour. *Strengthening National Agricultural Research Systems in the Humid and Sub-Humid Zones of West and Central Africa.* Technical Paper No. 318. Washington, DC: World Bank, 1996.

Technical Advisory Committee/CGIAR. *CGIAR Priorities and Future Strategies*. Rome: TAC/CGIAR/ Food and Agriculture Organization of the United Nations, 1987.

Terleckyj, N.E. *Effects of R&D on the Productivity Growth of Industries: An Exploratory Study*. Washington, DC: National Planning Association, 1974.

Terleckyj, N.E. "Direct and Indirect Effects of Industrial Research and Development on the Productivity Growth of Industries." Chapter 6 in *New Developments in Productivity Measurement and Analysis*, edited by J.W. Kendrick and B.N. Vaccara. NBER Studies in Income and Wealth No. 44. Chicago and London: The University of Chicago Press, 1980.

Thirtle, C.G. *A Summary of Arguments for and against the Public Provision of Agricultural R&D*. Manchester Working Papers in Agricultural Economics No. 2. Manchester, UK: Department of Agricultural Economics, University of Manchester, 1986.

Thirtle, C.G. *Agricultural Research, Development and Extension Expenditure in the United Kingdom, 1947–1993*. EPARD Working Paper No.14. Reading, UK: University of Reading, 1989.

Thirtle, C., and R.G. Echeverría. "Privatization and the Roles of Public and Private Institutions in Agricultural Research in sub-Saharan Africa," *Food Policy*, Vol.19, No.1 (1994): 31–44.

Thirtle, C.G., and V.W. Ruttan. *The Role of Demand and Supply in the Generation and Diffusion of Technical Change.* London: Harwood Academic Publishers, 1987.

Thirtle, C., J. Piesse, and V.H. Smith. "Agricultural R&D and Technology in the United Kingdom." Paper prepared for the Office of Technology Assessment, Washington, DC, 1995.

Thirtle, C.G., H.S. Beck, P. Palladino, M. Upton, and W.S. Wise. "Agriculture and Food." In *Science and Technology in the United Kingdom,* edited by R. Nicholson, P. Cunningham, and P. Gummett. London: Longmans, 1991.

Tribe, D.E. *Doing Well by Doing Good*. Leichardt, NSW: Pluto Press Australia Ltd (in association with the Crawford Fund for International Agricultural Research), 1991.

UNESCO. *International Standard Classification of Education.* Paris: United Nations Educational, Scientific and Cultural Organization – Division of Statistics on Education, Office of Statistics, 1976.

Usher, A.B. *A History of Mechanical Inventions*. Cambridge, MA, USA: Harvard University Press, 1954.

Vloten-Doting, L. van. "Fair Competition op de Markt voor Landbouwkundig Onderzoek." In *Sturing van Wetenschappelijk Onderzoek*, edited by F.J.M. Zwetsloot. The Hague: DELWEL Uitgeverij, 1997.

Weijenberg, J., M. Dagg, J. Kampen, M. Kalunda, A.M. Mailu, S. Ketema, L. Navarro, and M.A. Noor. *Strengthening National Agricultural Research Systems in Eastern and Central Africa.* Technical Paper No. 290. Washington, DC: World Bank, 1995.

Wicksteed, P.H. *An Essay on the Co-Ordination of the Laws of Distribution*. Series of Reprints of Scarce Tracts in Economic and Political Science No. 12. London: London School of Economics, 1932. First published in 1894.

Wilson, V.S. "Public Administration Reform and the 'New Managerialism': A Comparative Assessment of a Fundamental Challenge Confronting Canadian Public Administration." *International Journal of Public Administration* Vol. 19, No. 9 (1996): 1509–53.

World Bank. *World Tables*. Washington, DC: World Bank, various years.

World Bank. *Agricultural Research – Sector Policy Paper*. Washington, DC: World Bank, 1981.

World Bank. *Methodological Problems and Proposals Relating to the Estimation of Internationally Comparable per Capita GNP Figures*. Washington, DC: Economic Analysis and Projections Department, World Bank, 1983.

World Bank. *World Development Report 1985*. New York: Oxford University Press, 1985.

World Bank. *World Tables*. Diskette version. Washington, DC: World Bank, 1995a.

World Bank. *African Development Indicators 1994–95*. Washington, DC: World Bank, 1995b.

World Bank. *World Development Report: Knowledge for Development.* New York: Oxford University Press, 1998.

Zerbe, R.O., and D.D. Devily. *Benefit-Cost Analysis in Theory and Practice.* New York: HarpinCollins College Publishers, 1994.

Annex A: The construction of agricultural R&D indicators

The Agricultural Science and Technology Indicators (ASTI) project, which has been the source of most of the statistics presented in part II of this dissertation, started as a spin-off from a major survey on national agricultural research systems in developing countries undertaken by the International Service for National Agricultural Research (ISNAR) in the mid-1980s.[1] The earliest work of the ASTI project focused on reconciling the new survey data with previous data collections on national agricultural investments, such as those by Boyce and Evenson (1975), Kassapu (1976), Piñeiro and Trigo (1983), Oram and Bindlish (1981), and Judd, Boyce, and Evenson (1983, 1986). Pardey and Roseboom (1989) reformatted, rescaled, and cleaned up these earlier data compilations and combined them with new data obtained from the survey, as well as from a large number of annual reports from agricultural research organizations, country reviews, and other publications. A major concern underpinning all this work was the weak comparability of the data over time and across countries. Building on the pioneering work by the Science and Technology Indicators Division of the OECD, better definitions and standard data collection and processing procedures were adopted. To the greatest extent possible, the ASTI project followed the OECD guidelines for surveys of R&D activity (also known as the *Frascati Manual* [OECD 1981, 1994]).[2]

This annex outlines some of the more general aspects of the data collection and construction of the agricultural R&D indicators reported in chapters 3-6, namely, (1) definitions and classification schemes, (2) the measurement of personnel and expenditures devoted to agricultural R&D, and (3) the comparability of expenditure data across countries and over time. This latter issue is of relevance to all international comparisons involving expenditure data.

A.1 *Definitions and classification schemes*

A major challenge in the construction of agricultural R&D indicators has been the need to find a compromise between the concept of a national agricultural research system (NARS), which bears all the hallmarks of an open or soft system with rather vaguely formed boundaries, and the statistical necessity for precise definitions and for boundaries that are sharp and stable.

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[1] Since 1995, the project has been implemented jointly with the International Food Policy Research Institute (IFPRI).

[2] The OECD also plays a coordinating role in the development of various other statistical guidelines for the measurement of certain aspects of science and technology, such as the technology balance of payments, innovation statistics (the Oslo manual), patents, and human resources for science and technology.

For statistical purposes, the ASTI project has adopted the following operational definitions of the three dimensions of a NARS (i.e., national, agricultural, and research):

(1) *National* research refers to research activities undertaken within the boundaries of a nation state and which target local production or societal issues. Research activities by international research agencies are excluded and treated separately.

(2) *Agricultural* research is research that directly targets primary agriculture and includes research on crops, livestock, forestry, fisheries, the use of agricultural inputs (but not research on the development of agricultural inputs other than those originating from within agriculture), natural resources, and socioeconomic aspects of primary agricultural production. Also included is research concerning the on-farm storage and processing of agricultural products. The off-farm component, however, should be attributed to the agricultural/food processing industry. The basic principle is to achieve congruency between R&D and production statistics, as our ultimate concern is how agricultural R&D affects agricultural production.

(3) *Research and experimental development (R&D*) comprise creative work undertaken on a systematic basis in order to increase the stock of knowledge, including knowledge of man, culture, and society, and the use of this stock of knowledge to devise new applications (OECD 1994). The basic criterion for distinguishing R&D from related activities is the presence in R&D of an appreciable element of novelty (OECD 1981). For instance, simply monitoring the incidence of plant and animal diseases in and of itself is not considered R&D and may only be undertaken to enforce quarantine regulations or the like. But, using this information to study the causes or control mechanisms associated with a particular disease is considered R&D.

R&D comprises a continuum of activities ranging from the search for new fundamental knowledge to its eventual application and use in daily life. The Frascati Manual (OECD 1994) distinguishes three principal R&D activities: *basic research*, *applied research*, and *experimental development*. The principal distinction between basic and applied research is the extent to which the research (i.e., the creation of new knowledge) is undertaken with a concrete application or use in mind. Experimental development distinguishes itself from research because it draws on existing knowledge gained from research and/or practical experience and focuses on producing new materials, products, or devices; installing new processes, systems, and services; or substantially improving those already produced or installed.[3]

[3] These definitions are not really exclusive and leave room for in-between categories such as strategic research (in between basic and applied) and adaptive research (in between applied research and experimental development). Moreover, experimental development gradually goes over into production, and it is at this end of the R&D spectrum that it can be rather difficult to establish the cutting-off point.

A national agricultural research system consists of various agencies, which jointly support agriculture by creating new knowledge and technology. The approach adopted by the ASTI project is to focus on performing agencies (rather than on funding agencies), which can, as suggested by the Frascati Manual, be classified in the following three institutional categories:

(1) Government agencies. This category includes all agencies that are controlled and mainly financed by the government. Agencies that are not directly controlled by the government, but which are mainly financed by the government, are also categorized as government agencies. Consequently, most national agricultural research organizations are classified as government agencies despite their "autonomous" status.

(2) Higher education agencies. This category includes all public and private universities, colleges of technology, and other institutes of higher education. Also included are all research institutes and experimental stations that are controlled directly by, administrated through, or associated with agencies of higher education.

(3) Business enterprises. This category comprises the following three subcategories: (3a) public enterprises, (3b) private enterprises, and (3c) nonprofit institutions. The first two subcategories cover all research activities undertaken within enterprises, while the third subcategory covers research activities undertaken on the collective behalf of business enterprises, which are controlled and mainly financed by these same business enterprises. Within agricultural research, this subcategory includes, for example, research activities controlled and mainly financed by commodity boards and farmer organizations. This category has sometimes also been labeled "private non-profit" or "semi-public."

In addition to the institutional classification, there is also the often-used distinction between public and private R&D, which can relate to the following: (a) the source of funding, (b) the status of the performing agency, or (c) the exertion of property rights regarding the new knowledge or technology generated. Depending on the perspective taken, the public-private picture can look quite different. Moreover, most R&D agencies tend to operate somewhere in between the public and private dichotomy. Table A.1 gives a rough indication of how funding sources tend to differ across different implementing agencies. .

Table A.1: *Sources of funding for agricultural R&D per institutional category*

Source of funding	Government agencies	Higher education	Business sector		
			Nonprofit agencies	Public enterprises	Private enterprises
General tax revenues	80%	80%	20%	30%	10%
Collective schemes	10%	5%	60%		
Private funds	10%	15%	20%	70%	90%

Note: This is a very impressionistic illustration that may differ substantially from country to country, depending, among other things, on the relative weight of each institutional category in the total.

The most polarized public-private distinction is that between a government agency funded by general tax revenues and a private business enterprise funding its own R&D. In between these two extremes, many variations are possible. Taking an institutional perspective, public R&D is made up of the R&D activities undertaken by government agencies and establishments of higher education, while from a funding perspective, public R&D would include all R&D activities funded by general tax revenues. Non-profit agencies supporting the business sector as well as collective funding schemes find themselves somewhere in the middle of the public-private dichotomy. Hence, their allocation to either the public or private category is rather arbitrary and may create confusion in cross-country comparisons.

The third dimension, which addresses the issue of executing proprietary rights, complicates things even more. Publicly funded government agencies may take out patents on the knowledge and technology they produce and execute their right to compensation, while private companies, financing their own R&D, may find that a great deal of the knowledge and technology developed in-house leaks away into the public domain without proper compensation. Information on this third dimension tends to be relatively weak, as data collection has focused almost exclusively on the input side of agricultural R&D rather than on the output side. There is, however, substantial anecdotal evidence that government agencies and establishments of higher education are increasingly establishing proprietary rights on the output they produce.

A.2 *The measurement of agricultural R&D personnel and expenditures*

In the previous section, national agricultural research has been delineated and institutional categories established. In this section, the focus will be on the actual measurement of human and financial resources used by agricultural R&D.

There are two international schemes for classifying personnel: one by occupation (ILO 1990) and one by education (UNESCO 1976). The ASTI project has adopted a hybrid of these two classification schemes (see table 5.2), and focuses on qualified researchers, defined as "professionals conducting or managing research, with a formal qualification of at least a Bachelor's of Science (BSc) degree, which is equivalent to three to four years of full-time university training." More detailed surveys covering all staff use three additional categories: (a) technical support staff, (b) administrative support staff, and (c) other support staff. Persons holding a research position, but lacking the formal qualifications, have been attributed to technical support staff. However, technicians holding a university degree are not classified as researchers. The minimum qualification for either a technical or administrative position is secondary school plus two years of full-time professional training. The category "other support staff" is a rest category and is comprised mainly of jobs for which more limited educational qualifications are required.

Table A.2: *Occupational and educational classifications*

Occupational classification	*Educational qualification*	*Further breakdown*
Research staff	Minimum of three years of full-time university training	National/expatriate PhD/MSc/BSc
Technical support staff	Minimum of secondary school plus two years of professional training	
Administrative support staff	Minimum of secondary school plus two years of professional training	
Other support staff	No minimum requirement	

Statistics on agricultural R&D expenditures cover *all* intramural expenditures, whatever their source of funds, for R&D performed by the agencies that make up the national agricultural research system. They cover both current and capital expenditures. The Frascati Manual advises collecting actual capital expenditures, so capital depreciation is to be excluded. For small or emerging research systems, this may imply relatively large fluctuations of total R&D expenditures because of one-off capital investments.[4] Total expenditures can be broken down in two ways: (a) by type of cost (i.e., personnel, operating, and capital) and (b) by source of funding. These two measures are usually not exactly the same because, for a given financial year, expenditures may differ from funding.

Many agricultural R&D agencies have mandates that are considerably broader than just agricultural R&D, either because they undertake R&D that contributes to economic activities other than primary agriculture or because they combine agricultural R&D with activities such as education, extension, or production. In all such instances, the agricultural R&D activity has to be isolated from these other activities, which may

[4] As Pardey, Eveleens, and Hallaway (1991) showed for the US agricultural experiment stations, a depreciation method of measuring capital expenditure results in a substantially different cost picture than a direct measure of capital expenditure. This is particularly true when agricultural research systems are rapidly expanding.

require prorating of human and financial inputs (e.g., most faculty positions include only part-time work on R&D).

A.3 *Cross-country and over-time comparability of agricultural R&D expenditures*

It is difficult to construct measures of expenditure data that are comparable across countries and over time. The ideal conversion method – using R&D-specific, chained deflators and undistorted, R&D-specific exchange rates – is beyond reach (at least for the moment). One has to accept that certain distortions are introduced in the conversion process and that these distortions can be quite significant.

There are two sets of issues that need to be dealt with in the selection of a conversion method: (1) the choice of deflator and exchange rate and (2) the order in which the two are applied. Regarding the choice of deflator and exchange rate, there are only a few that one can choose from in an international comparison that covers countries from all over the world. Although at the national level, R&D-specific deflators (i.e., those based on the composition of inputs used in R&D) sometimes exist, there is no international dataset of such deflators. Moreover, most deflator series are of the fixed-weight Laspeyres type, while a discrete approximation of a Divisia index is to be preferred as deflator (Pardey, Roseboom and Craig 1992; OECD 1994).[5] The requirement of availability across a large number of countries limits the choice of deflator between the consumer price index (CPI) and the GDP deflator, both of which are of the fixed-weight Laspeyres type. The latter has been preferred as it approximates the bundle of inputs used in R&D better than the CPI.

Also, the choice of exchange rate tends to be limited to the following three options:

(1) the official market exchange rate;
(2) the Atlas exchange rate as developed by the World Bank;
(3) the purchasing power parity (PPP) index as developed by the UN International Comparisons Project and which is also used by the World Bank nowadays.

While the official market exchange rates are still used in many international comparisons, it has long been known that they can be hugely distorted due to interventionist monetary policies as well as to speculation in financial markets. The Atlas exchange rate and the PPP index have both been developed as a more appropriate alternative for international comparisons. The Atlas exchange rate is a rather crude correction of the official market exchange rate made by country experts within the World Bank. It is based more on expert knowledge than on a transparent and consistent methodology (World Bank 1983; 1985). In addition, market-determined "equilibrium" exchange rates are based on an assumed equilibrium, involving internationally traded goods and services as well as financial transactions, but they may poorly reflect the value of local production that is relatively isolated from world market forces.

[5] See also chapter 7.

In contrast, the PPP index covers all economic output and is based on a carefully crafted theoretical framework, which has been discussed extensively in the literature. In a nutshell, the idea is that by buying the same average basket of goods and services in each country, an artificial PPP index or exchange rate can be constructed. The crux of the problem is to establish the composition of the "average" basket of goods and services because this composition can differ hugely, for example, between the US and India. The International Comparisons Project "solves" the problem by using the Geary-Khamis procedure by which both the "average" basket of goods and services and the PPP index are calculated simultaneously. PPP indices are specific to the set of countries for which they have been calculated and deviate significantly from official and Atlas exchange rates. For some of the poorer countries, a conversion with an official or Atlas exchange results in expenditure figures in US dollars that are only one-quarter of the figure obtained by using a PPP index.[6]

An advantage of the PPP index methodology is that it provides a conceptual framework for the construction of specific PPP indices. Kravis, Heston, and Summers (1982) and Summers and Heston (1988), for example, have constructed indices for the government sector and the capital-goods sector in addition to the economy-wide PPP indices. MacDonald (1973) and OECD (1981) discuss at some length the construction of a PPP index specifically for R&D in the OECD area. Unfortunately, not much progress has been made in this area and the OECD S&T statistics now use general PPP indices for making cross-country comparisons.[7]

Related to the choice of deflator and exchange rate is the order in which they should be applied in the conversion. The method most frequently used in international comparisons is to first convert (a times series of) expenditure data to a common currency (usually the US dollar) using annual average exchange rates, and then deflate to a constant year by using a US deflator. The origin of this method stems from the times that exchange rates were more easily obtained than local deflator series. Moreover, it is often assumed that the other route (of first deflating with a local deflator to a constant year and then using the constant-year exchange rate) should yield the same results. This can only be the case when exchange rate adjustments are uniquely and instantly driven by differences in inflation between countries. However, as Pardey, Roseboom, and Craig (1992) have shown, this is certainly not true for the often-used combination of official market exchange rates and GDP deflators. Just altering the order of conversion results in major differences in measured volumes, which in turn affect growth rates as well as a region's relative share in the global total.

[6] The most extreme difference between the PPP index and the official exchange rate was observed for Bangladesh in 1985. The PPP index resulted in an expenditure figure in US dollars that was 7.5 times higher than what the official exchange rate gave. The difference between the official exchange rate and the PPP index is strongly correlated with income per capita. On average, the measured volume of resources invested in agricultural R&D was about 65% higher for developing countries (ranging from 7% higher in sub-Saharan Africa to 123% higher in Asia) when using the PPP index rather than the official exchange rate (Pardey, Roseboom, and Craig 1992).

[7] A popular version of the PPP method is the MacDonald index, published once or twice a year by the *Economist*. The basket consists of only one product (the Big Mac), but one that uses a broad range of inputs and is therefore considered a reasonable approximation of the general price level in a country.

The difference between convert-first and deflate-first is considerably less when a combination of a PPP index and a GDP deflator is used. Still, when cross-sectional variability is more important than the inter-temporal variability within each country, the deflate-first method is preferred, as it demands less of the data (Pardey, Roseboom, and Craig 1992). When the deflate-first method is used, one can expect biases in the volume measures whenever the composition of each country's aggregate in the base year is not representative for the whole time period under consideration. However, when the convert-first method is used, volume measures will be biased unless the numeraire country's aggregate in the base year is representative for *all other countries in all years* of the sample. The latter is a far more demanding assumption.

A.4 *Some closing remarks*

Statistics have an aura of being exact as they are expressed in exact numbers. When one writes "about half" or "50%," people tend to identify the latter as more precise. As shown in the previous sections, what is being captured in statistics depends a lot on the definitions that are used and on how well they can be applied when observing the real world. Hence, some error in the construction of statistics is unavoidable. However, those who use and interpret statistics often introduce errors that are far more disturbing. A selective and loose use of statistics can result in interpretations that are way off from the real world.

Statistics on agricultural R&D investments should capture information that is of relevance to policymakers and analysts. However, policy issues change over time and require statistics to follow suit. In that sense, the emphasis placed on personnel statistics during the 1960s and 1970s (reflecting, particularly in the developing countries, a scarcity of human resources) has shifted to financial statistics (reflecting a scarcity in financial resources) during the 1980s and 1990s.

Samenvatting

Dit proefschrift bestaat uit drie delen waarin de volgende drie vragen worden gesteld:

(1) Waarom investeren we als samenleving in landbouwkundig onderzoek en wat zijn volgens de economische theorie de incentives en wat de beperkingen?
(2) Hoeveel investeren we in landbouwkundig onderzoek wereldwijd en hoe verschillen investeringsintensiteiten tussen landen en door de tijd heen?
(3) Waarom wordt er, gezien de indrukwekkende impact, niet méér geïnvesteerd in landbouwkundig onderzoek?

Deel I van dit proefschrift is een verkenning van de economische literatuur over de rol van wetenschap en technologie in de economie. Hiermee wordt een antwoord gezocht op de eerste vraag. Wat zijn de concepten die economen gebruiken om innovatieprocessen te beschrijven en te analyseren, en hoe kunnen onderzoeksinvesteringen worden gerelateerd aan onder-zoeksimpact?

In deel II wordt beschreven hoeveel er geïnvesteerd wordt in landbouwkundig onderzoek. Aan de hand van vier eerder gepubliceerde artikelen worden de ontwikkelingen geschetst in investeringen in landbouwkundig onderzoek op wereld, regionaal en nationaal niveau. De gebruikte data zijn afkomstig van het langjarige *Agricultural Science and Technology Indicators* project.

Deel III van dit proefschrift probeert een antwoord te geven op de derde vraag. Het test de veronderstelling dat er te weinig in landbouwkundig onderzoek wordt geïnvesteerd. Dit wordt gedaan d.m.v. een model dat een nieuwe en meer consistente interpretatie geeft aan de bestaande rendementscijfers.

Deel I

De *induced innovation theory* en de *endogenous growth theory,* beiden voortkomend uit de neoklassieke traditie, modelleren technische verandering als een verschuiving van de productiefunctie; ofwel het produceren van dezelfde output met minder input of meer output met dezelfde input. Cruciaal in dit proefschrift is de aanname dat investeringen in (landbouwkundig) onderzoek de verschuiving van de productiefunctie bevordert en versnelt en dat er een link bestaat tussen onderzoeksinvestering en impact.

De *induced innovation theory* beweert dat de relatieve schaarste van productiemiddelen de richting van de technische verandering stuurt. Bijvoorbeeld als grond relatief schaars is ten opzichte van arbeid, dan is het meer winstgevend om te investeren in grondbesparende dan in arbeidsbesparende technologieën. Het resultaat is een hogere kostenbesparing. De *induced innovation theory* richt zich met name op de richting van de technologische innovatie, en minder op de snelheid waarmee deze technologische innovatie plaatsvindt. Het legt dus geen expliciete link tussen onderzoeksinvestering en impact.

Metcalfe (1995), voortbouwend op Nordhaus (1969), doet een poging om de link tussen onderzoeksinvestering en impact expliciet te modelleren en introduceert het concept van een *innovation possibility curve.* Met deze curve probeert hij de relatie bloot te leggen tussen de reductie in productiekosten en de omvang van de investering in onderzoek binnen een gegeven tijdsperiode. Metcalfe stelt, geheel binnen de neoklassieke traditie, dat het optimale niveau van onderzoeksinvestering door een bedrijf wordt bepaald door het punt waar de marginale onderzoekskosten gelijk zijn aan de marginale onderzoeks-baten.

Metcalfe's model van een bedrijf als optimaliserende innovator geeft een interessant inzicht in de verschillen in innovatie-intensiteit tussen bedrijven. Echter het model faalt waar het gaat om het modelleren van de interactie tussen bedrijven in een markt of industrie en hoe deze interactie de innovatieprikkels of overwegingen voor bedrijven zou kunnen beïnvloeden. Macro-economische groeitheorieën geven ook geen antwoord op deze vraag – ze abstraheren industrieën en markten volledig. Wat ontbreekt, is een model dat zich richt op de snelheid van technologische verandering op het niveau van een sector of een industrie. In deel III van dit proefschrift wordt een model geïntroduceerd dat probeert deze lacune op te vullen.

Winstmaximalisatie, is simpelweg het antwoord van de neoklassieke economische traditie op de vraag waarom we investeren in landbouwkundig onderzoek. Hoewel daar weinig tegen in valt te brengen, laat dit antwoord vele andere factoren die ook een rol zouden kunnen spelen buiten beschouwing. *Evolutionary economics* levert een veel realistischer beschrijving van het innovatieproces. Winst speelt daarin een belangrijke rol, maar niet noodzakelijkerwijs winstmaximalisatie. Daarnaast heeft de neoklassieke theorie volgens *institutional economics* geen oog voor de rol van instituties in innovatie. Het negeert het feit dat hoge transactiekosten kunnen leiden tot vertraging of zelfs blokkering van het technologische innovatieproces. Met andere woorden, als we ons afvragen waarom innovatiesnelheden of onderzoeksintensiteiten verschillen in de tijd en tussen industrieën en landen, vormen instituties en marktstructuren een belangrijk onderdeel van het antwoord op deze vraagstelling. Dit inzicht speelt ook een belangrijke rol in het *innovatie systeem denken* dat de afgelopen jaren brede aandacht heeft gekregen.

In de literatuur over wetenschap en technologie wordt vaak benadrukt dat innovatie-processen vroeg of laat vastlopen en dat om die reden de opbrengsten van investeringen in onderzoek op den duur zullen afnemen. Voor specifieke innovatieprocessen zal dit zeker gelden, maar er ontwikkelen zich ook telkens nieuwe innovatieprocessen. Het is dus nog de vraag of afnemende meeropbrengsten ook van toepassing zijn op het totale innovatieproces. Door de *endogenous growth theory* wordt dit beeld van afnemende meeropbrengsten volledig omgekeerd. Het postuleert dat er op macroniveau sprake is van toenemende meeropbrengsten wat betreft kennis en, in het bijzonder, kennis gecreëerd door onderzoek. Dit idee wijkt sterk af van het traditionele *afnemende meeropbrengsten denken* en geeft daarmee een heel optimistische visie op de toekomst.

De *endogenous growth theory* kent een grote rol toe aan *human capital* in de verklaring van verschillen in economische groei en welvaart. Alhoewel een grote stap voorwaarts, een groot deel van de verschillen blijven ook in de *endogenous growth theory* nog onverklaard. Er bestaat een groeiende consensus dat er nog steeds een belangrijke factor ontbreekt in de huidige economische groeimodellen, namelijk dat van de sociale dimensie van de economie. Dit betreft de manier waarop economische actoren met elkaar omgaan en de instituties waarop zulk gedrag is gebaseerd. Door velen wordt dit *social capital* gezien als een belangrijke verklarende factor, naast *physical* en *human capital*, voor de waargenomen verschillen in economische groei en welvaart. Net zoals aan *human capital* worden ook aan *social capital* toenemende meeropbrengsten toegeschreven. Hoe *social capital* valt te definiëren en te meten is echter nog onderwerp van diepgaande discussie.

Deel II

Gedurende de 20^e eeuw is het publiek landbouwkundig onderzoek enorm toegenomen in capaciteit en intensiteit. In de tweede helft van de 20^e eeuw echter is in deze groei een vertraging opgetreden. Groeiden de reële uitgaven aan publiek landbouwkundig onderzoek in de ontwikkelingslanden in de periode 1961-71 nog met 7,2% per jaar, in de periode 1981-91 was dit gedaald naar gemiddeld 3,9% per jaar. Voor de ontwikkelde landen daalden de groeicijfers over dezelfde periode van gemiddeld 5,5% naar 1,7% per jaar.

Met uitzondering van de voormalige Sovjet Unie en Oost Europa, werkten er in 1991 wereldwijd een geschatte 190.000 onderzoekers voltijds in het publieke landbouwkundig onderzoek met een gezamenlijk budget van bijna $15 miljard (1985 internationale dollars). Rond 65% van deze onderzoekers (125.000) was werkzaam in ontwikkelings-landen met een aandeel in de totale uitgaven van 54%, ofwel $8,1 miljard.

De *Consultative Group on International Agricultural Research* (CGIAR) coördineert de activiteiten van 16 internationale onderzoeksorganisaties in de landbouw. Tezamen hadden deze 16 instituten slechts een ‘bescheiden’ aandeel van 1,8% van de $15 miljard besteed aan publiek landbouwkundig onderzoek in 1991. In datzelfde jaar bedroegen de investeringen in de ontwikkelde landen in privaat onderzoek in de landbouw en aanverwante industrieën minstens $6,6 miljard (1985 internationale dollars). In tegenstelling tot het publiek landbouwkundig onderzoek dat zich voronamelijk richt op de primaire landbouw, richt het privaat landbouwkundig onderzoek zich voornamelijk op de toeleverende en verwerkende industrieën. Gedurende de periode 1981-91 groeide het privaat landbouwkundig onderzoek in de ontwikkelde landen substantieel sneller dan het publiek landbouwkundig onderzoek (5,2 % tegen 1,7% per jaar). Vergelijkbare cijfers m.b.t. de omvang van het privaat landbouwkundig onderzoek in ontwikkelingslanden ontbreken, maar worden verondersteld beduidend lager te liggen.

De jaarlijkse groeicijfers van uitgaven aan publiek landbouwkundig onderzoek geven grote verschillen te zien tussen regio's en landen. Regio's waar uitgaven zijn afgenomen of slechts heel beperkt zijn gegroeid tijdens de periode 1981-91, zijn Latijns Amerika en de Cariben (-0,5% per jaar) en Afrika ten zuiden van de Sahara (gemiddeld +0,8% per jaar). Voor een groot gedeelte kan dit worden toegeschreven aan de slechte economische en financiële situatie in deze regio's gedurende deze periode. Binnen de regio's bestaan echter grote verschillen. In Afrika bijvoorbeeld liepen de jaarlijkse groeicijfers van investeringen in landbouwkundig onderzoek tijdens deze periode uiteen van –9,1% in Nigeria tot +14,4% in Ghana. In de meeste ontwikkelingslanden overschreed de groei van de onderzoeksstaf dat van de onderzoeksuitgaven, wat resulteerde in een (soms dramatische) daling in uitgaven per onderzoeker.

De uitgaven aan publiek landbouwkundig onderzoek als een percentage van de toegevoegde waarde in de landbouw, de zgn. onderzoeksintensiteit, steeg in ontwikkelingslanden van 0,26% in de beginjaren zestig, naar 0,42% in de beginjaren zeventig, naar 0,50% in de beginjaren tachtig. Tot de beginjaren negentig is dat rond 0,50% gebleven.

Voor de ontwikkelde landen steeg de onderzoeksintensiteit van het publieke landbouwkundig onderzoek van 0,96% in de beginjaren zestig, naar 1,38% in de beginjaren zeventig, naar 1,98% in de beginjaren tachtig, en tot 2,39% in 1991. Ondanks de veel snellere groei van landbouwonderzoekuitgaven in ontwikkelingslanden, is het verschil in onderzoeksintensiteit tussen ontwikkelde landen en ontwikkelingslanden juist toegenomen in plaats van afgenomen. Dit wordt veroorzaakt door het feit dat de landbouw in de ontwikkelingslanden doorgaans nog snel groeit, terwijl de landbouw in de meeste ontwikkelde landen juist stagneert. Het verschil in onderzoeksintensiteit komt nog sterker tot uitdrukking inzake onderzoeksuitgaven per boer. Ontwikkelingslanden besteedden in 1991 per boer gemiddeld $7 aan publiek landbouwkundig onderzoek en ontwikkelde landen $354.

Een specifieke studie naar het Nederlandse landbouwonderzoeksysteem belicht de meer institutionele aspecten van het landbouwkundig onderzoek. Het laat zien hoe veranderingen in landbouwbeleid, wetenschap, en politieke ideologie t.a.v. de rol van de overheid in de samenleving, de institutionele context waarbinnen het publieke landbouwkundig onderzoek opereert heeft veranderd. Dit heeft tot belangrijke veranderingen geleid in het Nederlandse landbouwonderzoeksysteem m.b.t. mandaat, formulering en coördinatie van beleid, organisatie en structuur, management, en ook de financiering van het onderzoek. Hoewel specifiek voor de Nederlandse situatie, worden soortgelijke veranderingen ook in andere landen waargenomen.

Deel III

Sinds de publicatie eind jaren vijftig van Griliches' studie naar het economische rendement van onderzoek naar hybride maïs in de Verenigde Staten (Griliches 1958), zijn rendementsstudies uitgegroeid tot een vrij algemeen geaccepteerde manier om de economische impact van (landbouwkundig) onderzoek te documenteren. De geschatte rendementen voor landbouwkundig onderzoek verschillen sterk van elkaar, maar het gemiddelde bevindt zich tussen de 40% en 60% (Alston *et al* 2000). Door velen wordt de nauwkeurigheid van deze schattingen (zie hoofdstuk 7), als ook de representativiteit van de geselecteerde onderzoeksprojecten in twijfel getrokken. Toch leeft er de wijdverbreide veronderstelling dat deze hoge rendementen robuust genoeg zijn om deze kritiek te weerstaan en dat ook na neerwaartse correctie zij zich ruim boven het vereiste minimum rendement bevinden. Op basis hiervan, heeft Ruttan (1980) de stelling geponeerd dat er ernstige onderinvestering bestaat in publiek landbouwkundig onderzoek. Deze stellingname is sindsdien door vele landbouweconomen overgenomen. Elke vertraging in de groei of, erger nog, afname van investeringen in publiek landbouwkundig onderzoek wordt daarom met bezorgdheid tegemoet getreden.

Wat is er nu echter daadwerkelijk bekend over deze veronderstelde onderinvestering? Is deze hoger in ontwikkelingslanden dan in ontwikkelde landen? Is er verschil in onderinvestering tussen bepaalde soorten van landbouwkundig onderzoek? En, hoeveel meer zouden we in landbouwkundig onderzoek moeten investeren om het investeringsgat te dichten? Om deze vragen te kunnen beantwoorden, is het nodig om het begrip onderinvestering nader te definiëren. Om die reden wordt in hoofdstuk 8 een simpel model geïntroduceerd dat een weergave geeft van de ideale, economische selectie van landbouwonderzoeksprojecten.

Het model neemt aan dat de distributie van alle mogelijke onderzoeksprojecten op een te-verwachten-rendementsschaal asymptotisch afneemt. Onder de neoklassieke condities van volledige informatie en winstmaximalisatie, begint de selectie van onderzoeksprojecten met het project met het hoogste rendement en gaat door tot het budget op is of het laatst gekozen project het minimum rendement heeft bereikt, al naar gelang wat het eerste plaatsvindt. Onderinvestering kan dus worden gedefinieerd als het verschil tussen het rendement van het marginale onderzoeksproject en de minimumrendementseis. Drie variabelen zijn nodig om het investeringsgat te schatten: het vereiste minimum rendement, het marginale rendement, en de hellingscoëffient. Hoofdstuk 8 laat zien hoe, rekening houdend met onvolledige informatie en beperkte economische rationaliteit, de laatste twee variabelen afgeleid kunnen worden van een voldoende representatieve steekproef van ex post rendementen van landbouwonderzoeksprojecten. Vanuit het model zelf kan worden afgeleid dat niet het gemiddelde maar de modus van de ex post rendementsdistributie de relevante variabele is voor het schatten van het investeringsgat. Een hoog gemiddeld rendement op de onderzoeksportfolio is geen sluitend bewijs voor onderinvestering.

Een database met rendementen voor landbouwkundig onderzoek, samengesteld door Alston c.s. (2000), levert de empirische data voor het schatten van de vorm en positie van de optimale selectie van landbouwonderzoeksprojecten voor respectievelijke ontwikkelingslanden en ontwikkelde landen. Aan de hand van deze schattingen, kunnen de volgende uitspraken worden gedaan:

- Onder de aannames van volledige informatie en winstmaximalisatie, hadden in de beginjaren tachtig ontwikkelde landen ongeveer 40% meer in publiek landbouwkundig onderzoek kunnen investeren, en ontwikkelingslanden zo'n 137% meer. Wat betreft onderzoeksintensiteit (uitgaven aan publiek landbouwkundig onderzoek als een percentage van de toegevoegde waarde in de landbouw), hadden de ontwikkelde landen 2,8% kunnen investeren in de periode 1981-85 in plaats van de daadwerkelijk bereikte 2,0% en ontwikkelingslanden 1,0% in plaats van 0,4%.

- Lage investeringen in publiek landbouwkundig onderzoek in ontwikkelingslanden worden in eerste instantie veroorzaakt door een relatief kleinere portfolio van goed renderende landbouwonderzoeksprojecten waaruit gekozen kan worden. Onderinvestering speelt zeker een rol (het gat is groter voor ontwikkelingslanden), maar het verklaart slechts een klein deel van het verschil in intensiteit in landbouwkundig onderzoek tussen de ontwikkelde landen en de ontwikkelingslanden.

- Inspanningen om het investeringsgat te dichten (zoals het verbeteren van de selectie van projecten en de mobilisatie van politieke steun) moeten zeker worden gecontinueerd. Meer nadruk echter moet er worden gelegd op het ontwikkelen van beleid dat het rendement van landbouwkundig onderzoek in het algemeen zou kunnen verhogen.

Het model is nuttig, niet zozeer vanwege een goede weergave van de realiteit, maar omdat het een ijkpunt levert waartegen de realiteit kan worden afgezet. De geschatte onderinvesteringen zijn gebaseerd op de aanname van volledige informatie en economische rationaliteit tijdens de allocatie van het onderzoeksbudget. In werkelijkheid echter is de ex ante selectie van onderzoeksprojecten suboptimaal en dit verduistert het zicht op het investeringsgat ex ante, als ook ex post. Om een beter zicht te krijgen op het investeringsgat en om het te kunnen schatten, moet deze suboptimaliteit worden verwijderd. Uiteindelijk is het model nuttig niet omdat het in staat is om de onderinvestering in landbouwkundig onderzoek in het verleden te schatten, maar omdat het een hulpmiddel is om te begrijpen waarom onderinvestering zich voordoet. Het is dit inzicht dat ons kan helpen de toekomstige landbouwonderzoeksmogelijkheden te creëren en te exploiteren.

Eén groep van verklarende factoren betreft de positie en vorm van de rendementsdistributie van alle potentiële onderzoeksprojecten. Er bestaan belangrijke verschillen in innovatiemogelijkheden tussen bedrijven, industrieën, landen, en door de tijd heen. Naast puur technologische mogelijkheden (welke gestimuleerd kunnen worden d.m.v. fundamenteel onderzoek), zijn er andere factoren zoals schaal en structuur van de markt, de schaal en snelheid van adoptie, risico en onzekerheid, en effectiviteit en efficiëntie in onderzoek. Elk van deze factoren kan, indien verbeterd, leiden tot een verhoging van de onderzoeksbaten of een daling van de onderzoekskosten en daarmee een vergroting van de optimale onderzoeksportfolio.

De andere groep van verklarende factoren betreft het verschijnsel dat overheden te weinig in landbouwkundig onderzoek investeren. Mogelijke verklaringen zijn het gebrek aan (betrouwbare) informatie, suboptimale selectie mechanismen (inclusief distortie door lobbyen), rigiditeit in budgetten, de kosten van economische distortie door belastingheffing, en het ontbreken van politieke en organisatorische capaciteit in de samenleving. Verbetering van elk van deze factoren zou het investeringsgat kunnen helpen verkleinen.

Beide groepen van factoren hebben belangrijke *social capital* dimensies die cumulatief zijn. Het is dit *social capital* dat maakt dat rijke landen niet alleen een grotere portfolio van winstgevende onderzoeksprojecten hebben om uit te kiezen, maar ook een betere capaciteit om deze onderzoeksprojecten te selecteren, te financieren, en uit te voeren. Een voorwaarde voor armere landen om technologisch en economisch vooruit te komen bestaat niet alleen uit meer investeren in *human capital* maar ook in het ontwikkelen van het benodigde *social capital* om de baten van innovatie te kunnen oogsten.

Summary

This dissertation addresses the following three sets of questions:

(1) Why do we, as society, invest in agricultural research and development (R&D) – what are, according to economic theory, the incentives and what are the constraints?
(2) How much do we invest in agricultural R&D and how do agricultural R&D investment levels differ between countries and change over time?
(3) Why, despite an impressive record of accomplishment, have we not invested more in agricultural R&D?

For an answer to the first question, part I of this dissertation explores the science and technology (S&T) economics literature. What are the principal concepts that economists use to describe and analyze innovation processes and how do they relate R&D investment to impact? In a series of four, previously published articles, part II of this dissertation addresses the question of how much we invest in agricultural R&D. These four articles describe in detail agricultural R&D investment patterns and trends at the global, regional, and national levels. The reported data are based on long-term data-collection efforts through the Agricultural Science and Technology Indicators (ASTI) project. Part III critically reviews the hypothesis that there is underinvestment in agricultural R&D by introducing a model that provides a new and more consistent interpretation of the existing rate-of-return evidence.

Part I

The *induced innovation theory* and the *endogenous growth theory*, both squarely rooted in the neoclassical tradition, model technical change as a shift in the production function – i.e., producing the same output with fewer inputs. A basic assumption made in this dissertation is that investments in (agricultural) R&D enhance and speed up this shift and that there is a link between R&D investment and impact. The induced innovation theory argues that relative factor scarcities will steer the direction of technical change. When land is scarce relative to labor it is more profitable to invest in land-saving rather than labor-saving technologies – it will yield a higher cost reduction. While focusing strongly on the direction of technical change, induced innovation theory says very little about the rate of technical change. It fails to specify an explicit link between R&D investment and technical change.

Metcalfe (1995), building on work by Nordhaus (1969), makes this link explicit conceptually by introducing the concept of an *innovation possibility curve*, which relates the reduction in unit production costs achieved in a given time period to investment in R&D. Strictly within the neoclassical tradition, Metcalfe argues that the optimal level of R&D investment by a firm is determined by the point where marginal research costs equal marginal research benefits.

While Metcalfe's model of the firm as optimizing innovator provides some important elements for understanding differences in innovation rates across firms, the model largely fails to capture the interaction between firms in a market or industry and how this may affect innovation incentives. At the other end of the spectrum, macroeconomic growth theory completely abstracts from industries and markets and focuses on aggregate economic growth. What is missing is a consistent model that looks at the rate of technical change at the sector or industry level and which links R&D input to impact. This challenge is taken up in part III of this dissertation.

With regard to "Why we invest in agricultural R&D?" the simple answer of neoclassical economics is profit maximization. There is certainly considerable truth in this, but the profit argument abstracts very much from many other factors that may play a role as well. As many authors have pointed out, a major weakness of the neoclassical innovation theory is its weak foundation in microeconomics. This makes that it is incapable of capturing how the interaction between economic actors in a market affects the ultimate outcome of the innovation process at the macro level. In that sense, *evolutionary economics* provides a far more realistic description of the innovation process. Profit plays an important role, but not necessarily profit maximization. In addition, neoclassical innovation theory has according to institutional economics a blind spot for the role of institutions. It ignores the fact that high transaction costs at various stages of the innovation process may slow down or even block technological innovation. In other words, if we want to understand why innovation rates differ or why investments in R&D differ over time and across industries and countries, institutions and market structures constitute an important part of the puzzle. This is also very much reflected in the innovation system approach.

The S&T literature is full of theories that stress that innovation processes eventually run out of steam and which predict that returns to R&D will diminish. While for discrete innovation processes this may be true, there are also new innovation processes that emerge all the time. Therefore, diminishing returns may not apply to all innovation activities taken together. The contribution of the endogenous growth theory is that it made this idea explicit by assuming increasing returns to knowledge and, in particular, to knowledge created through R&D. It is an idea that sits very uncomfortably with what economists (and most other people) usually think, but, if true, it suggests a very optimistic future.

While a big step forward compared to traditional growth theories, endogenous growth theories also leave a large part of the differences in economic growth unexplained. There is an emerging consensus in the literature that there is still an important factor missing in the present economic growth models, namely, that of the social dimension of economic activity – the way economic actors interact and organize themselves and the institutions on which such interactions are based. This "social capital" is what many see as perhaps a far more important factor that could explain differences in economic growth. Similar to human capital, increasing returns have also been attributed to social capital. However, a clear consensus on how to define and measure social capital has not yet emerged.

Part II

During the 20th century, the world's public agricultural research capacity saw tremendous expansion. This expansion, however, gradually slowed during the latter half of the 20th century. Public agricultural research expenditures in developing countries grew, on average, 7.2% per annum in real terms during the 1960s, 6.4% during the 1970s, and 3.9% during the 1980s. For developed countries, these growth rates were 5.5%, 2.7%, and 1.7%, respectively.

By 1991, some 190,000 full-time-equivalent researchers were employed worldwide (excluding the former USSR and Eastern Europe) in public agricultural research, spending nearly $15 billion (1985 international dollars). About 65% of these researchers were located in developing countries, spending about 54% of the global budget. The 16 international agricultural research centers under the umbrella of the Consultative Group on International Agricultural Research (CGIAR) represented only 1.8% of the nearly $15 billion spent on public agricultural R&D worldwide in 1991 – a very modest contribution indeed. In the developed countries, private agricultural and agriculture-related R&D contributed at least another $6.6 billion (1985 international dollars) in 1991. Contrary to public agricultural R&D that focuses mainly on primary agriculture, private agricultural R&D is concentrated mainly in agricultural input and processing industries. During the 1980s, private agricultural R&D expenditures in the developed countries grew substantially faster than public agricultural R&D expenditures (5.2% compared to 1.7% per annum). Corresponding private R&D figures for developing countries are not available, but are estimated to be substantially lower.

Annual growth rates of public agricultural research expenditures differ highly across regions and between countries within regions. During the 1980s, both sub-Saharan Africa and Latin America and the Caribbean stood out as regions with very sluggish growth in agricultural research capacity (+0.8% and –0.5% per annum, respectively). Largely, this can be attributed to the economic and financial crises that hit these regions quite severely at that time. However, a lot of diversity is hidden below these average figures. In sub-Saharan Africa, for example, growth in expenditures on public agricultural research during the 1980s ranged from –9.1% per annum in Nigeria to +14.4% per annum in Ghana. In most developing regions, growth in research staff has exceeded that of expenditures, leading to a (sometimes very dramatic) decline in expenditures per researcher.

In developing countries, the agricultural research-intensity ratio (public agricultural research expenditures as a percentage of agricultural GDP) rose from 0.26% in the early 1960s, to 0.42% in the early 1970s, to 0.50% in the early 1980s, at which level it more or less stagnated for the rest of the 1980s and early 1990s. The intensity ratio for developed countries rose from 0.96% in the early 1960s, to 1.38% in the early 1970s, to 1.98% in the early 1980s, and to 2.39% in 1991. So despite faster growth in agricultural research expenditures in developing countries, the distance between developing and developed countries in terms agricultural research intensity has expanded rather than narrowed. The gap in research intensity is even more dramatic when expressed in terms of research dollars spent per agricultural laborer. In 1991, developing countries spent, on average, $7 on public agricultural R&D per agricultural laborer, and developed countries spent $354.

These aggregate statistics are rather sterile when it comes to telling the story of why growth in agricultural research capacity has differed so much across countries and over time. A case study on the Dutch agricultural research system provides important insights into how changes in agricultural policies, advancements in science, and ideological changes regarding the role of government in society has changed the institutional context within which the agricultural research system operates. This has had important implications for the Dutch agricultural research system in terms of mandate, policy formulation and coordination, organization and structure, management, and financing. While a very country-specific story, many of the same issues can be found in other countries.

Part III

Starting with a study on hybrid corn by Griliches (1958), rate-of-return studies have become standard practice in documenting the economic impact of agricultural R&D. Although the estimated ex post rates vary quite substantially, the average tends to range in the order of 40%–60% (Alston *et al*. 2000). Though many have questioned the accuracy of these rates and expressed doubt about how representative the selected projects are (see chapter 7), a widely shared belief is that the estimated rates are robust enough to accommodate such criticisms and still be in a range that is substantially above the social rate. Based on this evidence, Ruttan (1980) argued that there is serious underinvestment in public agricultural R&D. This argument has become a widely accepted opinion (if not fact) among agricultural economists. Therefore, any slowdown in the growth or, even worse, any contraction of public agricultural R&D expenditures is reason for serious concern.

However, what do we actually know about this underinvestment? How real is it? Is it higher in developing countries than in developed countries? Is it higher for some types of research than for others? Moreover, how much more should we have invested in agricultural R&D? In order to answer these questions, the underinvestment argument needs to be defined more clearly. Therefore, a simple model is introduced in chapter 8 that represents the ideal economic version of the selection of R&D projects.

The model assumes that the distribution of all possible R&D projects on an expected rate-of-return (ERR) scale declines asymptotically. Under the neoclassical conditions of full information and profit maximization, R&D project selection starts with the project with the highest ERR and continues until the budget is finished or the last project hits the social rate, whichever comes first. Hence, the underinvestment gap can be defined as the difference between the ERR of the marginal R&D project (the actual cutoff rate) and the social rate. Only three variables need to be known to estimate the underinvestment gap:

the social rate, the actual cutoff rate, and the slope coefficient. Taking less than full information and economic rationality into account, chapter 8 discusses how the latter two can be derived from a sufficiently large and representative sample of ex post rates of return on agricultural R&D. One of the things that becomes immediately clear from the model itself is that it is not the *mean* but the *mode* of the ex post rate-of-return distribution that is the relevant variable for assessing underinvestment in agricultural R&D. A high average rate does not provide conclusive information about under-investment.

The empirical evidence for the shape of the rate-of-return distribution for developing and developed countries has been obtained from a database on rates of return to agricultural R&D compiled by Alston *et al.* (2000). When the model was applied to the reported rate-of-return distributions, the following findings emerged:

- Under the assumption of full information and profit maximization, developed countries could have invested about 40% more in public agricultural R&D and developing countries could have invested about 137% more. In terms of agricultural R&D intensity (i.e., R&D expenditures as a percentage of AgGDP), developed countries could have invested 2.8% rather than 2.0%, and developing countries, 1.0% rather than 0.4% in 1981–85.
- Low investment in public agricultural R&D in developing countries is caused first and foremost by a relatively smaller portfolio of profitable R&D projects to choose from. Underinvestment certainly plays a role (the gap is bigger for developing countries) but it explains only a small part of the difference in agricultural R&D intensity between developed and developing countries.
- While efforts to reduce the underinvestment gap should continue (e.g., better priority setting and mobilization of political support), more emphasis should be placed on designing policies that help to shift (the portfolio of) R&D projects higher up on the ERR scale, even at the risk of increasing the underinvestment gap.

The usefulness of the model is not that it is a good approximation of reality, but that it provides a benchmark against which reality can be compared. The estimated under-investment gaps are conditional – they assume full information and economic rationality in the allocation of R&D resources. In reality, the ex ante selection of R&D projects is suboptimal and this obscures our sight of the underinvestment gap ex post. It has to be eliminated in order to see the underinvestment gap more clearly and to be able to estimate its size. Ultimately, however, the model is useful not because it estimates past R&D underinvestment gaps, but because it helps to better understand why they exist. It is an understanding that may help us to create and better exploit the R&D investment opportunities of tomorrow.

One set of explanatory factors relates to the position and shape of the distribution of all potential R&D projects. There are important differences in innovation opportunities across companies, industries, countries, and over time. Besides purely technological opportunities (which may be enhanced by investing in basic R&D), other factors come into play, such as the size and structure of the market, the rate and speed of adoption, risk and uncertainty, and R&D effectiveness and efficiency. Each of these factors could, if improved, increase R&D benefits or reduce R&D costs and, hence, create a larger optimal R&D portfolio.

The other set of explanatory factors relates to why governments underinvest in public agricultural R&D. Possible explanations are a lack of information, suboptimal selection mechanisms (including distortion due to lobbying), budget rigidity, excess burden due to taxation, and last but not least, a lack of political and organizational capacity in society. Improvements in each of these factors should bring the underinvestment gap down.

Both sets of factors have important social capital dimensions that tend to be cumulative. It is this social capital that results in rich countries having not only a bigger portfolio of profitable agricultural R&D projects to choose from, but also a better capacity to select, finance, and implement them. Hence, a prerequisite for poorer countries to catch up is not only more investment in human capital (i.e., agricultural R&D), but they also have to develop the social capital needed to reap the benefits from innovation.

Curriculum Vitae

Johannes Roseboom was born January 15, 1959 in Dalen, the Netherlands. He attended Wageningen Agricultural University from August 1978 until September 1985, when he graduated as an agricultural economist with a major in development economics and minors in general economics and the “Agrarian Question in Latin America” at the Center for Education and Documentation Latin America (CEDLA) of the University of Amsterdam. During his studies, he spent time for his internship in the Dominican Republic and Tunisia.

Since September 1985, he has worked for the International Service for National Agricultural Research (ISNAR), in The Hague, initially as a research assistant, later as a research associate, and since 1994, as a research officer. Throughout his career at ISNAR, he has been closely involved with the Agricultural Science and Technology Indicators (ASTI) project. In recent years, his research has focused on agricultural research policy issues such as the financing of agricultural research, the role of agricultural input industries in agricultural innovation, and institutional innovation. He has traveled widely for his work and has visited some 30 countries around the world.