Research Report 23

Optimizing Investment in Agricultural Research, or the Quest for Prosperity

Johannes Roseboom

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About the author

Johannes Roseboom was until recently a research officer at ISNAR. He has extensive experience in agricultural research investment issues. This Research Report is based in part on his dissertation *Essays on Agricultural Research Investment*, published in 2002.

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Johannes Roseboom

Abstract

The growth in agricultural R&D investments around the world has slowed considerably in the past 20–30 years, even though most experts agree that there is substantial underinvestment in agricultural R&D. Introducing a simple economic model of the ex ante selection of R&D projects allows us to make a more insightful interpretation of the available ex post rate-of-return evidence.

Two sets of factors can be identified that determine the level of investment in agricultural R&D: (1) the ex ante choice set of R&D projects for a given domain and time and (2) the extent to which the assumptions of full information and selection rationality apply.

There are important differences in innovation opportunities between industries, between countries, and through time. Apart from purely technological opportunities, factors that also play a role are the size and structure of the market, the rate and speed of technology adoption, risk and uncertainty, and R&D effectiveness and efficiency. If improved, each of these factors could either increase R&D benefits or reduce R&D costs, creating a larger choice set of profitable R&D projects.

By assuming less than full information and selection rationality, various explanations for underinvestment in agricultural R&D can be tested. The model also allows us to gain insight into the political economy aspects of R&D project selection by examining situations in which two distinctive R&D choice sets are competing with each other for funding, or in which projects are selected according to the different perspectives of social planners, farmers, or consumers.

Executive Summary

Since an initial study of hybrid corn research in America (Griliches 1958), rate-of-return studies have become standard practice in documenting the economic impact of agricultural R&D. The reported ex post rates of return vary substantially (from very high to negative), but on average range from approximately 40% to 60% (Alston et al. 2000; Evenson 2001). Despite criticisms of the accuracy of these rates, and of the extent to which the selected projects are representative, it is widely believed that the estimated rates are robust enough to accommodate such criticisms and still fall within a range substantially above the social rate of return. Based on this evidence, Ruttan (1980) argued that there is serious underinvestment in public agricultural R&D, and this opinion has become widely accepted by agricultural economists. Any slowing in the rate of growth of public agricultural R&D expenditure, or, worse still, any reduction, therefore gives rise to 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? How much more should be invested in agricultural R&D? To answer these questions, the underinvestment hypothesis must be defined more clearly. This study addresses the issue by introducing a relatively simple economic model of the process of selecting R&D projects. The model is based on the idea that the distribution of all possible R&D projects on an expected rate-of-return (ERR) scale (i.e., the ex ante choice set) can be thought of as declining asymptotically. The higher the ERR, the lower is the number of R&D projects from which to choose. Such a distribution can be approximated by a semilog function with a negative slope coefficient. Assuming full and correct information and rational economic behavior, the process of selecting R&D projects for implementation begins with the project with the highest ERR and continues with the next highest until either the R&D budget has been exhausted, or the ERR on the last (i.e., marginal) R&D project approaches the social rate of return, whichever comes first. In strictly economic terms, 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 are needed to estimate the underinvestment gap: (1) the social rate, (2) the actual cutoff rate, and (3) the slope coefficient. Taking less than full information and economic rationality into account, the second and third variables can be derived from a sufficiently large and representative sample of ex post rates of return on agricultural R&D projects.

The methods used to estimate rates of return on investments in agricultural R&D, and the many problems that surround them, are discussed extensively in chapter 2. However, the empirical evidence used in this report, obtained from a recent IFPRI study, had to be taken largely as it came.

The most important findings of the model are the following:

- The *mode* rather than the *mean* 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, in the period from 1981 to 1985, developed countries should have invested about 40% more in public agricultural R&D and developing countries about 137% more. In terms of agricultural R&D intensity (i.e., expenditure as a percentage of AgGDP), developed countries should have invested 2.8% rather than 2.0%, and developing countries 1.0% rather than 0.4% over the same period.
- Low investment in public agricultural R&D in developing countries is primarily the result of having a relatively small set of profitable R&D projects from which to choose and in which to invest. Although underinvestment certainly plays a role (since the gap is larger for developing countries), 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., through better priority setting and mobilization of funding), more emphasis should be placed on formulating policies that help shift the choice set of R&D projects higher up the ERR scale.

There are two sets of explanatory factors that determine the level of underinvestment. One set relates to the position and shape of the ex ante choice set (i.e., the distribution of all possible R&D projects on an ERR scale). There are important differences in innovation opportunities between companies, industries, and countries, and also through time. Apart from purely technological opportunities (which may be enhanced by investing in basic R&D), other factors come into play, including the size and structure of the market, the rate and speed of adoption of new technologies, risk and uncertainty, and R&D effectiveness and efficiency. If improved, each of these factors could increase R&D benefits or reduce R&D costs and thus create a larger optimal R&D portfolio. This may sometimes require either very specific government policies, such as removing particular bottlenecks in the adoption of new technologies, or policies of a more general nature, such as securing political and economic stability.

The second set of explanatory factors relates to the reasons why governments (seem to) underinvest in public agricultural R&D. This set can be divided into two categories: (1) incomplete and distorted information, and (2) compromised economic rationality.

Both ex ante and ex post estimations of rates of return to agricultural R&D depend on many different variables, each of which can only be predicted (ex ante) or estimated (ex post) with limited precision. Nevertheless, this type of inaccuracy is not in itself a problem provided that overestimations roughly compensate for underestimations. In other words, considerable stochastic noise is unavoidable. More problematic, however, are those cases in which, across all R&D projects, (1) certain variables are systematically over- or underestimated, or (2) cause and effect are modeled inaccurately. Both can lead to a systematic bias in the estimated position of the R&D opportunity curve and distort our view of the underinvestment gap.

An example of such a systematic bias has been expressed in the public-finance literature, where it has been argued that a dollar of tax revenue actually costs substantially more than a dollar, because taxation distorts factor and product markets and creates "deadweight" economic losses. If this concept is not included in the rate-of-return estimation (as is often the case), the rate of return of all R&D projects will be systematically overestimated. Another example is provided by the notion that most rate-of-return calculations tend to underestimate the length of the benefit stream. Ex ante this would result in a systematic underestimation of the rate of return (because the benefit stream is truncated), whereas ex post, the reverse will occur if regression techniques are used to estimate the lag weights.

Compromised economic rationality may be revealed in the form of weak or politically distorted selection mechanisms. Underinvestment in agricultural R&D may be more pronounced than in other government activities as a result of (1) weak political lobbying by rural constituencies, (2) short political time horizons that are at odds with the long-term impact of R&D, and (3) a very diffuse benefit distribution that provides little incentive for beneficiaries to lobby strongly for agricultural R&D.

Political distortion may also occur at the level of agricultural R&D project selection. For example, asset-rich farmers lobbying for research projects of particular interest to them may distort the research agenda in their favor. Such a distortion would express itself as a differential in cutoff rates between those projects benefiting mainly affluent farmers and those benefiting mainly poor farmers. Nevertheless, after eliminating this distortion (i.e., after equalizing the cutoff rates for both sets of R&D projects) it may still be economically rational to invest more in those projects that benefit asset-rich farmers, simply because their choice set of potentially profitable R&D projects is larger.

In relation to poverty targeting, it can be argued that an extra dollar accruing to a poor farmer is worth more than an extra dollar accruing to a rich farmer. We have addressed this argument here by examining the way in which the allocation of R&D resources would change if a benefit premium was introduced for projects targeted at poor farmers. However, even with a premium of 100%, the optimal allocation of R&D resources changed only slightly: the intrinsic problem is that profitable R&D projects that target poor farmers are in short supply.

Political economy problems may arise not only as a result of different interests among farmers, but also because the interests of farmers and consumers differ. Collectively, farmers will underinvest in agricultural R&D from a social point of view, because they do not take into consideration the benefits accruing to consumers when making their R&D cost-benefit calculations. Depending on the share of benefits that reaches the consumers (which tends to be high when demand is inelastic), the R&D opportunity curve as seen collectively by farmers is positioned significantly below the R&D opportunity curve as seen by social planners. Consequently, if the funding and selection of R&D projects is left exclusively to farmers, R&D projects with a good social rate of return may not be funded; government intervention is therefore warranted. In this report, we have calculated the outcomes of various funding instruments and scenarios, assuming different levels of benefit accruing to consumers, and compared the outcomes preferred by social planners to those preferred by producers and consumers.

The two sets of explanatory factors that determine the level of underinvestment in agricultural R&D have important social capital dimensions that tend to be cumulative. Ultimately, it is this social capital that allows rich countries to generate not only a larger set of profitable agricultural R&D projects from which to choose, but also a better capacity for identifying, selecting, financing, and implementing them. If poorer countries are to catch up, they must first develop sufficient social capital to bring innovation opportunities within reach.

Acronyms

AgGDP	agricultural gross domestic product
ERR	expected rate of return
GDP	gross domestic product
IRR	internal rate of return
PPP	purchasing power parity
R&D	research and development
TFP	total factor productivity

Introduction

Since Griliches' (1958) study of US hybrid corn research, rate-of-return studies have become standard practice in documenting the economic impact of agricultural R&D. The reported ex post rates of return vary substantially (from very high to negative), but on average range from 40% to 60% (Alston et al. 2000; Evenson, 2001). Despite criticisms of the accuracy of these rates, and of the extent to which the selected projects are representative, it is widely believed that the estimated rates are robust enough to accommodate such criticisms and still fall within a range substantially above the social rate of return.[1] Based on this evidence, Ruttan (1980) and many others[2] have argued that there is serious underinvestment in public agricultural R&D, and this opinion has become widely accepted by agricultural economists and research policy analysts. Hence, any slowing in the rate of growth of public agricultural R&D expenditure, or, worse still, any reduction, gives rise to 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? Or for some types of research than others? How much more should be invested in agricultural R&D? If there *is* underinvestment in agricultural R&D, has it increased or decreased over time? In order to answer these questions, the underinvestment hypothesis needs to be defined more clearly. This report addresses the issue by introducing a simple model that represents the ideal economic version of the selection of agricultural R&D projects. The outcome in real life is, of course, different, because the assumptions of full information and strict economic behavior are only partly true. Nevertheless, it should still be possible to retrospectively detect the "invisible" forces shaping the process, and to reconstruct the ex ante choice situation (in the form of an R&D opportunity curve) from data on investment in agricultural research and the corresponding rates of return.

An approximate idea of the position and shape of the R&D opportunity curve (or, in other words, the link between R&D input and impact) not only makes it possible to estimate the underinvestment gap, but also to test the various explanations for its existence suggested in the literature. Such explanations can be roughly divided into two groups: (1) incomplete or distorted information and (2) compromised economic rationality. Although none of the suggested explanations alone can fully explain the underinvestment gap, together they go some way towards doing so.

In contrast to many others, this study explicitly assumes that the link between R&D input and impact is not fixed but can differ between countries and through time. Hence, it is logical to examine the underlying factors that determine the shape and position of the R&D opportunity curve. In this way, we have a better understanding of why R&D investment intensities differ between companies, industries, and countries, and through time. Moreover, these underlying factors can provide a basis for identifying government policies that can help improve the position of the R&D opportunity curve and hence stimulate innovation.

The selection model adopted in this study assumes that the selection process is conducted by a social planner whose only goal is to maximize *total* social benefits. The model therefore does not consider the distribution of R&D costs and benefits between producers and consumers, or between different producer groups. Introducing a political economy perspective to the model enriches the

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1 This is the minimum rate of return that governments require from their investments. See section 1.1 for further discussion.

2 See Fox (1985) for an overview.

picture substantially. By distinguishing between the R&D costs and benefits accruing to different groups, a better understanding can be obtained of the incentives for each group to lobby for a particular research agenda, or to allocate their own resources to R&D. Depending on the assumed scenario and variables, the outcome of these allocation processes may differ from those preferred by the social planner. The political economy approach also provides a basis for exploring the workings of various financial instruments and the effects of specific policies, such as explicitly targeting poor farmers.

This report provides a conceptual framework for better understanding what constitutes an optimal level of investment in agricultural R&D. While this topic is primarily of interest to agricultural research policymakers and analysts, research managers and others concerned with agricultural research investment issues may also find the study valuable for its insights into the broader context within which they operate. Furthermore, while the focus is on agricultural research, many of the ideas presented here are equally applicable to other sectors of the economy.

The report is structured as follows: chapter 1 introduces a stylized model of the economic selection of R&D projects, which provides new insights into how one could interpret a representative sample of ex post rates of return on agricultural R&D investments. Given the prominent role of rates of return to agricultural R&D in the model, chapter 2 discusses the art of calculating such rates and identifies the most important shortcomings in such calculations. Chapter 3 provides an overview of the accumulated empirical evidence on returns to agricultural R&D as compiled by Alston et al. (2000), and uses this evidence to estimate the agricultural R&D underinvestment gaps in developed and developing countries, and through time. The concept of an R&D opportunity curve is introduced in chapter 4. For illustrative purposes, such curves have been constructed by linking agricultural R&D investment data with two key variables derived from corresponding rate-of-return samples (i.e., the mode and the slope coefficient). Chapter 4 also identifies a number of factors that may determine the position of an R&D opportunity curve, and discusses government policies that could help enhance the position of such curves. Having determined the magnitude of underinvestment in agricultural R&D in chapters 3 and 4, chapter 5 explores the various possible explanations for the existence of the underinvestment gap. Chapter 6 adopts a political economy perspective by differentiating between R&D benefits accruing to different groups of farmers, and between those accruing to farmers and consumers.

Chapter 1. A Model of the Economic Selection of R&D Projects

In a strictly formal priority setting exercise, R&D projects are ranked on the basis of their expected rate of return (ERR).[1] This ERR is the internal rate of return (IRR) that equalizes the costs of an R&D project with the benefits resulting from it:

[1.1] $$\sum_{t=0}^{t=n} C_t (\hat{IRR})^{-t} = \sum_{t=0}^{t=n} B_t (\hat{IRR})^{-t}$$

where C_t and B_t represent the (expected) R&D costs and benefits in year t, and n the number of years between the start of the R&D project and the moment that the benefit stream is expected to end.

However, not only does n differ from project to project, but the cost and benefit streams also differ in length and shape. Some R&D projects, for example, take only one year to complete, while others (such as plant breeding) take 10 years or more before benefits emerge. Some technologies are adopted very rapidly, while others are adopted only very slowly. Assumptions have to be made concerning all such aspects in order to estimate the ERR. Figure 1.1 provides an example of the cost and benefit streams attributable to a particular R&D project. The benefit stream represents the sum of benefits accruing each year across all individuals in the target society, relative to the situation if the project had not been undertaken.

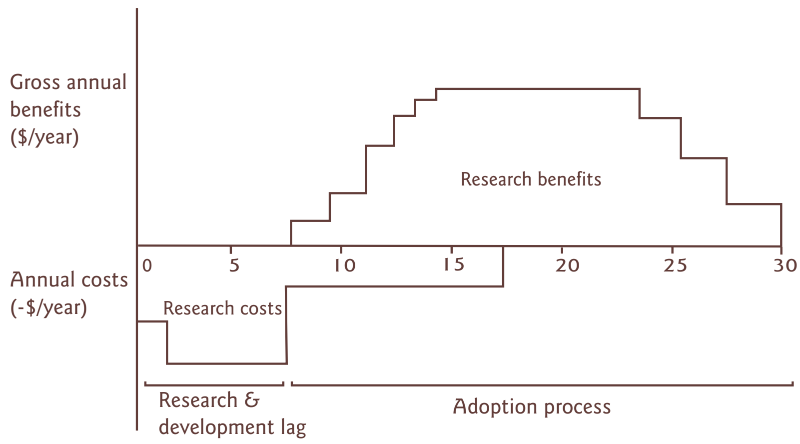

Figure 1.1: Flows of resources, benefits, and costs

Source: Alston, Norton, and Pardey (1995).

[1] It is assumed that R&D projects are independent of each other. If they are not, they should be considered together. For example, when R&D projects target the same technical problem, only the project with 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 selecting several R&D projects targeting the same problem simultaneously. In such cases, the selected projects should be considered as a single, joint R&D project.

In chapter 2, we discuss in more detail both the various methods that can be used to estimate a rate of return to agricultural R&D (either ex ante or ex post) and the problems that surround such estimates.

To examine the optimal (or, for that matter, suboptimal) allocation of agricultural research resources, some idea is needed of the set of agricultural R&D projects from which society chooses ex ante (i.e., the choice set). A simple representation of both the choice set and the selection procedure will help explain this concept. In the first instance, we assume that the number of possible agricultural R&D projects decreases from a low to a high ERR, as depicted in figure 1.2; the exact position and shape of the choice set are unknown however. Second, we assume full information and rational economic behavior. The selection of R&D projects starts with the project having 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 social rate of return, whichever comes first.[2] The social rate is the minimum rate of return required by governments on their investment activities; it is usually higher for developing than for developed countries. If the highest ERR in the ranking fails to exceed the social rate, no R&D projects should be implemented. The selection of the appropriate social rate will be discussed in section 1.1.

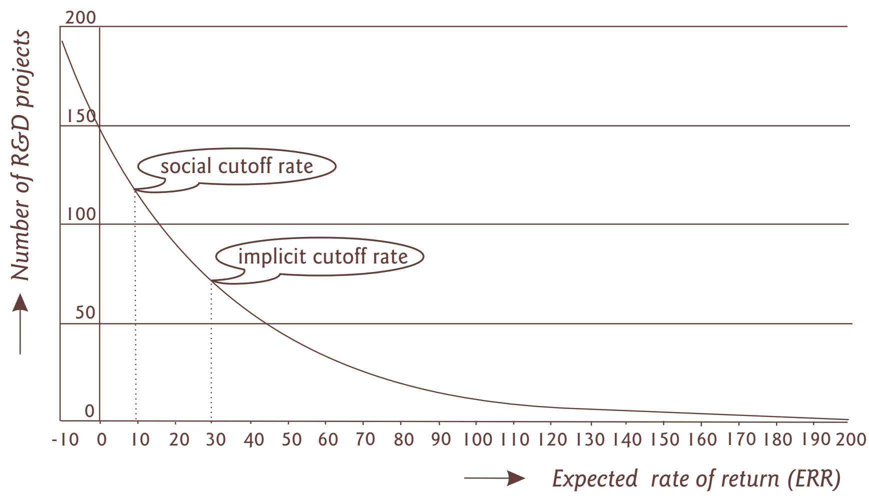

Figure 1.2: A hypothetical distribution of all possible R&D projects

When adequate funding is available (i.e., when every project with an ERR equal to or higher than the social cutoff rate will be financed), the mode of the distribution of selected projects can be expected to coincide with the social rate. When funds are limited, however, the selection of research projects stops before the social rate is reached. This creates an implicit cutoff rate, which can be expected to coincide with the mode of the distribution of the selected projects.

As shown in figure 1.2, the choice set of all imaginable R&D projects increases steadily beyond the cutoff rate. Negative rates of return indicate that the expected costs of the R&D project exceed the expected benefits.

[2] The focus here is on the marginal R&D project and not on the marginal dollar spent on a project.

The postulated choice set of R&D projects on an ERR scale can be thought of as taking the following semilog form:

$$[1.2] \qquad Y = e^{\beta_0} e^{\beta_1 X}$$

where Y is the number of R&D projects and X is the ERR. The coefficient β_1 has to be negative in order to obtain an asymptotic curve as shown in figure 1.2. The closer the slope coefficient is to zero, the flatter the choice set will be.

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

$$[1.3] \qquad Y_r = \int_r^{\infty} e^{\beta_0} e^{\beta_1 X} dx = \left[\frac{1}{\beta_1} e^{\beta_0} e^{\beta_1 \infty} \right] - \left[\frac{1}{\beta_1} e^{\beta_0} e^{\beta_1 r} \right] = e^{\beta_0^*} e^{\beta_1 r}$$

where Y_r is the number of R&D projects with a rate of return greater than or equal to r. A simpler notation for the cumulative version of the choice set is:

$$[1.4] \qquad Y^* = e^{\beta_0^*} e^{\beta_1 X}$$

where Y^* represents 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 cumulative [1.4] and the non-cumulative [1.2] version of the choice set—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:

$$[1.5] \qquad \left[\frac{\int_s^{\infty} e^{\beta_0} e^{\beta_1 X} dx}{\int_r^{\infty} e^{\beta_0} e^{\beta_1 X} dx} - 1 \right] \times 100 = \left[\frac{\int_s^{\infty} e^{\beta_1 X} dx}{\int_r^{\infty} e^{\beta_1 X} dx} - 1 \right] \times 100 = (e^{\beta_1 \Delta X} - 1) \times 100$$

where s is the social rate, r is 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 postulates:

I. Assuming full information and a strict economic selection of R&D projects, underinvestment in R&D manifests itself in a cutoff rate that is higher than the social rate.
II. The size of the R&D underinvestment gap depends on only three variables (a) the relevant social or private rate, (b) the actual cutoff rate, and (c) the slope of the choice set.

To determine whether or not there is underinvestment in R&D and, if so, by how much, variables *b* and *c* must be estimated and a value set for *a*.

1.1 Selecting the relevant social or private rate

Since underinvestment is a relative concept, it is important to determine an appropriate benchmark against which to compare the actual level of investment. The relevant benchmark for private investment in R&D is the minimum rate of return that a company sets for itself across all its activities. For companies in developed countries, such rates are typically in the range of 15–20% (real), before tax.

For public agricultural R&D investments, the relevant benchmark is not the private rate of return, but the social rate of return. By applying the same social rate across all their activities, governments try to identify those activities in which an additional dollar of investment will create the highest social benefit (i.e., those in which underinvestment is most severe).

The literature contains several definitions of the social rate, as well as various suggestions as to how it should be estimated. At present, there is no consensus among economists or policymakers regarding either issue. For our purposes, the following definitions of the social rate are the most relevant (1) the opportunity cost of capital, and (2) the social time preference rate (i.e., the rate at which society is willing to trade off present for future consumption).

The former is the most widely accepted definition and is used, for example, by the US Government and by 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 for use in evaluating 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" (Office of Management and Budget 1992). A comparable rate for developing countries is believed to lie somewhere between 8 and 15% in real terms (Gittinger 1982). A common choice, and one adopted by the World Bank, is 12%.

Zerbe and Devily (1994) made a strong and convincing case for adopting the definition based on the social time preference rate, estimating the social rate on the basis of 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 those close to 5% coming closest to the average length of an agricultural R&D project.[3] However, while market statistics for government bonds are readily available for developed countries, the same cannot be said for most developing countries, where such markets are often either nonexistent or are weak and volatile. Thus an attempt to replicate Zerbe and Devily’s estimate of the social rate for developing countries foundered on a lack of data, causing us to revert to the more traditional definition of the social rate as the opportunity cost of capital, and to adopt 7% as the relevant social rate for developed countries and 12% for developing countries. These rates are in any case probably closer to political realities. 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 estimated in chapter 3 may therefore be somewhat conservative.

It has been suggested that, for agricultural R&D, the social rate should be supplemented by a risk premium to reflect the fact that this is a significantly more risky activity than the average government project. But the White House circular argues that any notion of risk specific to agricultural R&D (or any other project) should be included in the ERR calculation rather than in the social rate. This is certainly the only correct rate against which to assess ex post results since they already include the "risk" element.

[3] Zerbe and Devily (1994) discuss at length the problem of displacement of private capital, but show that in most cases this issue can be neglected, or, if necessary, borderline cases can be accommodated by a 10% adjustment in costs. Only when government agencies are in direct competition with the private sector should the private-sector rate be applied to all proposals.

1.2 Estimating the implicit cutoff rate

In the real world, most selection committees do not rank R&D projects on the basis of expected rates of return, nor do they have a clear idea of the cutoff rate that they implicitly apply. Nevertheless, the selection criteria that are actually used do tend to reflect some kind of economic rationality. Since the selection is less than economically optimal, however, a number of R&D projects with expected rates of return 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 distribution of selected R&D projects that takes the form of a bell-shaped distribution, skewed to the right (figure 1.3).[4]

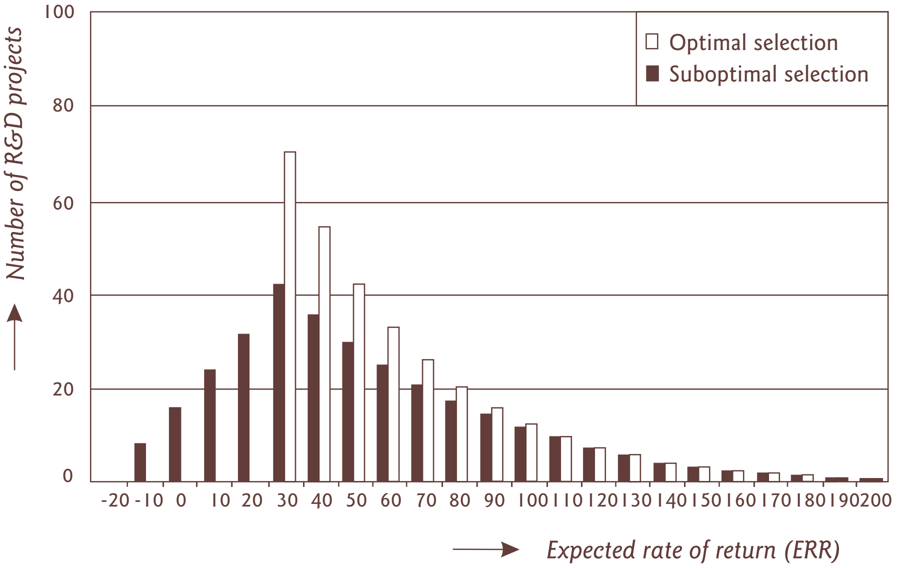

Figure 1.3: The optimal versus suboptimal selection of R&D projects

However, within reasonable limits, we can assume that the mode of both the optimal and the suboptimal distributions more or less coincide. Although this may appear to be a rather bold assumption, the opposite case—that the two modes are significantly different—is considerably less likely. Everything depends on the selection procedure. When the selection process is weak (i.e., deviates strongly from rational economic behavior), the mode of the suboptimal selection will lie to the right of the mode of the optimal selection. This implies that a large number of R&D projects with expected rates of return equal to or higher than the cutoff rate are *not* selected, while those with lower expected rates of return *are* selected, creating a relatively long left-hand tail to the distribution. Although some suboptimality in the selection procedure is unavoidable (due to imperfect information, etc.), one needs to avoid confusing an inefficient selection procedure with underinvestment (i.e., a high cutoff rate). Relevant parameters of the distribution that can indicate exceptionally poor selection efficiency are the following:

1. the percentage of R&D projects with a rate of return lower than the mode of the distribution (the higher the percentage, the more imperfect the selection procedure);
2. the position of the median of the distribution (which should always be lower than the mean, and preferably higher than the mode).

[4] For the distribution to be skewed to the right, the median of the distribution must be smaller than the mean.

It is difficult to determine at which level of selection inefficiency the assumption breaks down that the optimal and suboptimal modes coincide and, if so, how the optimal mode can be estimated, knowing only the suboptimal one. For now, it is assumed that with a moderate level of selection inefficiency the two modes roughly coincide.

An alternative possibility is that the mode of the suboptimal selection is not higher but lower than the mode of the optimal selection. This is only possible if the selection committee uses a two-step selection process: initially selecting all R&D projects with an ERR above a certain cutoff rate, and then randomly selecting from these projects until the R&D budget is exhausted. The mode of this suboptimal distribution will coincide with the cutoff rate used in the first step of this hypothetical selection procedure. Although this is, perhaps, a reasonable characterization of some selection procedures, it makes the rather implausible assumption that information concerning the ERR of R&D projects is used in the first step of the selection procedure but not in the second step. The importance of the first step in this hypothetical procedure is that without it, selected "suboptimal" R&D projects would be more spread out (creating a left-hand tail) rather than more concentrated, with a distinct mode in the distribution. All in all, the chance of finding, ex ante, a suboptimal mode that is lower than the optimal mode is negligible.

The next step in the modeling procedure is to link the ex ante distribution of rates of return to the ex post distribution. The two should be roughly identical if the following assumptions hold: (1) that expected and actual rates of return of R&D projects differ only stochastically and not systematically, and (2) that the outcome distributions of the expected rates of return are more or less symmetrical. The latter assumption clearly will not hold if the outcome of an R&D project is considered to be discrete—i.e., either a complete success or a complete failure. It is more realistic to assume that the success of R&D projects (especially biological ones) is relative rather than discrete, resulting in a continuous statistical distribution. Given the various parameters involved in an ERR calculation, each of which has its own probability distribution, the overall probability distribution of the ERR of an R&D project or program is not easy to calculate. This is particularly true if the relationships between parameters and benefits are not linear. In such cases, a Monte Carlo simulation can be used to estimate measures of 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, however, only a few studies (Greig 1979; Anderson 1991) have actually used this approach in connection with agricultural R&D, and these authors reported only slightly skewed probability distributions.

Based on a fairly strict economic interpretation of the R&D priority-setting process (i.e., that R&D investments are based on full information concerning profit opportunities and on rational priority setting), a third postulate is proposed in addition to those given previously:

III. Assuming that the *ex post* rates of return of R&D projects are selected at random and differ only stochastically and not systematically from the expected rates of return, the mode of the *ex post* distribution of rates of return of R&D projects provides a rough indication of the implicit cutoff rate used in the *ex ante* optimal selection procedure.

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 choice set is also needed to estimate the optimal R&D budget by which all R&D projects with an ERR equal to or higher than the social rate are funded. Some strict assumptions must be made to distill this information from the ex post rate-of-return results. Figure 1.4 illustrates the problem (note that all projects are assumed to cost the same). As a result of suboptimal selection, some projects with an ERR higher than the cutoff rate have not been selected, while some projects with an ERR lower than the cutoff rate have been selected. If the selection had been optimal, only R&D projects at or above the cutoff rate would have been selected. To reconstruct the ex ante, optimal distribution, the number of selected R&D projects with an ERR below the cutoff rate must be redistributed over the right-hand side of the rate-of-return distribution.

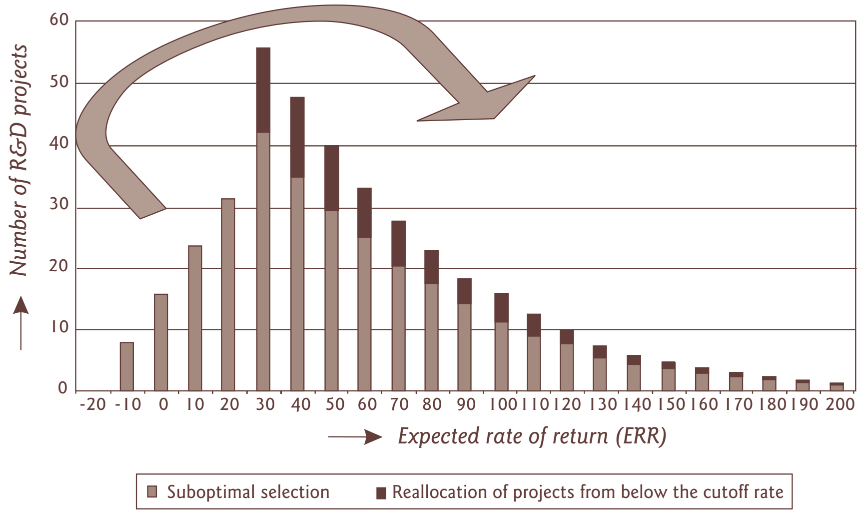

Figure 1.4: A reconstruction of the optimal selection of R&D projects

Of the various ways in which this could be accomplished, distributing the suboptimal R&D projects proportionally seems to be a reasonable approximation and has the practical advantage that the adjusted and unadjusted right-hand sides of the distribution have the same slope coefficient. However, a proportional distribution implies that all R&D projects above the cutoff rate have the same chance of not being selected. A more realistic assumption is that R&D projects close to the cutoff rate have a higher chance of not being selected than do projects with higher expected rates of return. Such a probability differential would result in a steeper optimal slope and hence a larger underinvestment gap. However, lacking empirical evidence of the probability distribution, the second-best solution, which assumes equal chance and proportional distribution, has been adopted here. Hence the following postulate:

IV. 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.

1.4 Conclusions

In this chapter, we have introduced a very simple and stylized model of the selection of R&D projects that provides the basis for a more structured interpretation of the rate-of-return evidence for agricultural research investments. By introducing imperfect information and selection, the model provides a compelling explanation for the shape of observed rate-of-return distributions. Moreover, by postulating *a priori* the type of rate-of-return distribution that can be expected, and the characteristics that can be distilled from it, substantially more information can be derived from existing rate-of-return compilations than has previously been attempted. This will be explored further in chapter 3. First, however, we will examine the problems associated with calculating a rate of return on investment in agricultural R&D.

Chapter 2. The Art of Calculating the Rate of Return to R&D

The model of R&D project selection outlined in the previous chapter is based entirely on estimated rates of return on investment in agricultural R&D. The two most common approaches to the estimation of such rates are (1) the economic-surplus approach, and (2) the production-function approach. Alston, Norton, and Pardey (1995) discuss both approaches in great detail.[1] Sections 2.1 and 2.2 of this chapter provide a brief summary of the principal characteristics of each approach. A critical step in both methods is the modeling of the relationship between investment in R&D and the benefits that result. Section 2.3 addresses the particular problems associated with the (assumed) link, through time, between R&D investments and benefits. Section 2.4 reviews the suggestion, widely discussed in the literature, that rates of return to (agricultural) R&D are generally overestimated, and overall conclusions are drawn in section 2.5.

Readers not interested in the technical details of rate-of-return calculations may omit this chapter, although we recommend reading the conclusions.

2.1 The economic-surplus approach to 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 2.1 for a closed economy.

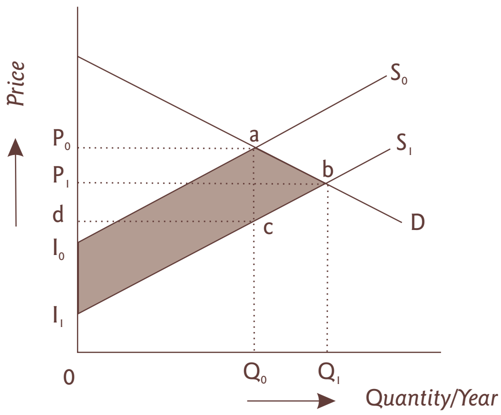

Figure 2.1: Consumer- and producer-surplus measures

[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 a number of the pitfalls associated with the parametric method used in the productio- function approach. Chavas and Cox (1992) list the following advantages of a nonparametric approach relative to parametric approaches: (1) there is no a priori restriction on substitution possibilities among inputs, (2) it allows joint estimation of production technology, technical change, and the effects of research on technical progress using very disaggregated inputs, (3) it provides flexibility in the length and shape of the lag distribution between research and productivity, (4) it permits an investigation of the separate effects of private and public research on technical progress, and (5) the method is empirically tractable. To date, however, the nonparametric approach has not been widely used to evaluate the impact of agricultural research.

D represents the demand for a homogeneous product and S_0 and S_1 represent, respectively, the supply of the product before and after a research-induced technical change. All curves (and the economic-surplus measures) are defined as flows per unit time (typically annually). The initial equilibrium price and quantity are P_0 and Q_0; those after the supply shift 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 ($\Delta TS = area\ I_0abI_1$). 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: (1) the cost saving on the original quantity (the area between two supply curves to the left of Q_0 – area I_0acI_1), and (2) 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 ($\Delta PS = area\ P_1bcd$).

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

[2.1] $$\Delta CS = P_0Q_0\, Z\, (1+0.5Z\eta)$$

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

[2.3] $$\Delta TS = \Delta CS + \Delta PS = P_0Q_0\, K\, (1+0.5Z\eta)$$

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 $Z = K\varepsilon/(\varepsilon+\eta)$ represents 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 is relatively small (reflecting a relatively small decline in price and a relatively inelastic demand respectively), it is reasonable to approximate the research-induced benefits as follows:

[2.4] $$\Delta CS = P_0Q_0\, Z$$

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

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

Or, referring back to figure 2.1, when the decline in price is small or the demand is relatively inelastic (i.e., a steeper slope than that depicted in figure 2.1), the benefits represented by triangle *abc* are negligible in comparison to the benefits represented by area P_0acP_1.

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. However, 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, a number of alternatives to this simple representation have been proposed and tested, including *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.[2] Depending on the model, the measure of estimated benefits can differ quite substantially with different alternatives. For example, given a linear supply curve function, total bene-

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

fits 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).

Not only is the elasticity of the supply curve important, but so, too, is that of the demand curve. The more inelastic the demand curve, the more likely it is that the benefits from a technical change will pass from producers to consumers in the form of lower prices. The same is true if the supply elasticity is absolutely larger than the demand elasticity: again, consumers will tend to receive a larger share of the benefits than will producers (Norton and Davis 1981). In the case of a pivotal supply shift and inelastic demand, farmers may actually be worse off after the technical change.

Having reviewed all these various supply-shift forms, Alston, Norton, and Pardey (1995) concluded 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]

The basic economic-surplus model addresses a single commodity market in isolation: no interactions with the rest of the economy (or the world) are taken into account. Alston, Norton, and Pardey (1995, chapter 4) discuss a range of possible modifications and extensions of the basic model, which (1) allow the disaggregation of economic-surplus effects across multiple markets both horizontally (e.g., across geopolitical regions, socioeconomic groups, or commodities) and vertically (e.g., across stages of production or among factors of production), (2) capture the effects of interregional and international spillovers of research-induced price changes and research results, (3) incorporate general-equilibrium feedback and economy-wide adjustments, (4) accommodate market distortions and the effects of research on the creation (or amelioration) of market distortions caused by government intervention or production externalities,[4] and (5) account for the costs of taxation in financing government spending. It is these modified and extended versions of the economic-surplus model that have attracted so much attention in the economic literature.

Whatever the size of the measured R&D benefits, a critical step in calculating expected rates of return is the linking of those benefits to past investments in R&D (or, in the case of an ex ante rate-of-return estimation, linking present-day investment in R&D to a future benefit stream). This issue is discussed in more detail in section 2.3, since it is fundamental to both the economic surplus and the production-function approach.

In summary, the process of estimating the benefits from a research-induced supply shift reduces 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 flow of benefits (the research lags) (Alston et al. 2000).

Evaluations of R&D investments based on an economic-surplus method either estimate the K-shift on the basis of information derived (preferably) from on-farm trials and observed adoption patterns (Maredia, Byerlee, and Anderson 2000), or on the basis of historical time-series data of outputs (and corresponding inputs), using econometric techniques. In the latter case 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

3 A side issue is whether the shift should be 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 the definition $dQ/Q=\varepsilon dP/P$ and therefore, $J = \varepsilon K$, where ε is the elasticity of supply (Alston, Norton, and Pardey 1995).

4 Agricultural subsidies in developed countries, for example, keep the agricultural prices used in the rate-of-return calculations artificially high. Lower prices would reduce the profitability of agricultural R&D projects across the board and lead to fewer profitable R&D projects in which to invest.

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, to calculate the *K*-shift (which amounts to the question of what it would cost to produce Q_0 using today's technology). Index number theory stresses the importance of the method by which the raw data are combined into a manageable number of subaggregates, and in turn reaggregated (Antle and Capalbo 1988). The preferred method is a chained index, such as the *Divisia* index, since it minimizes the impact of relative price changes on the aggregate quantity index. However, while the *Divisia* index proper requires continuous measurement of input prices and quantities and is therefore unattainable, several discrete approximations to it are possible, such as the *Laspeyres*, *Paasche*, *Fisher ideal*, and *Tornqvist-Theil* approximations.[5] Diewert in particular (Diewert 1976, 1980, 1981) has contributed much to a better understanding of the economic assumptions and the underlying aggregation functions implicit in the choice of an indexing procedure.[6] This improved understanding may help in matching the correct index to the correct aggregator function. Growth accounting and index number theory are also of relevance to the production-function approach discussed in the next section.

2.2 The production-function approach to 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 a given level of inputs) or the saving in inputs (for a given output) attributable to past investments in R&D.

A correct estimation of the production function is essential in order to differentiate between various possible explanations for observed differences or increases in productivity. Figure 2.2(a), adapted from Antle and Capalbo (1988), shows two single-output 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 periods 1 and 2, respectively. The 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 produced output Q_1'.
2. *Economies of scale:* Q_2 was produced with greater input than was Q_1, implying 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 figure 2.2(b). The isocost line (W_1) defines the economically efficient combination of inputs X_1, X_2 (point *a*). The observed input combination (point *b*) used to produce Q_1 is economically inefficient, and this can be separated into *technical* and *allocative* inefficiency. Technical inefficiency refers to a failure to operate at the production function (*bc*), while allocative inefficiency refers to a failure to minimize production costs (*ca*) while at the production function.

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5 See Alston, Norton, and Pardey (1995) for further details.

6 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 homogeneous translog production function. Hence, the importance of index number theory lies in the linkage of the growth accounting approach to production theory (Antle and Copalbo 1988).

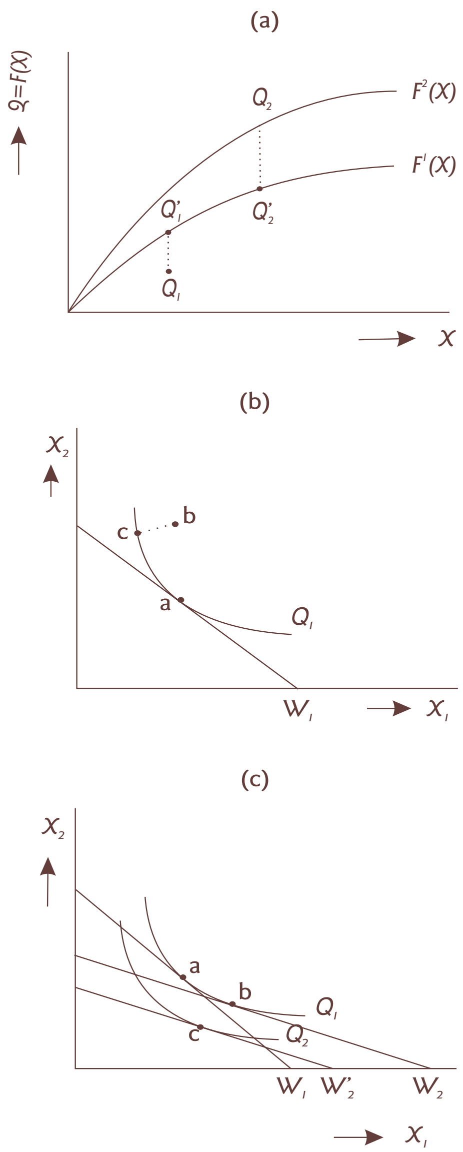

Figure 2.2: Possible explanations of productivity increases

Figure 2.2(c) depicts two production functions for periods 1 and 2. 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 to W_2) shifts, for a given technology, the economically efficient optimum from *a* to *b*. The situation becomes more complicated if, at the same time, there is a (neutral) productivity improvement so that the same level of output can be produced with fewer measured inputs (isoquant Q_2). This would lead to a new optimum, at point *c*. The difficulty in differentiating between these two phenomena lies in the fact that points *a* and *c* can be observed, whereas point *b* cannot.

The TFP, which is a key concept in the production-function approach, can be defined as aggregate output (*Q*) divided by aggregate input (*X*). For *Divisia* indices of aggregate output and input, TFP growth is therefore simply equal to the rate of growth of aggregate output minus the rate of growth of aggregate input. However, while the basic principles of the proper measurement of TFP growth are clear, some important decisions must be made regarding the extent to which inputs and outputs should be kept disaggregated when the indices are constructed. Ideally, inputs and outputs should only be preaggregated if they are perfect substitutes, or grow at the same rate (Alston, Norton, and Pardey 1995). If this is not the case, preaggregation of data may distort the measurement of TFP growth. Another, rather different, measurement problem is that, typically, no explicit allowance is made for the reduction in environmental and natural resources associated with agricultural production (e.g., as a result of land degradation, depletion of soil fertility, chemical pollution of air and groundwater, buildup of resistant pests and diseases, etc.). If the contribution of these inputs is ignored, TFP growth will be overestimated. Setting these measurement problems aside, TFP growth can be attributed to technical change and hence to past investments in R&D.

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

[2.7] $$Q_t = F(X_t , \tau_t)$$

Hence, technological progress (i.e., $d\tau/dt > 0$) is perceived as an upward shift of the production function or, equally, 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) showed 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. Under the assumptions 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 of 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 factors will be discussed briefly here, while the last factor will be examined further in section 2.3.

Choices regarding functional form are to a large extent dictated by the availability of data and the purpose of the analysis. The functional form most frequently used in the agricultural production literature is the Cobb-Douglas production function, although, since the early 1960s, more flexible forms have also been explored, including constant elasticity of 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 such an extent that they often do not make much sense (Mundlak 2000).

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

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

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

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

$$\ln Q_t = \alpha_0 + \sum_{i=1}^{m} \alpha_i \ln X_{i,t} + \sum_{g=1}^{k} \beta_g \ln K_{g,t} + \sum_{h=1}^{l} \psi_h \ln Z_{h,t} + \mu_t \quad [2.8]$$

The translog production function (suppressing the *Z* variables) can be expressed as:

$$\begin{aligned} \ln Q_t = {} & \alpha_0 + \sum_{i=1}^{m} \alpha_i \ln X_{i,t} + \sum_{g=1}^{k} \beta_g \ln K_{g,t} \\ & + \tfrac{1}{2} \sum_{i=1}^{m} \sum_{h=1}^{m} \alpha_{ih} \ln X_{i,t} \ln X_{h,t} + \tfrac{1}{2} \sum_{g=1}^{k} \sum_{h=1}^{k} \beta_{gh} \ln K_{g,t} \ln K_{h,t} \\ & + \tfrac{1}{2} \sum_{i=1}^{m} \sum_{g=1}^{k} \gamma_{ig} \ln X_{i,t} \ln K_{g,t} + \mu_t \end{aligned} \quad [2.9]$$

Where *X*, *K*, and *Z* represent, respectively, the quantities of conventional inputs, variables that determine the stock of knowledge in use (approximating the state of technology,), and various "fixed" institutional, infrastructural, and policy-related variables. As can be seen, the Cobb-Douglas production function is simply a special case of the translog production function, in which the parameters associated with 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 the so-called dual approach, which formulates production in terms of a cost or profit function. The advantage of dual functions is that they contain information concerning both optimal behavior and the structure of the underlying technology or preferences, whereas primal functions describe only the latter. Statistically, they also have the advantage of using factor prices (rather than quantities) as explanatory variables, which may avoid the problems of simultaneity that arise when input choices are jointly endogenous with output; 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) seriously questions the use of dual functions, arguing that many of 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.

Variables usually included in a production function include conventional inputs such as land, labor, and capital as well as (some selected) purchased inputs. If the available data do not differentiate inputs according to their intrinsic quality (e.g., the reporting of 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 additional careful handling, as the 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 nature of productivity change, Jorgenson and Griliches (1967) stressed the importance of all such measurement issues and pointed out 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 US private domestic economy during 1945–65, their initial estimate of annual productivity growth of 1.6% (explaining 52.4% of output growth) dropped to only 0.1% per annum (explaining only 3.3% of output growth) after correcting

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

for the following measurement distortions: (1) error of aggregation, (2) the prices of investment goods, (3) errors in relative utilization, (4) errors in aggregation of capital services, and (5) errors in aggregation of labor services. Data for other periods and with different adjustments produced less extreme differences, but did not affect the validity of their principal argument, namely that the construction of output and input indices needs careful attention if spurious TFP growth estimates are to be avoided.[11]

In addition to the conventional inputs and their quality modifiers, two sets of nonconventional inputs are usually included: 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 known whether the proposed proxy is a sufficiently close approximation of the actual phenomenon that is assumed to be having an impact on agricultural production.

Finally, since most production studies ignore annual fluctuations in weather, production indices fluctuate from year to year as a consequence of unmeasured weather influences.[12]

2.3 Modeling the link between R&D investment and R&D benefits

A range of different approximations of technological change can be found in the literature. The most common approach is to explain a change in TFP or   through past investments in R&D, but this then raises the questions of R&D expenditure *on what*, *where*, *when*, and *by whom*? Of these four questions the third (*when*) question is technically the most challenging, although the other three also need careful consideration.

Defining *agricultural* R&D has its own pitfalls. One definition characterizes R&D activities on the basis of the economic activities that are being targeted *directly*. This establishes a one-to-one relationship between agricultural R&D and agricultural production. According to this definition, R&D activities conducted by (nonagricultural) supply and processing industries (e.g., the chemical, machinery, and food-processing industries) are excluded.[13] If input indices correctly reflect quality and price changes, then the (new) technology embodied in nonagricultural inputs is already accounted for, and R&D activities by these supply industries should not be included when explaining changes in . However, if input indices fail to correctly reflect quality and price changes, then R&D activities in supply industries may explain some of the observed productivity changes in primary agriculture.[14]

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[11] The importance of constructing correct price and product indices is reflected in the findings of a study commissioned by the US Senate Finance Commission, which found that the US Consumer Price Index (CPI) overstated inflation by approximately 1.1% annually, of which 0.5% was due to index problems and 0.6% to new products and quality changes (Nordhaus 1997). With an average CPI rate of 2–3% per annum, this upward bias was far from negligible. This finding has resulted in the introduction of new and corrected price indices in the US, which have produced lower inflation rates and higher TFP growth rates than the traditional price-index methods.

[12] Alston, Norton, and Pardey (1995) argued that this practice is correct provided that the included explanatory variables are not correlated with the omitted weather variables. However, since in many cases it is quite likely that farmers adjust their input use according to the weather, the assumption that weather and input use are uncorrelated does not hold.

[13] A major exception, however, is the seed industry, which, according to the international economic activity classification scheme, is classified under primary agricultural production.

[14] As shown in section 2.4, a (substantial) proportion of the benefits of R&D activities undertaken by supplying industries are appropriated by those industries. Hence the relationship between τ and R&D in supplying industries is different between industries and also between supply industry R&D and that which directly targets agricultural production.

But basic research, by its very nature, does not fit into a classification scheme based on economic activity. Possible solutions to this problem include (1) ignoring it, (2) prorating it, or (3) including it as a separate variable. Each solution has a different effect on the link between R&D expenditure and . If the productivity analysis focuses on just one commodity or cluster of commodities, it is not only necessary to identify the R&D specific to that commodity (or cluster of commodities), but also the generic (i.e., not commodity-specific) agricultural R&D activities. In this case, the solutions listed above for basic R&D can also be applied. 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 the preferred approach.

Regarding the question of *where* the R&D expenditure took place, the answer is usually determined by the geographical location of the production under consideration, such as a state or province, a country, or a particular region of the world. The underlying assumption is that the R&D taking place in a particular geographical location is targeted primarily at production in that location. This assumption holds reasonably well for public agricultural R&D, which tends to be location specific. If the assumption of location does not completely hold, the concept of technology "spillovers" has been adopted to deal with the issue, at least conceptually.[15] In the case of R&D activities conducted by supplying industries, there can be a significant difference between the location in which the research is carried out and the geographical area in which it has an impact on agricultural production. In the case of multinational corporations, this area could encompass a large number of countries. In such cases, the assumption of location specificity has little validity, and trade data (assuming that technology becomes embodied in products) may be a better way of tracing the geographical impact of such R&D (Roseboom 2000).

By *whom* R&D is undertaken (or by whom it is financed) is of minor importance in explaining TFP growth. However, some differentiation between R&D practitioners may be warranted if 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 may differ from that of private companies in terms of lag, length, and form (Griliches 1973). It is in establishing the link between the research activity and the benefit stream that some differentiation on the basis of R&D practitioner or by research field may be relevant. Thus the lag, length, and form of the R&D benefit stream from forestry research may differ from those of crop, livestock, or fisheries research, or, for that matter, from R&D in other industries.

In order to link present changes in TFP to past research investments (the *when* question), the concept of a *knowledge stock* has been introduced, which, in a similar way to the capital stock concept, allows for an estimation of a service flow measure of knowledge. 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:

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

where *I* represents additions to the knowledge stock as a result of R&D and *D* represents depreciation 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 the equation above, 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). The one exception is when $\delta = 1$, which implies that the knowledge stock completely depreciates in one period and $K_t = I_t$. The opposite extreme is to assume that the stock of useful knowledge does not depreciate at all ($\delta = 0$), implying that increments in knowledge in the past are just as effective today as are the most recent increments in

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

knowledge. Neither extreme is realistic. Alston, Craig and Pardey (1998) cite several studies from the literature on industrial R&D 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 that $\delta = 1$), 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 $_t$) as a function of a finite lag of research investments, $R_{t\text{-}GL\text{-}LL}$, so that

[2.11] $$K_t = I_t = \mathrm{i}(R_{t\text{-}GL}, R_{t\text{-}GL\text{-}1}, \ldots\ldots, R_{t\text{-}GL\text{-}LL}, \;_t)$$

where GL represents the gestation lag (the time taken before research makes its first impact), LL represents the total lag length (the period over which R&D is assumed to have an impact), and $_t$ represents chance. Other possible explanatory variables, which have been omitted here, include (1) the current state of knowledge, (2) various factors affecting the productivity of research, such as research orientation (it is easier to make progress in some areas than in others), or improvements in the organization and management of research, and (3) spillovers of knowledge from other industries or from research conducted elsewhere.[16]

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, depicted in a stylized way in figure 2.3: (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 or failure of crop-protection chemicals) or to obsolescence (replacement by a better technique) (d–e). Based on the diffusion literature, an S-shaped diffusion pattern is assumed, as well as an adoption ceiling (A^{MAX}). The R&D benefit stream can be infinite, depreciate gradually (since biological innovations tend to erode), or end abruptly as the technology is replaced by a better one (Schumpeter's "creative destruction"). In the latter instance, a mirrored S-shaped phasing out of the technology can be expected, complementary to the diffusion of the new technology.

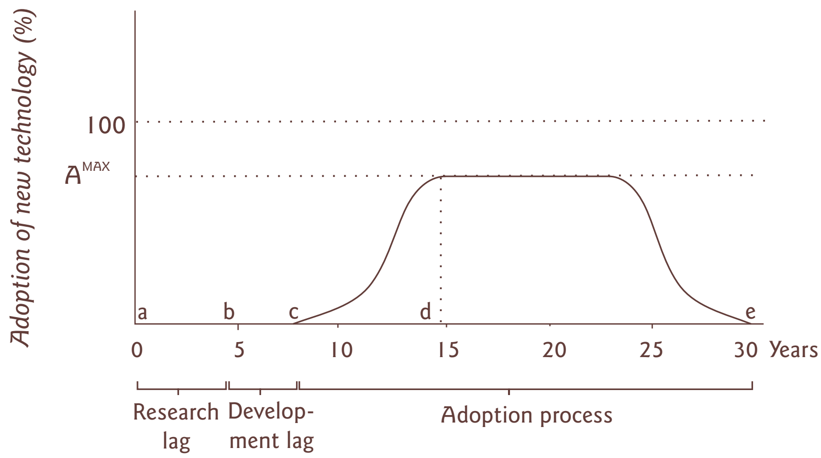

Figure 2.3: Research, development, and adoption lags

[16] Griliches (1979) provides an excellent discussion on modeling within-industry and within-economy knowledge spillover effects.

Evenson (1968) was the first to investigate the question of research lag and length using an econometric approach, and he found that an "inverted-V" distributed lag form best fitted his data, with the greatest influence arising after a lag of 5–8 years and the total effect dying out in about 10–16 years. In most rate-of-return studies on agricultural R&D investments, however, a functional form is imposed on the R&D expenditure data, rather than being formally derived. This is usually done to avoid multicollinearity and degrees-of-freedom problems, rather than on the basis of prior theoretical considerations. Furthermore, 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.[17] Pardey and Craig (1989), using a free-form lag structure to model the relationship between agricultural output and public-sector agricultural research in the USA, found evidence to suggest that the impact of research expenditure on agricultural output may last as long as 30 years—considerably longer than had previously been assumed. Chavas and Cox (1988, 1992) produced similar evidence using a nonparametric approach. However, the questions of which length and functional form should be preferred when modeling research lags remain unanswered.

The use of the correct lag structure is important, because the implied internal rate of return 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) reinforced this point by comparing R&D benefit streams with different lags, lengths, and profiles and finding important differences in the implied internal rates of return. A further advance in tackling this problem was made by Alston, Craig, and Pardey (1998), who assumed the following linear form between TFP (τ_t) and the useful knowledge stock (K_t):

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

where W_t represents a single weather-related variable and u_t the usual random residual.[18] Quasi differencing this equation and using equation 2.12 gives:[19]

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

Taking innovation in equation 2.11 to be a linear function of a finite lag of past logarithms of research investments

[2.14] $I_t = \quad b_s \ln R_{t-s}$

The unobserved capital stock term in equation 2.13 can now be replaced by I_t (see equation 2.10) to yield:

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

This model nests the three depreciation alternatives discussed earlier: (1) the stock of knowledge never depreciates ($\delta=0$), (2) the stock of useful knowledge vanishes in finite time, ($\delta=1$) (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) used this model to evaluate typical assumptions concerning the shape of the research lag, as well as the implicit assumptions concerning knowledge depreciation associated with explicit assumptions concerning the research lag length. Their findings

[17] See Alston, Norton, and Pardey (1995, 178–185) for a detailed description of these functional forms.

[18] Alston, Norton, and Pardey (1995) suggest a far more complicated relationship between and K, involving the stock of farmers' human capital, extension expenditures, and the relative prices of outputs and inputs.

[19] In this case, quasi differencing involves lagging equation 2.12 by one period, multiplying with (1–), subtracting the result from equation 2.12, and reducing terms to get equation 2.13.

> "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 dramatic. The statistically preferred method indicated a real, marginal internal rate of return to public agricultural research in the United States of 6.8 % per annum, whereas a more typical model, using a trapezoidal lag structure with shorter lags, indicates a typical rate of 48% per annum." (Alston and Pardey 2000, p. 20).

2.4 Attribution imperfections affecting rate-of-return estimations

It should be clear by now that calculating rates of return on investments in agricultural R&D is not without problems. A wide range of factors can affect the ultimate outcome of such calculations, and, given the (on average) high rates of return reported by most studies, there is a general tendency to attribute these results, at least in part, to methodological flaws. Alston and Pardey (2000), for example, argued that rates of return on agricultural R&D investments tend to be overestimated as a result of attribution imperfections. They focused in particular on spillovers of research results from parallel research programs and on the temporal aspects of benefit attribution (see above).

Another major weakness in rate-of-return calculations lies in the treatment of purchased inputs. Usually only a limited number of the purchased inputs arising 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 are considered representative of all purchased industrial inputs (e.g., see Hayami and Ruttan 1985).[20] This would be acceptable to some extent if the R&D activity and subsequent spillover across all input suppliers was more or less the same, but this assumption is highly questionable. Moreover, in international comparisons, input quantities rather than values are used, so that process innovations in the input industry that lead to lower input prices are not accounted for. Neither are such quantities usually adjusted for quality differences and changes (Craig, Pardey, and Roseboom 1997).

Even when input prices are available (as in many national studies), the standard price indices tend to have some significant shortcomings. As discussed in section 2.2, one such shortcoming is the type of price index, while another is the general failure of price indices to correctly represent the introduction phase of a new product or new input. As Nordhaus (1997) pointed out, the standard procedure is to "link" new goods and services to the price index rather than to re-price the basic category taking into account the quality change. In other words, the first impetus given to economic growth by the introduction of a new product or new input is not measured.[21] In addition, the price of many new products or inputs often declines quite rapidly in the first few years following their introduction. The fact that there is usually some delay before new goods and services are included in the price index also contributes to the underestimation of their contribution to economic growth (Griliches 1979).

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[20] Mundlak (2000) and his colleagues at the World Bank made a major effort to improve the measurement of capital input into agricultural production in 58 countries. Their efforts yielded significantly different results from earlier cross-country productivity analyses.

[21] Nordhaus (1997) somewhat overextends his argument by comparing horses with automobiles. The first automobiles were little more efficient than horses: only with steady improvement have automobiles become so superior. Nevertheless, despite all technological progress, the average speed of traffic in London in the 1990s was the same as that observed a century earlier.

Overall, then, the way in which purchased inputs are treated in (agricultural) productivity analyses and rate-of-return studies is rather unsatisfactory and constitutes a considerable source of distortion. Only proper measurement of quality adjusted inputs and prices can limit this problem and correctly capture the benefits arising from input use in (agricultural) production, eliminating any unaccounted-for spill-ins related to their use.[22] Since this ideal is unlikely to be achieved, alternative approaches have been developed that try to explicitly measure technology spillovers (including those associated with purchased inputs), rather than eliminate 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 processes of other industries. It is assumed that technology proximity rather than transaction intensity facilitates such knowledge spillovers. The direction and intensity of rent and knowledge spillovers may therefore differ. In practice, however, because it is empirically difficult to dissociate rent spillovers from knowledge spillovers, there may be considerable ambiguity in any attempt at analyzing technology spillovers.

Figure 2.4, adapted from van Pottelsberghe (1997), provides a schematic overview of potential rent and knowledge spillovers. Intermediate inputs, investment goods, patent flows, and technology proximity are the four channels by which technology spills over from one industry to the next.[23]

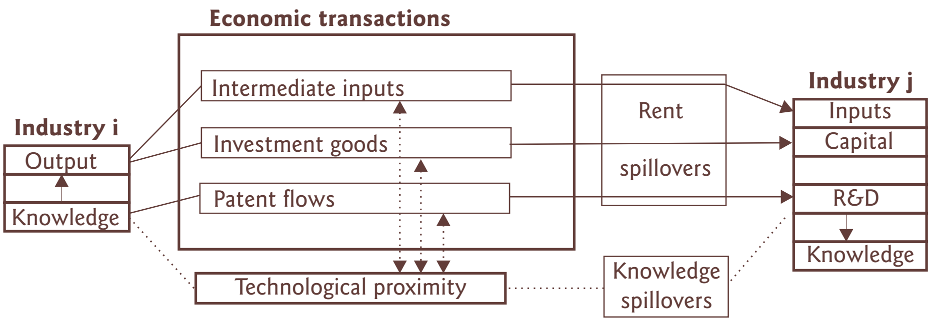

Figure 2.4: Potential rent and knowledge spillovers from industry i to industry j

Most studies of technology spillovers focus on only one type of spillover channel. Only a few studies have tried to compare different approaches or to 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:

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

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

[22] There is yet another type of spillover not accounted for by the correct measurement of input use and prices, namely the spillover of ideas and knowledge between industries.

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

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

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

$M_{i,j}$ 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 which are likely to be used by industry *j*;[24] $w_{i,j}$ is an indicator of industry *j*'s proximity to 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 rent spillovers and $S_{w,j}$ 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) concluded that the technology flow matrix is closer to the input-output matrix than to the technology proximity matrix, and hence better matches the rent than the knowledge spillover.

Roseboom (1999, 2000) gives an example of the application of the input-output matrix approach to the measurement of technology spill-ins into primary agricultural production. While the approximation of $S_{m,j}$ and $S_{k,j}$ in itself is interesting, the actual measure of technology spillover requires two additional pieces of information: (1) the success rate of R&D in each of the supplying industries (since this defines the total R&D benefit), and (2) the extent to which 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 (R&D input equals R&D output), and hence is ignored. This may not be a valid assumption. With regard to the second issue, some strong opinions have been expressed in the literature. For example, it has been suggested that multinational companies manage to appropriate all, or nearly all, of the benefits from their R&D, so that farmers have little or nothing 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 benefits from R&D (either from within or outside the agricultural sector) are passed on to processing industries or consumers through lower agricultural prices. Since farmers operate in a very fragmented and competitive industry, they are not in a strong position to appropriate much of the benefit from R&D.

From the perspective of the innovator, both the total benefits and the benefit distribution can be estimated by an economic-surplus model. One of the standard findings of such models is that the more inelastic the demand, the more the user, rather than the producer (and innovator) of the new input, will appropriate the benefits of the R&D. However, as discussed by Moschini and Lapan (1997), the economic-surplus model needs considerable modification in cases in which 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 not only affects the overall amount of R&D benefits, but, more important, their distribution. In their study of 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 the farmers (but with a negative effect on nonadopting farmers) and 40% to the 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 of the benefit distribution of the use of *Bt* technology in cotton in the USA.[25] They estimated that about half of the benefits from *Bt* cotton accrue to Monsanto and related seed companies, 40% to farmers, and 10% to consumers.

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[24] 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 royalty payment data are not available.

[25] *Bacillus thuringiensis* (Bt) is the name of a bacterium from which genes have been isolated and inserted into various crops in order to confer resistance to certain insect pests.

From the perspective of the user (rather than the innovator), the standard approach is to explain the growth in total factor productivity of an industry through their own R&D investments and through R&D investments by supplying industries, as well as by industries that supply patents, or by industries that are technologically close. A selective list of rate-of-return results from various studies using different approaches is presented in table 2.1. Including outside R&D in the rate-of-return calculation for one's own R&D usually considerably reduces the rate of return to the latter. The rate of return to external R&D could be interpreted as the "net" social rate of return, i.e., the social rate minus the private rate to the innovator. Hence the evidence provided here suggests not only that the social rate exceeds the private rate by a considerable margin (often more than double), but also that this margin differs significantly between industries and studies. Nevertheless, these studies all provide surprisingly consistent evidence for the existence of important technology spillovers (Griliches 1995).

Table 2.1: Selected Estimates of Returns to Own and Outside R&D

Type of study	Author	Rate of return to own R&D	Rate of return to external R&D
Case studies	Mansfield et al. (1977)	25	56
Input-output 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)

It is not easy to compare the results of various approaches to calculating R&D benefit spillovers because the information needed to do so is rarely available. For example, in order to translate the difference between the social and private rate of return into a benefit distribution, it is necessary to know the cost-benefit structure of the underlying R&D project(s). Thus the benefit distributions determined by Moschini, Laplan, and Sobolevsky (1999) and Falck-Zepeda, Traxler, and Nelson (1999) cannot be translated into a private or social rate of return, because the actual R&D expenditure by Monsanto and the other seed companies is unknown. Nevertheless, there is good reason to believe that the R&D benefit distribution between producers/innovators and users varies considerably, not only between industries, but probably also over time and between different groups of users.

2.5 Conclusions

Despite several decades of dedicated work by economists on rates of return to (agricultural) R&D, there are still considerable problems associated with such studies. This chapter has provided an overview of the most common of these problems. Three issues in particular stand out:

1. **The choice between adopting an economic-surplus, production-function (primal or dual), or a nonparametric approach.** Since each has its own strengths and weaknesses, the approach selected will ultimately depend on the context within which a particular analysis is conducted and on any 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) focuses in particular on the lag structures that are usually assumed in rate-of-return studies, as well as on the issue of knowledge stock depreciation. Some of their (still somewhat experimental) results suggested that lag structures are longer and more complex than usually assumed, resulting in lower rates of return than previously estimated.
3. **The importance of correctly measuring and aggregating inputs and outputs cannot be stressed enough, but in practice is hardly ever satisfactory.** The poor coverage of purchased inputs in most agricultural rate-of-return studies is particularly disturbing, since it creates a significant risk of attributing productivity increases to one's own R&D rather than to the use of inputs and the underlying R&D conducted by supplying industries. This seriously limits progress in the formal modeling of the relationship between R&D and production, and reduces the degree of confidence that one can place in the measured impact of R&D.

The fact that agricultural R&D impact assessments are still surrounded by considerable uncertainty is a major handicap in convincing policymakers and taxpayers that public investment in agricultural R&D is a profitable proposition, and that more, rather than less, should be invested in such R&D. Although the evidence may look impressive, it is not beyond criticism. Defenders of the underinvestment hypothesis share many of these published concerns, but argue that the average rate of return is so high that even after adjusting for the various uncertainties, the evidence will still hold. Although the evidence generated by Alston, Craig, and Pardey (1998) has somewhat undermined this position, at least for the USA, in the following chapters the reported rate-of-return results will be taken at face value, although they are interpreted rather differently, using a model that imposes considerably more structure on the underinvestment hypothesis.

Chapter 3. The Empirical Evidence

The agricultural-economics literature has frequently referred to the (on average) high rates of return reported for investments in agricultural R&D as being indicative 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 concerning relative underinvestment in agricultural R&D than does the mean or median. It is therefore necessary to reinterpret the rate-of-return results compiled by various authors in the past (Evenson, Waggoner, and Ruttan 1979; Echeverría 1990; Alston and Pardey 1996).

3.1 A sample of rates of return to agricultural R&D

The two most recent compilations of rates of return to agricultural R&D are those by Alston et al. (2000) and Evenson (2001). Both compilations overlap to a considerable extent and generate more or less the same descriptive statistics, such as averages and spread. In the present study, we use the data set compiled by Alston et al. (2000), which covered some 292 agricultural R&D rate-of-return studies published between 1958 and 1998. Together, these studies provided 1,886 rate-of-return observations. The meta-analysis conducted by Alston and his colleagues focused on how differences in rates of return can be explained by differences in the methods used to calculate them, and by differences in research focus, location, time, and so on.

For the purposes of the current study, a large number of the reported rates of return had to be eliminated because they were insufficiently comparable. Those eliminated were (1) rate-of-return observations that were not discrete [reduction in the number of observations = 32], (2) private rates of return [61], (3) nominal rates of return [512], (4) rates pertaining to extension only [41], and (5) rates of return pertaining to aggregate research programs (i.e., crops or livestock) or to all agricultural research [430].[1] This left us with 796 reasonably comparable rate-of-return observations of agricultural R&D projects or programs.

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). Since the analysis conducted here required only a single rate of return per project, multiple observations had to be reduced to just one. Since there is no solid theoretical basis for preferring one method to another, an average was calculated for each project.[2] This further reduced the number of observations to 201, of which 78 referred to developed countries (mainly USA) and 123 to developing countries. It is assumed that these 201 rate-of-return observations represented a reasonable sample of all agricultural R&D projects that have been undertaken worldwide. Although R&D projects with low or negative rates of return are probably underrepresented in the sample, we assumed that this had relatively little effect on the two parameters that we wanted to estimate: the implicit cutoff rate and

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[1] Such R&D programs are far too aggregated to provide meaningful information on the selection of R&D projects. Even after correction, the set of results we used was still somewhat biased towards research programs rather than discrete research projects. The latter are preferred to achieve as close a correspondence as possible with the ex ante choice situation. 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.

[2] Alston et al. (2000) discuss in detail the wide variety of methods available for calculating rates of return, and provide some quantitative insight into how rate-of-return results can be affected by the method used. However, they do not recommend any particular method.

the slope coefficient. Each observation was given the same weight, implying that the cost of each R&D project was the same.

The rate-of-return observations that we used covered a 40-year time period and included data from a wide variety of countries from all over the world. Ideally, we would have liked to have had rate-of-return samples for each country and each year. Unfortunately, we had to work with a substantially more limited data set, which allowed us to examine only the outer contours of the selection process. We divided the data set into two subgroups (developed countries and developing countries), but any further subdivision would have made the subsamples too small. Combining rate-of-return data in this way involves the implicit assumption that within each of the two groups, all countries operated under more or less the same budget constraints. Given the fact that a wide range of agricultural R&D intensity ratios (from as low as 0.01% to close to 5%) can be found among both developed and developing countries, this appears to be rather a bold assumption. However, weighting each country observation by the size of its agricultural sector gives a very different picture (table 3.1).

Table 3.1: Distribution of AgGDP across Agricultural Research Intensity Ratio Brackets

R&D intensity ratio (%)	Share of AgGDP operating under a particular R&D intensity ratio in 1981–85 (%)	
	Developing countries	Developed countries
0.25<	7.91	0.00
0.25–0.5	79.27	5.19
0.5–1.0	9.32	22.22
1.0–1.5	2.25	12.76
1.5–2.0	1.05	1.17
2.0–2.5	0.03	37.59
2.5–3.0	0.13	16.34
3.0–3.5	0.00	3.29
3.5–4.0	0.02	0.96
>4.0	0.02	0.48

Source: Based on Pardey, Roseboom, and Anderson (1991)

Over the period 1981–85, the average agricultural R&D intensity for developing countries was about 0.41%. As can be seen in table 3.1, the spread around this average intensity is relatively limited when country intensities are weighted by the size of their agricultural sectors: during the early 1980s, nearly 80% of all agricultural production in developing countries operated under an agricultural research intensity ratio of 0.25–0.50%. Hence, in this case, the assumption that developing countries as a group operated under more or less the same budget constraints is realistic.

The situation is different for developed countries. The average agricultural R&D intensity for developed countries was about 2.01% over the period 1981–85, but there is a greater range of intensity ratios, with one peak in the 2–3% intensity ratio bracket and one in the 0.5–1.5% intensity ratio bracket (table 3.1). The latter bracket was dominated by France, Italy, and Spain, all of which have significant agricultural sectors. These two peaks in the intensity ratio distribution would suggest that dividing the developed-country sample into two subsamples is warranted, one group (including France, Italy, and Spain) operated under a tighter budget constraint than the other. However, the rate-of-return sample for developed countries is dominated almost exclusively by American, Australian, and Canadian observations. The number of European rate-of-return studies in the sample is very limited, and the countries in the lower intensity ratio bracket are represented by only one rate-of-return observation in the sample. Splitting the developed-country sample was therefore not a legitimate option. At the same time, we can ignore our otherwise justifiable concern over combining rate-of-return observations from different countries operating under quite different budget constraints.

Figure 3.1 plots the distribution of ex post rates of return for both developed and developing countries. As can be seen, the "mode" is more obvious for developed than developing countries, which may be due to a greater diversity of innovation opportunities (i.e., the ex ante choice sets) among developing countries. This is confirmed by the differences in region-specific distributions reported in tables 3.2–3.4.

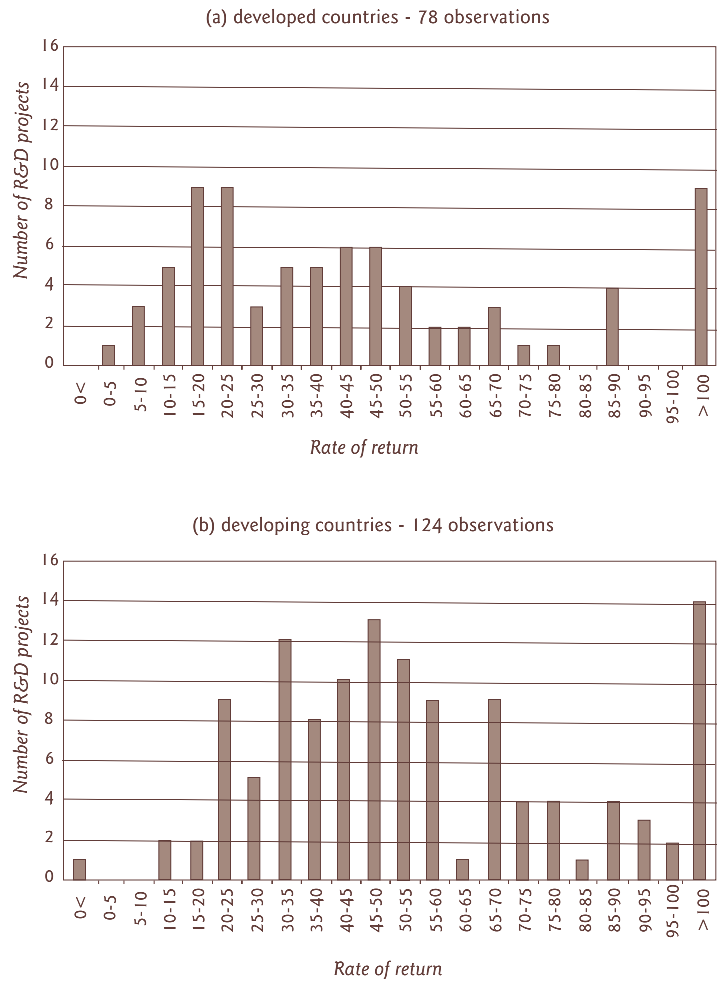

Figure 3.1: Ranked distribution of ex post rates of return to agricultural R&D

Table 3.2 provides more detailed and differentiated information concerning the characteristics of the rate-of-return distributions. The differentiation between developing regions is somewhat speculative due to the relatively small number of observations, but the distributions follow the expected pattern reasonably well. In all cases, the distribution is skewed to the right, 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 from 20 to 40%. If the distribution was perfectly representative (which, unfortunately, is not the case here), this share would give an objective indication of selection performance.

Table 3.2: Characteristics of the Various Rate-of-Return Distributions

	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 has been based on the date of publication.

The sample used here includes a few very high rates of return (up to 855%), which in some instances results in relatively high standard deviations, 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. Our rate-of-return sample may not only have a blind spot where failed R&D projects are concerned, but it may also be biased toward the extremely successful cases, since very successful R&D projects have a higher chance of being selected for an ex post evaluation.

When the samples are divided into two periods (i.e., studies published before and after 1985), the characteristics of the distributions remain largely the same, reinforcing the basic ideas of the model.

To estimate the underinvestment gap, it is relevant to know not only the implicit cutoff rate and the social rate, but also the slope coefficient, β_1. The approach adopted here is to estimate β_1 by regressing the right-hand-side rate-of-return observations (those above the cutoff rate) of the ex post *accumulated* ranked distribution. Rates of return higher than 100% were excluded to eliminate their distorting effect on the estimation of the slope coefficient. As shown in table 3.3, this leads to a substantially better statistical fit of the model. Moreover, by excluding rate-of-return observations above 100%, the normal probability plots of standardized residuals were considerably improved (i.e., they formed a more or less straight line), increasing our confidence in the predictive value of the slope coefficients.

Table 3.3: Regression Results for Estimating Slope Coefficient β_1

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

Varying the implicit cutoff rate by 5 percentage points for the developed countries and 10 percentage points for the developing countries only slightly affected the slope coefficient. Splitting the data set into two time periods neither radically changed the slope coefficients nor suggested a notable change in the cutoff rate over time. Splitting the developing countries into regions, however, led to differences in both implicit cutoff rates and slope coefficients, partly explaining why we did not find a very clear mode for the developing countries as a group. Given the relatively small number of observations, these latter results are not very robust statistically. Since the normal probability plots of the standardized residuals for Africa, Asia, and Latin America cast doubt on the normality of the data, the predictive value of the slope coefficient in these cases is relatively poor.

In summary, the estimated slope coefficients are a reasonable approximation of the slope coefficient of the ex ante optimal distribution of R&D projects provided that the following assumptions more or less hold:

1. The semilog function is a good approximation of the choice set of R&D projects.
2. The ex ante selection of R&D projects, although not optimal, has been sufficiently rigorous (in an economic sense).
3. All R&D projects with an ERR above the implicit cutoff rate have an equal chance of not being selected.
4. Differences in the ex ante and ex post rates of return are merely stochastic and not systematic.
5. The stochastic variation has a normal distribution.
6. The sample of ex post rates of return is only biased at the extreme ends.
7. The R&D projects in the sample are assumed to be equal in size.

3.2 Estimating the agricultural R&D underinvestment gap

With estimates available for both the implicit cutoff rates and the slope coefficients, and with the social rate set at 7% for developed countries and 12% for developing countries, the underinvestment gaps were calculated using equation 1.5 (see page 5). The results of these calculations are presented in table 3.4 and indicate a considerably larger underinvestment gap for developing countries (137%) than for developed countries (40%); separating the sample into studies before and after 1985 barely affects these results. However, since the identified mode was only very approximate, we adopted extreme values for it to generate the 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 reveals considerable variation in both the cutoff rate and the slope coefficient and suggests that underinvestment in agricultural R&D has been particularly high in Latin America. Statistically, however, these regional estimations are not very robust.

Table 3.4: Underinvestment Gap Estimates

	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% lower cutoff rate	15%	-0.0259	23.1%
5% 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% lower cutoff rate	30%	-0.0300	71.6%
10% 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%

While there is considerable room for improvement in the statistical data used in the present analysis (both in coverage and in the quality of the rate-of-return methods used), the model nevertheless quite nicely unravels what initially appeared to be a Gordian knot. It shows that the high *means* of the rate-of-return distributions do not, as such, constitute evidence of underinvestment in R&D, nor do they indicate the size of the underinvestment gap. The approximated *modes* of the rate-of-return distributions are substantially better indicators of underinvestment.

It is important to appreciate that under- or overinvestment in agricultural R&D is always relative to the choice set of profitable innovation opportunities available; (re)constructing the ex ante choice set of R&D projects is therefore important. This, in essence, is what priority setting methods attempt to achieve. Even with relatively simple priority setting tools (such as scoring methods), it is possible to adequately identify R&D projects with very low or high rates of return; the real problem lies in the region close to the cutoff rate, where one can expect to find the majority of R&D projects, and where differences in the rate of return between R&D projects are relatively small. Given the uncertainty surrounding the relative ranking of R&D projects, the advantage of using a more sophisticated (and costly) economic-surplus method in priority setting is less clear than is sometimes suggested. Reducing the choice issue to those R&D projects close to the cutoff rate, the gains to be made from a better ranking method may be relatively modest. The economic-surplus approach has a clear advantage over scoring methods in that it reveals ERR values. As indicated above, this is important for determining whether there is under- or overinvestment in agricultural R&D. A scoring method provides only a relative ranking.[3]

Innovation *needs* should not be mistaken for innovation *opportunities*. In poor countries in particular, innovation opportunities are far more limited than innovation needs. Although this is unfortunate, it is counterproductive to advocate investment levels that would lead to the funding of agricultural R&D projects with low or negative expected rates of return. In such cases, it would be better to place more emphasis on creating an environment in which innovation could prosper. This in turn may enhance the choice set of possible R&D projects, and hence attract more investment into R&D.

In the next chapter, the characteristics distilled from the rate-of-return distributions are linked to the corresponding agricultural R&D investment levels, leading to the construction of so-called "R&D opportunity curves," which show an approximate link between R&D input and impact. We then explore the factors that determine the position of an R&D opportunity curve and try to identify possible intervention points that could be used to improve its position.

[3] The highest-ranking R&D project may still have an ERR that is lower than the social rate; therefore neither it, nor any of the lower ranked projects, should be implemented.

Chapter 4. Linking Impact to Expenditures: the R&D Opportunity Curve

Any discussion of underinvestment in agricultural R&D is predicated on the assumption of a relationship between R&D investment and increased productivity. Without some relationship between innovative input and impact there is little for the policymaker to relate to. Metcalfe (1995) depicted this relationship in terms of an *innovation possibility frontier* (figure 4.1), which relates the reduction in unit production costs achieved in a given time period to investment in R&D.

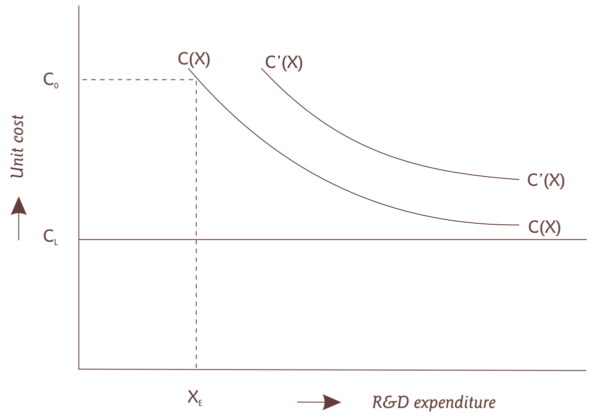

Figure 4.1: The innovation possibility frontier

C_0 in figure 4.1 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 more quickly) shifts the innovation possibility frontier upwards. In this simple model, the optimal level of R&D investment by a firm (or for that matter by a government research agency) is determined by the point at which marginal research costs equal marginal research benefits.[1] Metcalfe's innovation possibility frontier is purely theoretical: he provides no empirical evidence to support it, and the actual relationship between innovative input and impact (i.e., the position of the innovation possibility frontier) remains unclear. This chapter attempts to reveal this relationship for public agricultural R&D by introducing a somewhat modified version of Metcalfe's innovation possibility curve, namely the R&D opportunity curve.

1 See Nordhaus (1969), Binswanger (1978), and Metcalfe (1995).

4.1 The construction of an R&D opportunity curve

An *R&D opportunity curve* analogous to Metcalfe's innovation possibility frontier can be constructed by linking certain characteristics of the (reconstructed) ex ante choice set of agricultural R&D projects (i.e., the implicit cutoff rate and the slope coefficient β_1) with past agricultural R&D investment levels derived from Anderson, Pardey, and Roseboom (1994).[2] The implicit cutoff rate in combination with the actual investment level (either absolute or relative) provides the single point needed to fix the position of the R&D opportunity curve in the graph (see figure 4.2). The rest of the curve is defined by the slope coefficient.

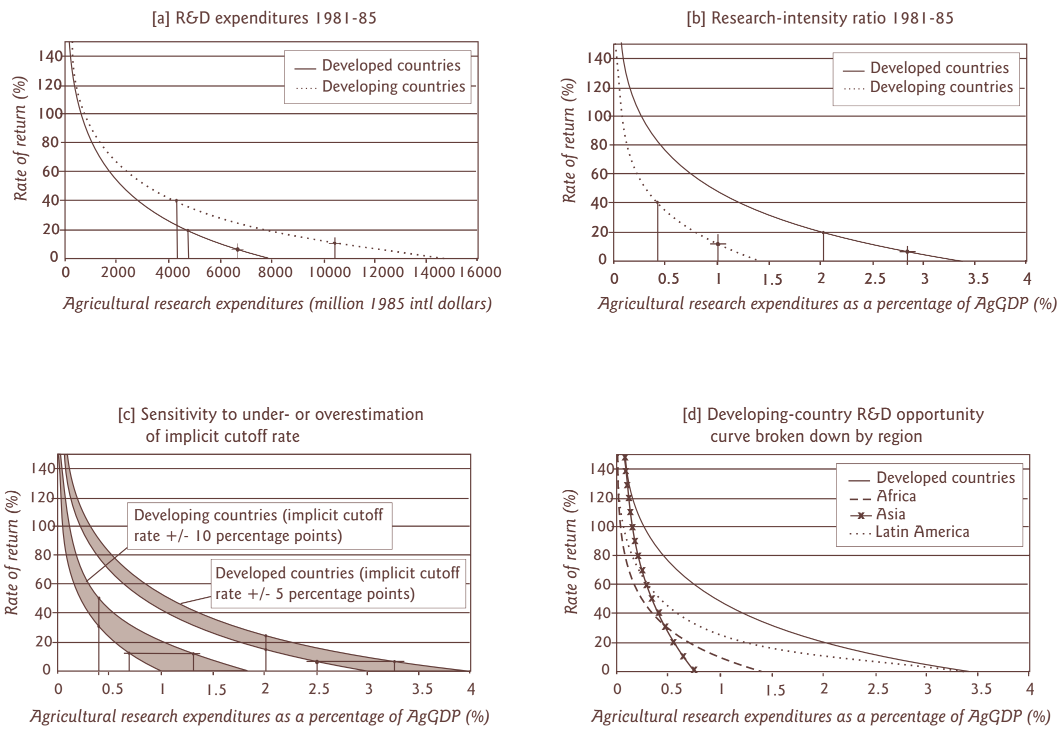

Figure 4.2: The R&D opportunity curve

The R&D opportunity curve differs from Metcalfe's innovation possibility frontier in that it uses the rate of return on research investment as the dependent variable rather than cost reduction per unit output. However, the selection principle is the same in both cases: the R&D project with either the highest ERR or the highest cost reduction for a given investment should be selected first. By using rates of return rather than cost reduction as an indication of productivity enhancement, three elements of Metcalfe's model can be discarded: (1) there is no minimum R&D investment requirement, (2) there is no limit to the physical improvements possible (they merely become too costly), and (3) the speed of the innovation process is always at its optimum.

The positions and slopes of the R&D opportunity curves succinctly summarize the differences in innovation opportunities between developed and developing countries. By lowering the cutoff rate from 20% to the social rate of 7%, the optimal level of investment in agricultural R&D for developed

[2] For more recent global compilations, see Alston, Pardey, and Roseboom (1998) and Pardey and Beintema (2001).

countries can be estimated in retrospect to be US$6.7 billion per annum, rather than the actual $4.8 billion spent.[3] For developing countries, the difference is substantially larger—$10.4 billion could have been spent before reaching the social rate of 12% rather than the actual figure of $4.4 billion (figure 4.2(a)). In relative terms, the developed countries clearly have a far larger choice set of profitable agricultural R&D investment opportunities than developing countries. Their optimal R&D intensity ratio is 2.8% compared to 1.0% for developing countries (figure 4.2(b)).[4]

In figure 4.2(c), the R&D opportunity curves are plotted assuming possible extreme values for the implicit cutoff rate. The implied extreme values for the optimal intensity ratios are 2.5% and 3.3% for developed countries and 0.7% and 1.3% for developing countries, suggesting distinct R&D opportunity curves for both groups of countries. A further differentiation of the R&D opportunity curve for developing countries by regions is presented in figure 4.2(d). Although the actual R&D intensities for all three regions are clustered around 0.5%, their estimated optimal R&D intensity ratios differ quite substantially: 0.9% for Africa, 0.6% for Asia, and 2.0% for Latin America. Given the small number of rate-of-return observations per region, the latter estimates are not very robust, but they illustrate how, with sufficiently good rate-of-return data, some far-reaching conclusions can be obtained regarding underinvestment in agricultural R&D.

In figure 4.3, the R&D opportunity curves have been plotted for two different time periods. The results of the rate-of-return studies published in or before 1985 have been related to the expenditure level for 1961–65, while those published after 1985 have been related to the expenditure level for 1981–85. It can be seen that, for both developed and developing countries, the R&D opportunity curve shifted outward between these two periods. If the R&D opportunity curve had not changed, the increase in R&D spending would have reduced the implicit cutoff rate and hence the underinvestment gap. For developing countries, this would have moved the cutoff rate close to 25%, while for developed countries the cutoff rate would have dropped below zero.

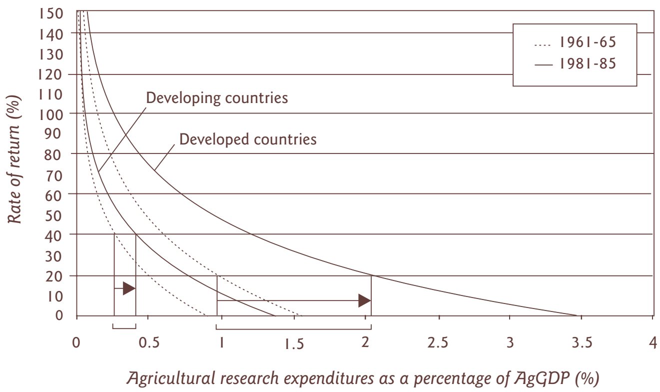

Figure 4.3: The shift of the R&D opportunity curve over time

An implicit assumption frequently made both in the literature and in policy advice, is that there is a single R&D opportunity curve that is the same for different countries and through time. For example, the recommendation 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.[5] Taking the developed-country investment level of the early 1980s as a target, and assuming that all countries

3 The expenditure data reported here are expressed in constant 1985 PPP dollars.

4 Defined here as public agricultural research expenditure as a percentage of agricultural GDP.

5 Even with only some appreciation of orders of magnitude, it should be clear that increasing agricultural R&D capacity by more than five-fold in just ten years is physically impossible.

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Optimizing Investment in Agricultural Research, or the Quest for Prosperity

Johannes Roseboom

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are on the same curve, closing the underinvestment gap then simply became a matter of moving along a fixed curve. If the advice had been followed, developing countries would have overinvested in agricultural R&D by a considerable margin. The results of the current analysis suggests that for 1981–85 the optimal investment level for developing countries was about 1.0% (rather than the actual 0.4%) and for developed countries about 2.8% (rather than the actual 2.0%). It is important to realize that even at modest investment levels, overinvestment may take place if profitable innovation opportunities are scarce or nonexistent. Issues of scale, for example, may place many innovation opportunities economically out of reach for small production areas or countries. More generally, institutional constraints such as nonexistent or poorly functioning markets may suppress innovation opportunities and hence the level of R&D investment.

The assumption that a single agricultural R&D opportunity curve is applicable to all countries and over different time periods implies a constant relationship between R&D input and output: time after time the same R&D opportunity curve repeats itself. The science-and-technology literature contains various theories that suggest that innovation processes eventually run out of steam, and that predict diminishing returns to R&D in the medium- to long-term. While this may be true for discrete innovation processes, it is perhaps more questionable at an aggregate level. Interestingly, the literature relating to the *endogenous growth theory* reverses this argument by assuming *increasing* returns to R&D: the knowledge created by today's research makes tomorrow's research even more productive. This idea does not fit comfortably with the typical thinking of economists (and most other people). Nevertheless, the outward shift of the agricultural R&D opportunity curve over time, as depicted in figure 4.3, does seem to be consistent with this assumption of the endogenous growth theory. However, there are other factors that play a role in determining the position of the R&D opportunity curve (see section 4.2) and that may explain the direction of the shift noted above.[6]

Developed countries invest far more in agricultural R&D per unit value added than developing countries, because (1) in relative terms, their choice set of profitable R&D projects is far larger (that is, positioned further to the right), (2) their social rate or optimal cutoff rate is lower (7% versus 12% in developing countries), and (3) their estimated (implicit) cutoff rate is substantially lower (20% versus 40% in developing countries). Also, over a period of 20 years, their choice set of profitable R&D projects grew considerably faster than their AgGDP, which resulted in more than a doubling of the agricultural research intensity ratio between 1961–65 and 1981–85. In contrast, the R&D opportunity curve for the developing countries moved only slightly in relative terms.[7] These observations suggest the following postulate:

V. Differences in research intensity between countries and industries and over time are due primarily to differences in the number of profitable innovation opportunities to choose from.

4.2 Factors shaping the R&D opportunity curve

The position of the ex ante choice set of possible R&D projects on the ERR scale (and hence that of the R&D opportunity curve) can be thought of as depending on the following interacting factors: (1) technology, (2) scale, (3) structure of the industry, (4) R&D efficiency and effectiveness, (5) adoption rate, and (6) risk and uncertainty.

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6 Shifts in the other direction are also possible. In the 1990s, for example, the oil industry more than halved its R&D budget compared to the 1980s because it assumed a substantially lower long-term oil price in its R&D cost-benefit calculations. This resulted in an inward shift of its R&D opportunity curve. Although positive research spillovers from one period to the other may have taken place, they were not detected.

7 In absolute terms, the developing country R&D opportunity curve has moved outwards much faster than has that of the developed countries.

The *technical* choice set of all imaginable R&D projects is based only on the technical merits of the imagined innovations relative to current technology (and economic structure), and can be expressed in terms of a percentage increase in the value of output in a standard production unit. This technical choice set is then multiplied by innovation-specific *scale* factors that reflect market potential or, in the case of public R&D, potential social impact.[8] This may change the original technical ranking quite considerably—promising technical improvements may turn out to have very low or negative expected rates of return because their potential use is limited, whereas small, insignificant technical improvements can have high expected rates of return because of their wide application.

The S&T literature often 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), create new opportunities for R&D. Assuming that all such new opportunities become available at the same time, a new and very promising choice set of possible R&D projects (i.e., one that extends far to the right) would become available. But because R&D capacity is limited, not all R&D projects can be implemented at the same time; instead, they are implemented sequentially, with the most promising first. As a result, the choice set of possible R&D projects retracts to the left over time, and the average rate of return of both the choice set and of the selected portfolio of R&D projects declines steadily until the next major breakthrough.

A more realistic scenario would suggest that only a small proportion of the possible R&D opportunities are immediately obvious or sufficiently profitable at the time of the scientific breakthrough or the introduction of a new design configuration. Technological innovation is thus a more incremental, cumulative, and path-dependent process, and R&D opportunities are created only gradually, resulting in a relatively stable R&D choice set through time. Although major breakthroughs constitute a necessary condition for creating new R&D opportunities, the rate at which these new opportunities unfold depends on many different factors. Biotechnology, for example, is a scientific breakthrough that has created a wealth of new technological opportunities, most of which will remain unexploited until research costs come down or until questions of safety and consumer acceptance are resolved.

The *structure of an industry* also plays an important role in shaping the choice set of possible R&D projects. A monopoly, for example, can expect to capture the entire potential market and hence appropriate all potential R&D benefits, while a small firm in a very fragmented market can expect to capture only a fraction of both the market and the potential R&D benefits. In the latter case, the incentive to invest in private R&D will be relatively small, leading to market failure in the provision of new technology. Intellectual property rights may overcome this problem to some extent, since 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 should also help avoid future duplication of R&D effort, which is another disadvantage of very fragmented and competitive industries. In contrast, in a monopolistic situation, the duplication of R&D effort is close to zero, while the potential choice set of profitable R&D projects is the largest possible, due to advantages of scale. Nevertheless, a monopoly may not result in the most dynamic situation from a technological point of view, since there are few competitive incentives to exploit potential innovation opportunities. An industry with oligopolistic tendencies is therefore considered to be the most conducive to technological innovation (Cohen 1995).

Primary agriculture is a classic example of a very fragmented industry in which market failure prevails when it comes to generating new technology. The benefits that an individual farmer can appropriate from an invention are far too small to constitute much of an incentive to invest substantial sums in own R&D. Collective action or government intervention is needed to overcome this mar-

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[8] This difference in focus also leads to different expected rates of return—the first is private, the second is social.

ket failure. Organizing and planning agricultural R&D as if the agricultural sector were a single national farm brings important scale advantages to the provision of agricultural technology in the form of a far larger choice set of profitable R&D projects. At the same time, duplication of R&D effort can be minimized, at least at a national level. Whether this potential is actually exploited also depends on competitive incentives (the monopolist dilemma) and on the organizational capacity of governments or farmer and industry groups. 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 do the open trade policies advocated in more recent years.

R&D efficiency and effectiveness determine the ultimate costs and successes of all R&D activities. These two performance indicators are assumed to be the same for projects within an organization, but to differ between R&D organizations and (to an even greater extent) between countries. Weak R&D performance usually reflects weak organizational capability in 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: once all salaries have been paid, there is little left for operating expenses or capital investment (Pardey et al. 1998).

If *adoption* is slow or incomplete, the potential benefits of an innovation may not be fully realized. For example, a new maize variety might potentially be grown by 70% of farmers, but past adoption rates indicate that only half of them will actually grow it. The choice set of R&D projects must therefore be corrected not only for scale, structure, and R&D efficiency and effectiveness, but also by a factor that reflects the adoption or diffusion rate of the proposed innovation. Low adoption rates are usually caused by weak institutions and high transaction costs—problems that are particularly prevalent in developing countries.

The way in which information concerning new technology is packaged and transferred to farmers, and how farmers assess the innovation relative to their own specific situation, are critical for the successful adoption of new technologies. Although farmers may be aware of new technology and be convinced of its superiority, they may still face other constraints that prevent adoption (e.g., lack of capital or credit, lack of required inputs at a given place and time, land-tenure issues, or seasonal labor shortages) (Pinstrup-Andersen 1982). Government policies targeting these constraints play an important role in improving adoption rates and in shifting the agricultural R&D choice set further up the ERR scale.

At times it may be difficult to distinguish between nonadoption and lack of economies of scale. In the example given above, for example, researchers may have argued that the new variety is appropriate for only 35% of farmers. In this case, the scale factor subsumes the adoption factor. It is important to keep the two factors separate since they may require different policy measures.

Since research is an inherently *risky and uncertain* activity, it is at odds with the risk-averse nature of humans. Depending on how averse to risk they are, private individuals and companies will avoid risky projects and will discount for the statistical variance of the ERR when ranking R&D projects. A suggestion made by Freeman and Soete (1999) is that high expected rates of return are usually associated with high risks (i.e., higher variance). Risk aversion therefore effectively biases private R&D towards the more certain, but usually less rewarding R&D projects. Thus the risk-averse version of the choice set of possible R&D projects can be thought of as positioned lower (i.e., further to the left) on the ERR scale than the risk-eutral version. This creates a divergence between the ex ante and ex post versions of the choice sets, with the latter more or less coinciding 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, thereby pooling some of the risks. In such cases, 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. Taking this argument a step further, Arrow and Lind (1970, 1972) suggested that, in a typical public-investment situation, governments could safely ignore risk as long as the investment was small relative to national income. Given that this is true for most public agricultural R&D investments, risk aversion should not play a significant role in the selection of public agricultural R&D projects or programs (Anderson 1991). In other words, public agricultural R&D projects with the same ERR, but differing in their relative risk (as reflected in the higher statistical variance of riskier projects), should be treated in the same way. The chance of a lower outcome in one project is compensated for by the chance of a higher outcome in another. This does not mean that risk and uncertainty can be ignored altogether when considering public agricultural R&D: as shown by Anderson (1991), they may play a role in accurately determining the mean project performance or ERR. The ERR obtained by taking the most likely value for every parameter 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, public-research administrators 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 as well. However, as Greig (1981) pointed out, public research administrators may well show some risk aversion and be anxious to establish a balanced R&D portfolio, so that they can meet demands for accountability with at least some positive results. Hence, even in the public sector, R&D projects with a high ERR but large variance may be discriminated against.

Risk and uncertainty are not static and may decline over time. R&D proposals initially 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 confidence in research effectiveness over time.

4.3 Policies that could enhance R&D investment opportunities

The list of underlying factors presented above is not necessarily exhaustive; other factors may also play a role. Moreover, the relative importance of each of the six identified factors differs between research fields. Market structure, for example, can be safely ignored when considering public (agricultural) R&D.[9] For other fields of research, however, this may be a highly relevant factor that affects the ERR of R&D projects and therefore shapes the available R&D opportunities. Understanding which factors are the most important is critical when considering policies that could shift the choice set higher up the ERR scale.

Table 4.1 summarizes some of the government policies that could have a positive effect on each of the six factors, although several have effects that go far beyond R&D. These policies condition the extent to which R&D can contribute to the overall economy. In developing countries in particular, the impact of R&D projects is often severely restricted by structural and institutional factors, such as infrastructure, education, and incomplete markets. One of the most important constraints is political instability, which disproportionately affects those investments (such as R&D) that have a long time-horizon.

[9] 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.

Table 4.1: Policies that Could Enhance R&D Investment Opportunities

Factors affecting the choice set	Policies that could positively affect the position of the choice set
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 antitrust legislation to avoid monopolistic situations and patent legislation to provide incentives for private investment in R&D
R&D efficiency and effectiveness	Development of the capacity to train researchers; improved management and organization of government research organizations
Adoption rate and speed	Markets, infrastructure, credit, education, etc.
Risk and uncertainty	Political stability; clear policies on intellectual property rights, ethical standards, and other regulatory measures

R&D can also be self-reinforcing in the sense that past R&D results and experiences can have a positive impact on (some of) the underlying factors shaping the current choice set of R&D projects. For example, gaining more experience in R&D increases the efficiency and effectiveness of R&D over time. Adoption of new technologies may proceed more easily once consumers and markets have become accustomed to rapid technical change. Risk and uncertainty may also be reduced by past R&D results.

Comparisons between developed countries show that the ranking of industries by R&D intensity is relatively stable (Freeman and Soete 1999). Despite substantially lower levels of investment in R&D in general, industries in developing countries show roughly the same ranking (Roseboom 1999). Thus, across all countries, food-processing industries have relatively low R&D intensities, while pharmaceutical industries have relatively high ones. This finding could be explained by assuming that some of the underlying factors (such as technology and industry structure) are more industry-specific, while other factors (such as scale, R&D efficiency and effectiveness, and technology adoption) are more country-specific. Risk and uncertainty could fit into either category. Explanations for differences in agricultural R&D intensities across countries should therefore be sought among the more country specific factors.

The above characterization of the choice set of R&D projects provides a rough outline of the factors that shape innovation opportunities. Depending on the specific industry and country, a more detailed examination of these factors should provide a better understanding of the innovation opportunities available, and also of what could be done to enhance them.

Chapter 5. Possible Explanations for the Underinvestment Gap

While Ruttan's (1980) claim that there is substantial underinvestment in agricultural R&D has been generally accepted, it has not gone completely unchallenged. Pasour and Johnson (1982), for example, argued that

> "[t]he 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." (Pasour and Johnson 1982, 306).

This argument is, of course, also valid for the underinvestment gap as estimated by our model. In other words, are there rational explanations for the existence of underinvestment gaps, and why are they bigger in developing countries than in developed countries? Such explanations may provide useful insights into how underinvestment gaps could be reduced. Possible explanations, many of which can be found in the literature, can be grouped into two categories: (1) incomplete or distorted information, and (2) compromised economic rationality. The two categories are closely related and suggest that the classical assumptions of full information and economic rationality are only ever partially met.

5.1 Incomplete or distorted information

Both ex ante and ex post estimations of rates of return to agricultural R&D depend on a large number of different variables, each of which can only be predicted (ex ante) or estimated (ex post) with limited precision. Nevertheless, this type of inaccuracy in itself does not necessarily constitute a major problem when analyzing a large number of rate-of-return results, since overestimations should roughly compensate for underestimations. More problematic, however, are those cases in which (1) certain variables are systematically over- or underestimated, and (2) cause and effect are modeled inaccurately. Both can lead to a systematic bias in the estimated position of the choice set of R&D projects.

Establishing the cause-and-effect relationship is perhaps the most problematic issue (see chapter 2). Alston and Pardey (2000), for example, argued that the imposed length of the benefit stream is often too short, leading to an overestimation of the rate of return. Similarly, research spillovers and spill-ins are often ignored in rate-of-return calculations (Maredia, Byerlee, and Anderson 2000). For reasons of simplicity and due to data limitations, the assumption is often made that spillovers and spill-ins roughly compensate for each other. While this may be true at the highest level of aggregation, at lower levels there may be major and persistent discrepancies, leading to systematic over- or underestimation of the actual rate of return to agricultural R&D.

Leaving aside these modeling issues, two well-known explanations for the agricultural R&D underinvestment gap are derived from the idea that either R&D costs are systematically underestimated ex post or that R&D benefits are systematically underestimated ex ante. Based on the idea (borrowed from the public finance literature) that the social opportunity cost of a dollar of government spending is larger than a dollar (due to the distortionary economic effects of taxation), Fox (1985) argued that the marginal rates of return to agricultural R&D investment in the USA were systematically overestimated. The alternative explanation, suggested by Oehmke (1986), is that rigidities in the budget process lead to a slow response to new opportunities. He incorporated this argument into a model that bases R&D investment decisions on quantities and prices in time period T-1 rather than T, which would lead to the systematic underestimation of research benefits ex ante. In the following two sections, we assess how these two explanations could affect the position of the R&D opportunity curve and hence explain the underinvestment gap.

5.1.1 Deadweight losses due to taxation

The argument concerning underinvestment in agricultural R&D has been critically appraised as part of a broader discussion in the public finance literature, which, as mentioned above, suggests that the social opportunity cost of a dollar of government spending is larger than a dollar. There are direct costs involved in collecting taxes, but more important, taxes introduce distortions in factor and product markets that create "deadweight" economic losses. It is these losses that have attracted considerable attention in the public finance literature. Ballard, Shoven, and Whalley (1985), for example, estimated that the marginal welfare costs or excess burden for the USA were 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 to the question of underinvestment in public agricultural R&D in the USA. He adopted the excess-burden rates calculated by Ballard, Shoven, and Whalley (1985) and used a rate-of-return model that assumes that research costs (C) are all incurred in the first year, while the benefit stream is distributed in equal portions (B) over a period of 16 years. The internal rate of return (ˆ) of this hypothetical R&D project can be derived as follows:

[5.1] $$C_0 = \overline{B}\sum_{t=0}^{T}(1+\hat{\rho})^{-t}$$

However, the true social cost of the project is $(1+\tau)\ C_0$, where τ represents the marginal excess burden or welfare cost of taxation. The internal rate of return adjusted for taxation losses, ˆ, solves as:

[5.2] $$C_0(1+\tau) = \overline{B}\sum_{t=0}^{T}(1+\hat{\rho})^{-t}$$

This equation can be rearranged as follows:

[5.3] $$\left[\frac{(1+\hat{\rho})^{T+1}-1}{\hat{\rho}(1+\hat{\rho})^{T}}\right] = \frac{C_0(1+\tau)}{\overline{B}}$$

which describes an implicit relationship between ˆ and τ.

Fox (1985) used the above expression to calculate the effect of the excess burden of taxation on the internal rate of return for US agricultural research by varying τ. Assuming that $\tau = 0.30$ for the USA (about the midpoint of the range), he found that the marginal rate of return of agricultural R&D adjusted for the excess burden of taxation is 26% rather than 37%. However, a major flaw in Fox's example is the assumed cost-benefit structure, which is not typical of an agricultural R&D project: all costs are assumed to take place in year 0, but in reality most R&D projects take several years before they are completed and start to have an impact. Plant-breeding projects, for example, may take 10 or more years. Adopting a more representative cost-benefit structure as presented in chapter 3 (see figure 3.3), equation [5.3] should be modified as follows:

[5.4] $$(1+\tau)\overline{C}\sum_{t=0}^{t=4}(1+\hat{\rho})^{-t} = \overline{B}\sum_{t=5}^{t=11}(\frac{t-4}{7})(1+\hat{\rho})^{-t} + \overline{B}\sum_{t=12}^{t=20}(\frac{21-t}{10})(1+\hat{\rho})^{-t}$$

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 that particularly affects this result.

Although 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), there has been some debate concerning specific aspects of it. 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 this is interesting for selecting the optimal tax instrument, for the current discussion it is more relevant to determine the marginal excess burden of the average taxation instrument, given that public agricultural R&D is usually funded by general tax revenues.[1] Second, there is a difference between gross and net measures of marginal excess burden or the welfare costs of taxation. The gross measure refers to the effect of a tax irrespective of its use, while the net measure takes into account the ultimate use of funds. 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).[2] Which, then, does one select? Alston and Pardey (1996), citing a study by Fullerton (1991), suggested a considerably more modest range of $1.07 to $1.25 for the USA. More relevant, perhaps, is the decision made in 1992 by the US Federal Government to set the marginal cost of a dollar government expenditure at $1.25, but to use lower cost rates if the investment leads to cost savings for the Federal Government (Office of Management and Budget 1992).[3] Whether this is the "economically" correct cost rate is not really relevant: it is the one adopted by the US Government when evaluating its programs.

Whatever excess-burden rate of taxation is considered appropriate, it will have the effect of shifting the choice set of R&D projects to the left and will also make it slightly steeper. The R&D opportunity curve also shifts to the left (assuming the same cost-benefit structure for all projects), as shown in figure 5.1. Keeping the level of expenditure constant, the underinvestment gap for developed countries decreases from 40% to 31% and for developing countries from 137% to 117%. The underinvestment gap can thus be explained partly by the excess-burden rate of taxation. Moreover, it has a greater impact on reducing the underinvestment gap for developed countries (-23%) than for developing countries (-15%).

Although often seen as a rather typically American antigovernment sentiment, the excess-burden literature has also had a significant influence on taxation policies outside the USA: the recent trend in developed countries of reducing high marginal tax rates is based on this literature. To our knowledge, however, there are no other countries that use an explicit excess-burden rate in their evaluations of government programs. Nevertheless, this does not mean that it is not an important factor when deciding whether or not to fund a government program. Politicians concerned with reelection (or at least, remaining in a position of power) know that raising taxes will be unpopular unless they can demonstrate that the programs being funded bring significant (economic) benefits to society. One could argue that the excess-burden rate makes explicit this economically rational resistance to taxation. It may also explain why, when no provision is made for the excess-burden factor, politicians stop funding agricultural R&D projects (or, for that matter, any other government projects) before the ERR of the marginal project reaches the social rate.

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1 Alston and Pardey (1996) argued that the marginal excess burden of a commodity-specific R&D tax is considerably lower than that for general taxes.

2 In the latter instance, the marginal cost of a tax dollar is less than a dollar, due to the positive effect of taxation on negative externalities, such as pollution.

3 To our knowledge there are as yet no real cases 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 as yet of the appropriate net excess-burden rate for agricultural R&D.

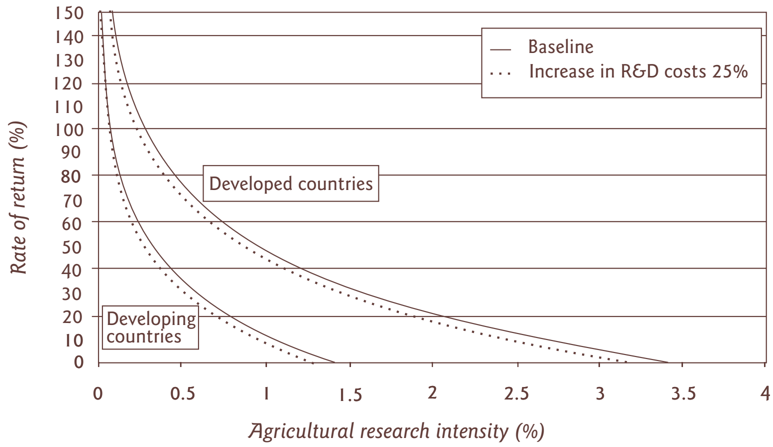

Figure 5.1: Shift in R&D opportunity curves due to a tax-burden rate of 25%

Fox (1985) was certainly ahead of his time in applying an excess-burden rate to public agricultural R&D investment, but he considerably overextended his argument by suggesting a social rate of about 20 % (nominal; approximately 15–16 % real) and an excess-burden rate of 0.30. In 1992, the US Federal Government adopted a standard that is considerable lower: a social rate of 7 % (real) and, as mentioned above, an excess-burden rate of 0.25 (adjusted downward if the investment leads to cost savings for the Federal Government).

5.1.2 Rigidities in the budget process

Oehmke (1986) argued that rigidities in the budget process preclude an immediate response to new agricultural R&D investment opportunities. Such new opportunities may arise, for example, through increases in product demand or improvements in research efficiency, which respectively translate into higher R&D benefits or lower R&D costs. Oehmke (1986) argued that these rigidities are relatively permanent and lead to persistent underinvestment in agricultural R&D. He encapsulated this idea in his economic model by basing R&D investment decisions on prices and quantities in period T-1 rather than period T, thereby underestimating R&D benefits and overestimating R&D costs.

Assuming that T-1 prices and quantities underestimate the actual benefits by 25% and overestimate the actual costs by 10% (across all R&D projects), a new R&D opportunity curve can be constructed for both developed and developing countries (figure 5.2). Again, the same cost-benefit structure is assumed across all projects. 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 prices and quantities in period T. Taking the social rate as the cutoff rate, the optimal investment level for developed countries would 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 optimal level of investment would have been 13.0% higher. Thus, despite the quite substantial price and quantity distortions assumed, the estimated underinvestment gaps are relatively modest compared to those actually observed. Budget rigidity can explain some of the underinvestment in agricultural R&D, but by no means all of it.

It is important to note that budget rigidities may also work in the opposite direction: a slow response to declining markets or prices will lead to overinvestment in agricultural R&D. It is rare to find an R&D choice set that only ever enlarges: it is more realistic to assume that some parts of the choice set expand while others contract. The speed with which such adjustments are made is probably less than optimal due to both rigidities in the budget allocation process and in organization and

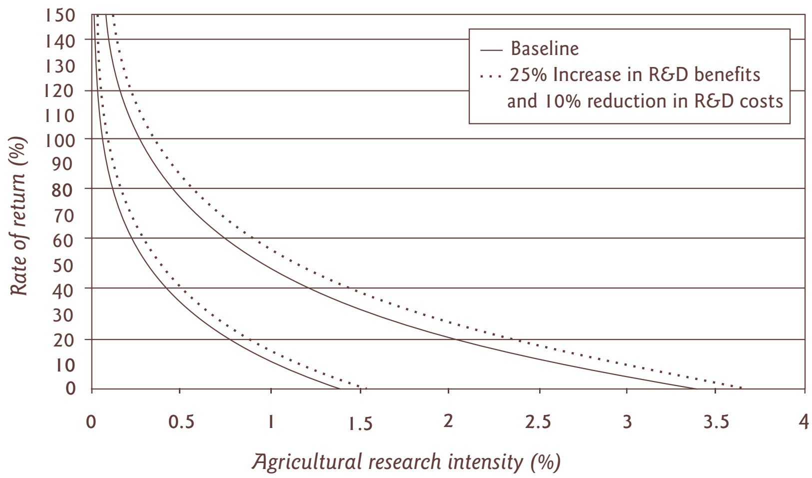

Figure 5.2: Shift in the R&D opportunity curves due to budget rigidity

staffing. Reducing or eliminating particular R&D activities may be even more difficult than trying to initiate new ones. Persistent overinvestment can be as much of a problem as persistent underinvestment.

5.1.3 Sample bias

Distorted information also plays a role at another level, namely in the assumption that our rate-of-return results represent a perfectly random sample. It is more than likely that the sample is biased towards the more successful R&D projects, since there is usually little interest in knowing the rate of return of projects that have failed. The observed distribution of the rate-of-return results supports this argument—only one of the 202 rates is negative. It is therefore reasonable to believe that the actual left-hand tail of the rate-of-return distribution is considerably longer than that observed.[4] 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 for estimating the underinvestment gap. The only possible effect of the bias in the sample could be an overoptimistic 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 thus to an overestimation of the underinvestment gap. In such cases, weak priority setting and selection is mistakenly interpreted as underinvestment.

[4] The relative share of negative rates of return also depends on the level of aggregation of the R&D "projects" or "programs" being evaluated. Aggregated R&D programs produce a substantially smaller range of rate-of-return results (and hence fewer negative rate-of-return observations) than do more disaggregated R&D projects. The same argument applies if R&D projects are split up into smaller subprojects. At a higher level of aggregation, negative research results are compensated for by positive research results and hence are less visible.

5.2 Compromised economic rationality

The selection of agricultural R&D projects may be suboptimal not only as a result of incomplete or distorted information, but also because the selection process itself is influenced by criteria other than pure economic rationality. Selection committees and research managers in the public sector seldom explicitly estimate the ERR of R&D projects, and even if they do, they may consider other selection criteria as well.[5]

Rather than explicitly estimating an ERR, most selection procedures in the public sector evaluate R&D projects by refering to a list of explicit (and often also implicit) selection criteria. However, since many of the selection criteria indirectly subscribe to basic economic rationality, the final selection of R&D projects often shows a great deal of economic rationality. Although selection criteria are often weighted for their relative importance, no explicit cause-and-effect relationship is assumed, and it is more by approximation than by precise calculation that economic rationality is introduced into the selection process. Overall, selection procedures are far from optimal in economic terms, and there is much to be gained from developing (and using) better selection procedures.

Our estimated underinvestment gaps assume optimal project selection: the fact that selection procedures are imperfect has been deliberately ignored in order to obtain a clearer perspective on underinvestment. Policymakers, however, no doubt realize that the selection of R&D projects is less than perfect, which may negatively affect their assessment of what constitutes an optimal level of investment in agricultural R&D. Every failed R&D project suggests to them that they may be exceeding their target. Although it is difficult to determine to what extent weak priority setting can explain the observed underinvestment gap, improved priority setting is often considered an important prerequisite for enhancing R&D budgets. The World Bank, for example, consistently includes better priority setting as a condition of its loans for agricultural research capacity building.

As mentioned in chapter 4, if risk and uncertainty are discounted for in the ex ante selection procedure, there may be a discrepancy between ex ante and ex post rates of return. There are few actual examples of the use of probabilistic cost-benefit approaches to project selection, but some idea of the probability of success probably enters the selection procedure, albeit in a rather informal way. Consequently, in choosing between R&D projects with the same ERR but different variances, the project with the smaller variance will be selected first. The risk-averse version of the ex ante choice set of R&D projects can therefore be thought of as positioned to the left of the risk-neutral version on an ERR scale. The ex post results should more or less coincide with the risk-neutral version of the distribution, which provides another possible explanation for the underinvestment gap observed ex post. The question is whether risk aversion in this case makes sense from a societal point of view. From an economic point of view, the answer is no, but political considerations may cause selection committees and research managers to act rather differently: after all, conspicuous failures are difficult to explain to the general public.

An implicit assumption made here is that the actions of governments can also be explained in terms of economic rationality. In other words, governments will actively identify all public investment opportunities, rank them, and implement all projects above the social rate after having collected the taxes to fund them. This is, of course, a very inadequate description of the political decision-making and budget-allocation processes. Without the political will and ability to articulate the economic necessity for government intervention and organize the funding (i.e., the tax base), many profitable proposals will not be funded and economic opportunities will remain unexploited. Tabor (1998), for example, listed, among other factors, the following political explanations for underinvestment in agricultural R&D:

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5 R&D project appraisal is more common in the private sector, but there, too, other criteria may influence the final ranking.

1. urban bias in political decision making;
2. weak political constituencies lobbying for either agricultural services or scientific programs;
3. short political cycles that place greater emphasis on activities with short-term payoffs than to long-term investments;
4. a broad distribution of relatively small returns to farmers, consumers, and industrial groups, none of whom may perceive the benefits of agricultural research to be large enough to be worth lobbying for.

In the next chapter, we examine the ways in which a political economy perspective may improve our understanding of underinvestment in agricultural R&D.

Chapter 6. Political Bias in the Selection and Funding of R&D Projects

One of the criticisms of a strictly neoclassical approach to the selection of R&D projects is that it is based exclusively on economic rationality and ignores both the initial distribution of assets and the question of who ultimately benefits from the projects that are selected and implemented. De Janvry, Sadoulet, and Fafchamps (1989) provided a more balanced perspective by introducing transaction costs and the concept of collective action to the debate.[1] They showed that transaction costs differ between farmers as a result of 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.[2] Consequently, there is no single optimum R&D portfolio which applies to all farms. It is this multiplicity of private optima that, in turn, makes collective action so important in influencing choices in R&D.

6.1 Getting the allocation right: Producers versus producers

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 are of greatest benefit to large commercial farmers. 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) argued that the bias is also affected by the size of the R&D budget, and with a sufficiently large R&D budget, the bias will converge towards neutrality. This latter finding can be explained as follows. The stronger lobbying by large commercial farmers ensures that R&D projects particularly beneficial to them will be selected first, although such projects will 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 the R&D projects preferred by poor smallholders will only be selected if any funds remain. In reality, the distortion is probably less extreme, but it is still reasonable to assume that there is considerable distortion in the selection process.[3]

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, we should not overlook the fact that the choice set of profitable R&D projects for large commercial farmers may be substantially larger than that for poor smallholders. A strictly balanced distribution of R&D resources may appear politically correct but can be counterproductive from an economic point of view. To illustrate this point, imagine a "global government" that could reallocate total world agricultural R&D funding and could do so by taking either an economic or a political perspective. The political perspective would argue for an egalitarian allocation of R&D funding, in which the distribution of R&D funding would be such that the R&D intensity across all countries is the same. Using the R&D opportunity curves as estimated in chapter 4, this would result in an intensity ratio of 0.7% and implicit cutoff rates of 22.6% (point *c* in figure 6.1) and 61.4% (point *d*) for developing and developed countries respectively. In contrast, an economic perspective would argue for an alloca-

1 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).

2 Other factors may also play a role, such as education and geographical location (farmers close to markets will have different transaction costs to farmers who are further away).

3 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.

tion 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.

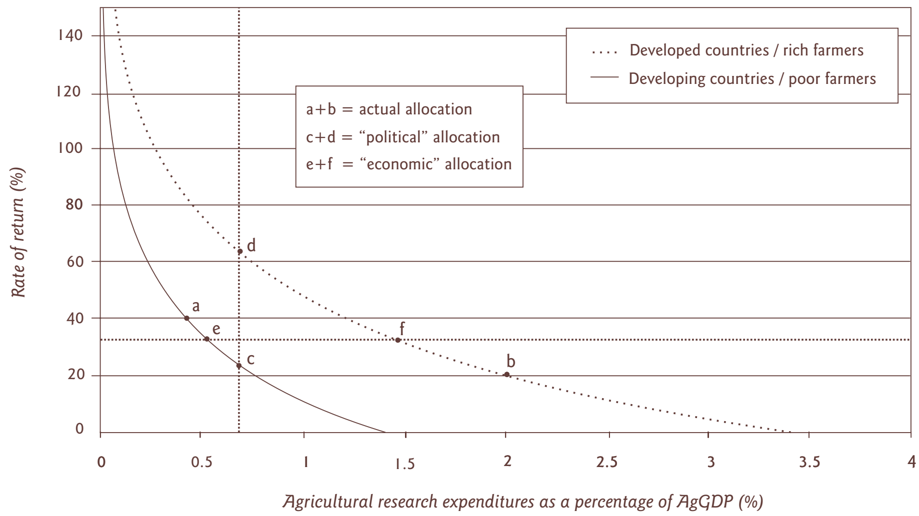

Figure 6.1: The political versus the economic equilibrium in the allocation of R&D resources

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 different innovation opportunities for the two groups and hence R&D opportunity curves as depicted in figure 6.1. In real life, the positions and shapes of the R&D opportunity curves are generally unknown. Instead, it is often assumed, usually implicitly, that both groups of farmers are on the same R&D opportunity curve. This can only lead to the conclusion that the R&D portfolio is very much biased in favor of large commercial farmers and that this bias is economically suboptimal.

The assumption that there are two distinctive R&D opportunity curves leads to very different conclusions. Although part of the bias in the R&D portfolio can be attributed to stronger lobbying by the large commercial farmers (leading to an economically suboptimal outcome), another (and, in this example, larger) part of the bias in the R&D portfolio does in fact make economic sense. The R&D investment opportunities are considerably better for large commercial farmers than for poor smallholders, and different R&D investment intensities are therefore justified from an economic point of view. The model also reveals another fact: strong lobbying by large commercial farmers should be explained not only in terms of their better conditions for collective action (de Janvry, Sadoulet, and Fafchamps 1989), but also in terms of economic incentives. The more "democratic" proportional distribution of R&D resources would leave unfunded many very profitable R&D projects targeted at the large commercial farmers (i.e., all projects with an ERR below 61.4%). In contrast, the economic incentive for poor smallholders to lobby for (additional) R&D would be less, since the cutoff rate for their preferred portfolio of R&D projects is considerably lower (i.e., 22.6%). Farmers not integrated into the market will have a particularly low incentive to lobby for R&D, since it will lead only to untradable surpluses (de Janvry and Dethier 1985).

6.2 Pro-poor policies

This is rather sobering news for those who wish to target R&D at the very poorest farmers, while still subscribing to economic rationality. But there are ways in which poverty targeting can be improved. One argument, for example, suggests that an extra dollar earned by a poor farmer should be valued more highly than an extra dollar earned by a rich farmer. As shown in figure 6.2, the model can easily accommodate such a correction under the assumption that the cost-benefit structure is the same across all R&D projects (i.e., 5 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 upwards and to the right. With a fixed R&D budget, the new equilibrium cutoff rate becomes 34.4% and the economically optimal agricultural research intensity ratios for poor smallholders and large commercial farmers become 0.55% (point *g*) and 1.40% (point *h*), respectively. In the model, the effect of a poverty premium is very modest, even with higher premiums (as shown in table 6.1). A one-dollar premium for every additional dollar earned by a poor farmer translates into a differentiated marginal cutoff rate of 28.1% for R&D projects targeting poor smallholders and 40.3% for 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.

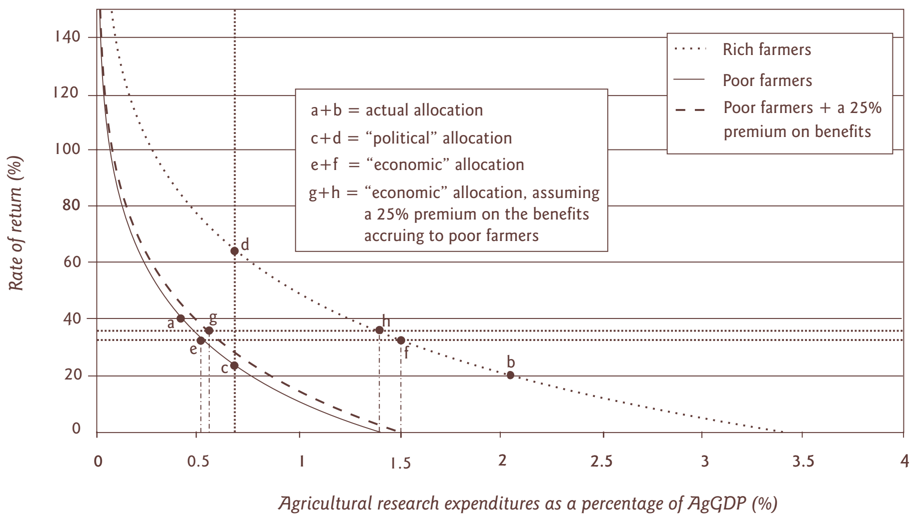

Figure 6.2: The welfare effects of introducing a poverty premium on R&D targeting poor farmers

To close the estimated R&D underinvestment gap (i.e., to increase the R&D investment level for both groups of farmers until the marginal rate reaches an assumed social rate of 10%) requires an additional R&D investment of $8109 million and creates a net benefit gain of $1489 million for poor smallholders and $201 million for large commercial farmers.[4] The additional sums invested in agricultural R&D significantly reduce the average rates of return, particularly for poor smallholders.

Reallocating R&D funding as suggested by economic equilibrium with the budget fixed would create a net benefit gain of $128 million. Compared to the actual net benefit of $5984 million, this represents a relatively minor improvement, leading to the conclusion that, aside from the (probably sub-

4 These benefit streams do not, of course, all go to either the rich or the poor farmers: a considerable proportion is passed on to consumers in terms of lower prices.

Table 6.1: Allocation of Agricultural R&D Funding under Different Assumptions

	Developed countries = rich farmers	Developing countries = poor farmers	All
AgGDP (million 1985 PPP$) [a]	237,089	1,075,293	1,312,381
Actual allocation			
Agricultural R&D expenditure (million 1985 PPP$) [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$) {[b]x[c]}/100	2811.6	3172.9	5984.5
Economic equilibrium at optimal budget			
Agricultural R&D expenditure (million 1985 PPP$)	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$)	3013.0	4661.6	7674.7
Economic equilibrium at fixed budget			
Agricultural R&D expenditure (million 1985 PPP$)	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$)	2494.7	3617.6	6112.2
Adjusted economic equilibrium: 25% poverty premium			
Agricultural R&D expenditure (million 1985 PPP$)	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$)	2420.2	3687.7	6108.0
Adjusted economic equilibrium: 50% poverty premium			
Agricultural R&D expenditure (million 1985 PPP$)	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$)	2355.8	3742.0	6097.8
Adjusted economic equilibrium: 100% poverty premium			
Agricultural R&D expenditure (million 1985 PPP$)	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.

stantial) 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.

An additional finding is that poverty premiums of 0.25, 0.50, and 1.00 dollar create net benefit losses of $4.3 million, $14.4 million, and $42.0 million, respectively. Again, compared to the total net benefits, these are minor distortions. The distributional effect, however, is more significant: with poverty premiums of 0.25, 0.50, and 1.00 dollar, poor smallholders would gain, respectively, $70.2 million, $124.5 million, and $205.3 million, while large commercial farmers would lose $74.4 million, $138.9 million, and $247.3 million.

The implicit assumptions made here are that R&D projects can be clearly differentiated into 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 becomes considerably more complicated when R&D projects have distributional effects that are less clear-cut. For example, an R&D project may result in a new technology that generates major benefits for large commercial farmers, but that at the same time has negative externalities for poor smallholders. Each R&D project may be affected differently by a poverty premium, making it difficult both to model the effects of such a premium and to formulate general conclusions. It all depends on the (assumed) benefit distribution within a given R&D project.[5]

Rather than *artificially* shifting the R&D opportunity curve for poor smallholders, it is perhaps more useful to consider policies that could actually shift the curve outwards. What factors limit R&D investment opportunities for poor smallholders compared with those available to large commercial farmers? Without doubt, the distribution of assets plays a major role, and land reform may lead to R&D opportunity curves that are both closer together and show a greater degree of overlap. Many other factors also have a positive influence on the adoption of new technology and help shift the R&D opportunity curve outward, such as market structure, access to credit, transport facilities, education, and health. 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. Investment in R&D can achieve very little if such an environment is either absent or deteriorating.

6.3 Consumers versus producers

While the dual economy perspective adopted by de Janvry, Sadoulet, and Fafchamps (1989) focused on the distribution of R&D benefits between rich and poor farmers, the political economy perspective suggested by de Gorter and Zilberman (1990) and Sunding and Zilberman (2001) focused on the distribution of R&D benefits between farmers and consumers, and on how this may influence their respective incentives for lobbying for public agricultural R&D, and for directing the public agricultural R&D agenda.

6.3.1 The distribution of R&D benefits

In our sample, the rates of return to agricultural R&D are all social rates, which include benefits accruing to both producers and consumers. Hence the R&D opportunity curve represents the curve as seen by a social planner who tries to maximize total R&D benefits without distinguishing

5 A classic example is provided by the Green Revolution: while richer farmers tended to profit more from this new technology than did poor farmers, lower food prices were particularly beneficial for poor consumers. Most authors have therefore come to the conclusion that the net poverty alleviation impact of the Green Revolution has been positive.

between the groups to whom the benefits accrue. In figure 6.3, the social planner's R&D opportunity curve for the developed countries has been plotted alongside three R&D opportunity curves that assume collective funding by farmers, with the farmers' share of the R&D benefits being 25%, 50%, and 75 %, respectively. As in the previous sections, the same cost-benefit structure has been assumed for all projects.

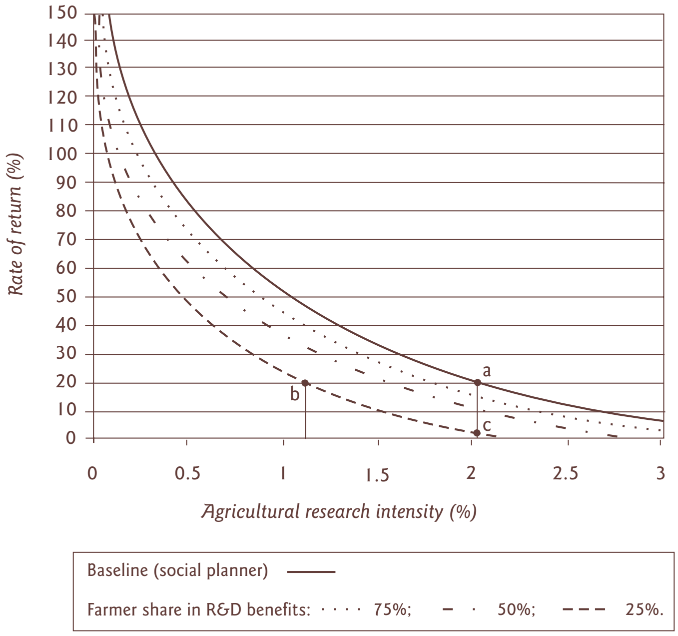

Figure 6.3: Collective funding by farmers versus the social planner's optimum

Figure 6.3 shows that when only 25% of R&D benefits accrue to farmers (across all agricultural R&D projects), farmers would stop funding agricultural R&D at an intensity ratio of 1.1 % of AgGDP (point *b*) rather than the 2.0% preferred by the social planner (point *a*) (assuming an implicit cutoff rate of 20% in both cases). Alternatively, fixing the level of R&D investment at 2.0%, the implicit cutoff rate from the farmers' point of view would be 2.9% rather than 20% (points *c* and *a*, respectively). The differences are smaller when more R&D benefits accrue to farmers than to consumers (i.e., when the producers' share of the benefits is 50% or 75%). The more elastic the demand for agricultural products, the more farmers can expect to capture the benefits from agricultural R&D.

The motivation of farmers to invest collectively in agricultural R&D is thus critically dependent on their share of the R&D benefits. The lower the share, the lower their incentive to invest in agricultural R&D, and the larger the number of agricultural R&D projects with a good social rate of return that will go unfunded. The basic political insight that can be derived from the model is that collective funding schemes for agricultural R&D are reasonably effective (but not optimal) when R&D benefits accrue mainly to farmers rather than to consumers. This explains why there are very few collective funding schemes for R&D on staple food crops, whereas they are relatively common for R&D on export crops.

A special type of collective funding scheme is that in which collective funding is supplemented by government funding, usually at a ratio of 1:1. From the farmers' point of view, this matching funding halves the R&D costs per project and so shifts their R&D opportunity curves outwards (figure 6.4).

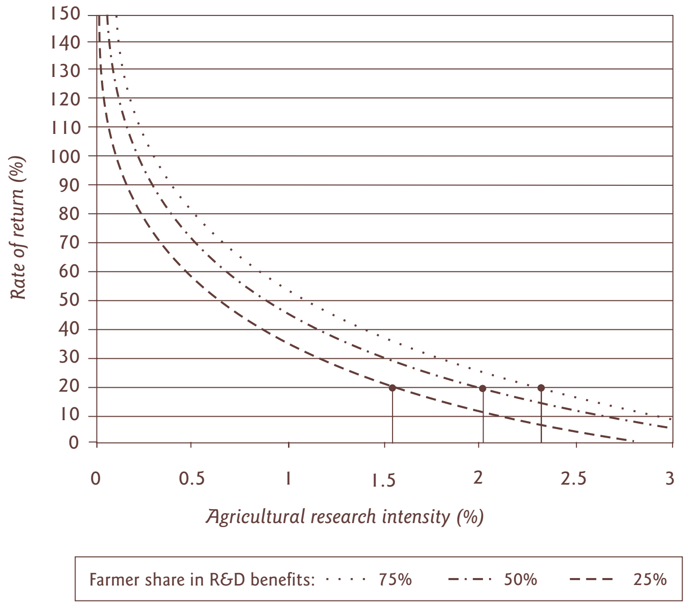

Figure 6.4: Collective funding by farmers plus 1:1 matching grant

Interestingly, when half of the R&D benefits accrue to farmers and the government pays half of the R&D costs, the resulting R&D opportunity curve coincides exactly with the R&D opportunity curve of the social planner (as shown in figure 6.3). When farmers are able to secure more than 50% of the R&D benefits, the matching grant scheme results in an investment level that is higher than that of the social planner, while the reverse is true if farmers secure less than 50% of the R&D benefits. Clearer insight into the distribution of R&D benefits between farmers and consumers may help fine-tune the matching grant instrument by varying the ratio between collective and government funding.

The matching grant instrument does not appear to be a very effective means of generating additional investment in R&D. When 50% of the R&D benefits accrue to the farmers, a collective funding scheme would invest 1.5% of AgGDP in agricultural R&D (figure 6.3). If the collective funding scheme was enhanced by a matching grant scheme at a ratio of 1:1, this intensity ratio would only be increased to 2.0% (figure 6.4). Furthermore, the additional R&D projects implemented as a result of the matching grant scheme have a relatively low social ERR.[6] The problem with a matching grant scheme is that it subsidizes all research projects, including those that have a sufficiently high private rate of return to be implemented collectively by the farmers without any subsidy. From a practical point of view, however, it would probably be impossible to separate R&D projects that need a subsidy from those that do not[7].

One argument in favor of the matching grant scheme is that it provides an important incentive for overcoming the many political and organizational problems associated with collective funding

6 As can be seen from table 6.1, a 35.5% increase in the research budget results in only a 12.7% increase in R&D benefits.

7 R&D tax-deduction schemes for private firms suffer from exactly the same problem. The tax revenues foregone are usually greater than the additional R&D stimulated by the schemes. For this reason, the UK has discontinued its R&D tax-deduction scheme, while the US only gives a tax deduction on R&D spending in excess of the previous year's R&D expenditure. Thus although many countries have an R&D tax deduction scheme, it is generally viewed as part of a broader package of competitive tax rules and regulations designed to attract "high-tech" foreign companies.

schemes. Although the economic rationale for collective action may be strong, it does not necessarily take place automatically.

The various perspectives on the position of the R&D opportunity curve are summarized in table 6.2. The R&D opportunities as seen by the social planner contrast with those seen by the farmers: while the social planner takes into account benefits to both producers and consumers, the farmers consider only those benefits accruing to producers. The first section of table 6.2 shows that the social planner will invest the same amount regardless of the farmers' share of the R&D benefits. Farmers evaluate the same investments quite differently, depending on their share of the total benefits. The lower their share, the lower their assessment of the R&D benefits and hence rate of return.

Table 6.2: Allocation of R&D Resources under Different Funding and Benefit Spillover Scenarios

	As seen by social planner			**As seen by farmers**		
	Social planner decides and allocates budget					
	R&D benefits accruing to farmers:			R&D benefits accruing to farmers:		
	75%	50%	25%	75%	50%	25%
R&D expenditure[a]	4812.9	4812.9	4812.9	4812.9	4812.9	4812.9
Intensity ratio (%)	2.03	2.03	2.03	2.03	2.03	2.03
Marginal rate of return (%)	20.0	20.0	20.0	16.0	10.8	2.9
Average rate of return (%)	58.4	58.4	58.4	51.9	43.5	30.8
Net benefits[a]	2811.6	2811.6	2811.6	2498.7	2092.2	1483.3
	Collective funding by farmers					
	R&D benefits accruing to farmers:			R&D benefits accruing to farmers:		
	75%	50%	25%	75%	50%	25%
R&D expenditure[a]	4312.7	3646.6	2631.5	4312.7	3646.6	2631.5
Intensity ratio (%)	1.82	1.54	1.11	1.82	1.54	1.11
Marginal rate of return (%)	24.3	30.8	43.5	20.0	20.0	20.0
Average rate of return (%)	62.7	69.2	81.9	55.9	52.7	47.8
Net benefits[a]	2703.5	2524.0	2155.5	2411.5	1920.7	1258.9
	Collective funding by farmers plus matching grant of 1:1					
	R&D benefits accruing to farmers:			R&D benefits accruing to farmers:		
	75%	50%	25%	75%	50%	25%
R&D expenditure[a]	5551.5	4812.9	3646.6	5551.5	4812.9	3646.6
Intensity ratio (%)	2.34	2.03	1.54	2.34	2.03	1.54
Marginal rate of return (%)	14.4	20.0	30.8	20.0	20.0	20.0
Average rate of return (%)	52.9	58.4	69.2	62.2	58.4	52.7
Net benefits[a]	2934.6	2811.6	2524.0	3454.9	2811.6	1920.7

[a] Million 1985 PPP dollars.

When farmers collectively fund R&D (the second section of table 6.2), they set the level of investment (i.e., at a cutoff rate of 20%). The lower their share of the R&D benefits, the lower their willingness to finance R&D. The social planner assesses the returns to R&D considerably more positively by also taking into account the benefits accruing to consumers. Consequently, there is (major) underinvestment in agricultural R&D from a social point of view (i.e., a high marginal rate of return).

When collective funding is combined with a matching grant (the third section of table 6.2), farmers also set the level of investment, and again, the lower their share of the R&D benefits, the lower their willingness to finance the R&D. The matching grant, however, halves their R&D costs, resulting in a higher level of investment. When 75% of the benefits accrue to the farmers, collective funding combined with a matching grant (1:1) leads to an investment level above the optimum for the social planner.

6.3.2 Differentiating R&D project characteristics

So far, we have assumed that the distribution of benefits to producers and consumers is the same for all R&D projects. In reality, this relationship will vary between projects: some will generate more benefits for farmers, others will generate more benefits for consumers. One could model this by assuming that the optimal R&D portfolio (i.e., the one preferred by the social planner) consists of three types of R&D projects, with the farmers' share of the R&D benefits being 25%, 50%, and 75%, respectively. Each type is represented equally in the optimal portfolio of the social planner, who merely selects all R&D projects with an ERR of 20% and higher, regardless of the benefit distribution between farmers and consumers (see first section of table 6.3). Farmers, of course, would prefer R&D projects that generate greater benefits for them than for consumers (see second section of table 6.3). Although their project selection will differ from that of the social planner, farmers will invest not only in R&D projects that produce large benefits for producers, but also in those producing large benefits for consumers, provided that they have a sufficiently high ERR.

Keeping the R&D budget fixed (i.e., the social planner decides the budget), the implicit cutoff rate across the three R&D opportunity curves as viewed by farmers is 9.8%. Rather than allocating resources equally, however, farmers will shift some of the funding to R&D projects that produce greater benefits for them than for the consumer. From the social planner's point of view, this translates into different and differentiated implicit cutoff rates. The R&D portfolio preferred collectively by farmers yields a net benefit to society of $2785.8 million, which is $25.8 million lower than the allocation preferred by the social planner ($2811.6 million). Compared to the social planner's allocation, farmers gain $20.2 million in R&D benefits ($2044.9 million minus $2024.7 million), while consumers lose $46.0 million. Hence, in this particular case, the effect of the allocation distortion is quite modest. The benefit gained by farmers is also a very modest 1%.

When the choice of R&D projects is left to consumers, they will shift the allocation of resources to projects mainly of benefit to themselves. In the case of projects in which only a low proportion of the benefits accrue to producers, such an allocation reduces the marginal rate of return on R&D to below zero from the farmers' point of view. In the example given above, the net R&D benefits accruing to farmers are some $85.3 million (4.4%) lower when consumers rather than farmers select the R&D projects. The social planner views the selections made by both groups as being exactly the same in terms of social welfare benefits. Only the selection preferred by the social planner (i.e., equal funding for each set of projects) yields a higher social welfare benefit ($2811.6 million).

Since consumers may select R&D projects that farmers would not, the question arises of whether, at the end of the day, farmers would adopt the new technology resulting from such projects. To answer this question, it is important to determine whether the adoption of the new technology requires an investment by the farmer; the original R&D costs are largely irrelevant and can be considered "sunk" costs. If adoption requires an investment, farmers may decide against the technology on the basis of a low or negative rate of return. For example, farmers will only adopt capital-intensive technologies that reduce air and water pollution (the benefits of which will accrue mainly to consumers) if the technology is either subsidized or imposed on them by legislation. However, in cases in which adoption of the technology does not require additional investment by farmers, they may well adopt technologies that they did not consider worthwhile developing in the first place. An

Table 6.3: Optimal Allocation of R&D Resources Assuming a Scenario in which the Social Planner Decides on the Budget and either Farmers or Consumers Decide on the Allocation of Funds

	As seen by social planner				As seen by farmers			
	Social planner decides and allocates budget							
	R&D benefits accruing to farmers:				R&D benefits accruing to farmers:			
	75%	50%	25%	Total	75%	50%	25%	Total
R&D expenditure[a]	1604.3	1604.3	1604.3	4812.9	1604.3	1604.3	1604.3	4812.9
Intensity ratio (%)				2.03				2.03
Marginal rate of return (%)	20.0	20.0	20.0		16.0	10.8	2.9	
Average rate of return (%)	58.4	58.4	58.4	58.4	51.9	43.5	30.8	42.1
Net benefits[a]	937.2	937.2	937.2	2811.6	832.9	697.4	494.4	2024.7
	Social planner decides on budget, farmers decide on allocation							
	R&D benefits accruing to farmers:				R&D benefits accruing to farmers:			
	75%	50%	25%	Total	75%	50%	25%	Total
R&D expenditure[a]	1901.4	1652.8	1258.8	4812.9	1901.4	1652.8	1258.8	4812.9
Intensity ratio (%)				2.03				2.03
Marginal rate of return (%)	13.4	18.8	29.5		9.8	9.8	9.8	9.8
Average rate of return (%)	51.8	57.2	67.9	57.9	45.7	42.5	37.6	42.5
Net benefits[a]	985.2	945.7	854.9	2785.8	869.2	701.9	473.8	2044.9
	Social planner decides on budget, consumers decide on allocation							
	R&D benefits accruing to farmers:				R&D benefits accruing to farmers:			
	75%	50%	25%	Total	75%	50%	25%	Total
R&D expenditure[a]	1258.8	1652.8	1901.4	4812.9	1258.8	1652.8	1901.4	4812.9
idctlparIntensity ratio (%)				2.03				2.03
Marginal rate of return (%)	29.5	18.8	13.4		24.8	9.8	-1.9	
Average rate of return (%)	67.9	57.2	51.8	57.9	60.8	42.5	25.9	40.7
Net benefits[a]	854.9	945.7	985.2	2785.8	764.7	702.1	492.8	1959.6

[a] Million 1985 PPP dollars.

example would be the development of a new pesticide that is as effective as the existing ones (and that is available at the same price), but that has fewer negative externalities.

Another aspect in which farmers may differ from social planners is in the optimal cutoff rate. As discussed in section 1.1, the cutoff rates used in the private sector in developed countries (15–20% before tax) are substantially higher than the one used in the public sector (7%). One could argue that farmers use a private rather than a public cutoff rate when collectively financing agricultural R&D (and also for collective funding combined with a matching grant). The implication of this higher cutoff rate is that, even when the R&D opportunity curves for both the social planner and the farmers (collectively) are the same, the latter has a lower optimal level of investment in agricultural R&D.

A further refinement that could be introduced is to assume that the farmers' share of the R&D benefit stream is not constant but changes through time. Initially, most of the R&D benefits will accrue to the farmers: the adoption of the new technology is at first only partial, and the market has not yet adjusted to a lower equilibrium price. However, as adoption of the new technology increases, the market will start to adjust in the direction of a lower equilibrium price, and an increasing proportion of the R&D benefits will spillover to the consumers. This is the "technology treadmill" as described by Cochrane (1958). Farmers adopt new technologies that initially appear very beneficial to them, but, as the new technology spreads, the price-lowering effect of innovation comes into play. Producing for the world market may slow this process somewhat (since demand is more elastic), but the price-cutting effect of innovation has had quite significant effects in the world market as well (as reflected by the steady decline of agricultural commodity prices during the past century).

Figure 6.5 illustrates both a constant (6.5(a)) and a dynamic (6.5(b)) sharing of R&D benefits. In both cases, half of the benefits accrue to farmers over the whole period. The social planner's rate of return for this project is 20%. When R&D benefits are shared equally through time between farmers and consumers, the farmers' rate of return on this project is 10.8% (see table 6.2). Assuming a more dynamic sharing of R&D benefits, as plotted in figure 6.5(b), a higher rate of return to farmers is realized (12.9% in this particular example). This implies that the R&D opportunity curves as seen by farmers and plotted in figures 6.3 and 6.4 (and used in tables 6.2 and 6.3) actually underestimate the actual position of the R&D opportunity curves—they are positioned somewhat higher and more to the right.

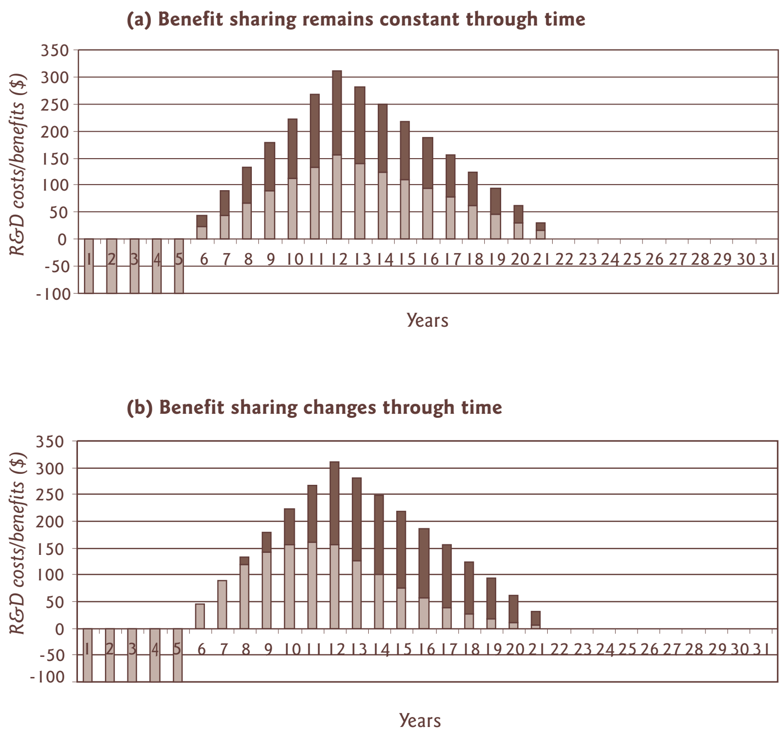

Figure 6.5: A constant (above) versus a dynamic sharing of R&D benefits

6.4 Conclusions

By differentiating between R&D benefits accruing to different groups of farmers and between those accruing to farmers and consumers, this chapter has clarified a range of issues associated with R&D funding and project selection. The model remains highly stylized (e.g., the same cost-benefit structure is assumed to apply to all R&D projects), and it addresses only one aspect of the problem at a time. In reality, the R&D benefit distribution is too complex and diverse to model. For example, as yet, no systematic investigations have been undertaken into the composition of public agricultural

R&D portfolios and the R&D benefits that spillover to consumers. This information is crucial if we are to assess the appropriateness of our present funding and project selection mechanisms.

Conclusions

Representing the distribution of all possible R&D projects on an ERR scale by a semilog function has greatly helped structure the underinvestment hypothesis, shifting the focus of the argument away from the average rate of return (the usual approach adopted in the literature), to the rate of return of the marginal funded R&D project. The model unambiguously defines R&D underinvestment by only three parameters: (1) the social cutoff rate, (2) the actual (or implicit) cutoff rate, and (3) the slope coefficient of the choice set. The first parameter is set outside the model, but the other two must be estimated. Taking into account less-than-complete information and economic rationality, these two parameters 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 following are the most important findings of the model:

- The *mode* rather than the *mean* of the ex post rate-of-return distribution is the relevant variable when assessing underinvestment in agricultural R&D.
- In the period 1981–1985, assuming complete information and economic rationality, developed countries should 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., expenditure as a percentage of agricultural GDP), developed countries should have invested 2.8% rather than 2.0%, and developing countries 1.0% rather than 0.4%.
- Low investment in public agricultural R&D in developing countries is caused first and foremost by the relatively small choice set of profitable R&D projects in which to invest. Although underinvestment *per se* certainly plays a role (since the gap is larger for developing than developed countries), it explains only a relatively small part of the difference in agricultural R&D intensity between developed and developing countries.
- While efforts to reduce the underinvestment gap should continue, more emphasis should be placed on developing policies that help shift the choice set of R&D projects further to the right on the ERR scale, even at the risk of increasing the underinvestment gap.

The model of R&D project selection presented here takes the underinvestment argument to extremes by assuming full information and economic rationality. 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 tested. The estimated underinvestment gaps are conditional in that 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 understanding of the underinvestment gap ex post. This suboptimal selection must be eliminated to see the underinvestment gap more clearly and to estimate its size. Ultimately, however, the model is useful not because it estimates past R&D underinvestment gaps but because it helps explain why they exist. It is this improved understanding that may help us create, and better exploit, the R&D investment opportunities of tomorrow.

One set of explanatory factors for underinvestment in agricultural R&D relates to the position and shape of the choice set of all potential R&D projects. There are important differences in innovation opportunities between companies, industries, and countries, and through time. Apart from purely technological opportunities (which may be enhanced by investing in basic R&D), other factors come into play, including the size and structure of the market, the rate and speed of adoption of technology, risk and uncertainty, and R&D effectiveness and efficiency. Each of these factors could, if improved, increase the benefits or reduce the costs of all R&D projects, thereby creating a larger set of profitable R&D projects from which to choose.

A second set of explanatory factors relates to *why* governments underinvest in public agricultural R&D. Possible explanations include distorted information, suboptimal selection mechanisms, budget rigidity, excess burden due to taxation, and, last but not least, the lack of political will and organizational capacity in society. Improvements in each of these factors could reduce the underinvestment gap.

Both sets of factors have important social capital dimensions that tend to be cumulative. It is the higher level of social capital in rich countries that not only results in them having a larger set of profitable agricultural R&D projects from which to choose, but also a better capacity for identifying, selecting, financing, and implementing them. If poorer countries are to catch up, they must first develop the social capital that will bring innovation opportunities within reach.

Adding a political economy perspective to the model (as described in chapter 6) produces additional important insights. Highly uneven asset distributions result not only in different technological development paths, but also in a very uneven distribution of the political power necessary to pursue the preferred technology path. There is thus good reason to believe that the suboptimality in the selection of R&D projects is not random but is affected by lobbying on behalf of different interest groups. More specifically, such a political bias would express itself in a lower cutoff rate for R&D projects preferred by the stronger lobbies. Eliminating this political bias does not necessarily result in equal agricultural R&D intensity ratios. Different intensity ratios may well be warranted if innovation opportunities are considerably better for one group of farmers than for another. Farmers with better assets, in particular, are more likely to have better innovation opportunities. Nevertheless, the political bias in the selection process could be eliminated by strictly adhering to economic selection mechanisms. In this case, poor smallholders in particular will gain from better priority setting.

A further step is to argue that an additional dollar earned by a poor farmer should be valued more highly than an additional dollar earned by a rich farmer. Assuming 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 relatively modest, both in terms of welfare and the distributional income effect. The intrinsic problem is that the number of profitable R&D projects is lower for poor smallholders than for large commercial farmers. This fact cannot be altered by a poverty premium, reinforcing the argument made earlier in favor of focusing on policies that enhance innovation opportunities.

The distribution of R&D benefits not only differs between different groups of farmers, but also between farmers and consumers. The social planner usually makes no distinction between the two and assesses R&D projects on the basis of their total benefits. By differentiating between the sectors to whom the benefits accrue, it becomes clear that, collectively, farmers may have a very different perspective of the profitability of the R&D choice set than does the social planner. The farmers' R&D opportunity curve is usually positioned below that of the social planner, which implies that if the financing of agricultural R&D was left to farmers, a considerable number of R&D projects with a good social rate of return would not be funded. Furthermore, the higher the proportion of R&D benefits accruing to consumers, the lower is the incentive for farmers to collectively invest in R&D. Other aspects in which the social planner may differ from the farmers include (1) the relevant cutoff rate, and (2) risk aversion.

A more complex funding scenario is that in which the social planner sets the level of funding and the farmers select the R&D projects. Assuming three equal groups of R&D projects, each with a different share of the benefits accruing to the farmers, such a scenario leads to a differential in budget allocation across the three project types: more will be spent on R&D projects that are mainly of benefit to farmers and less on projects that are mainly of benefit to consumers. The net welfare loss due to this differential in allocation is fairly small—only about 1% of the total benefits. The same is true for the additional benefits accruing to the farmers.

This research report has attempted to broaden and extend the R&D investment discussion. For the first time, an overall link between R&D input and impact has been made that is more than hypothetical and that is based on empirical data. At present, this link is only very approximate, but as more statistical evidence (in the form of rate-of-return studies) becomes available, we may be able both to see the link more clearly and to characterize it further. Our quest for prosperity has only just begun.

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