Estimating the benefits of plant breeding research: methodological issues and practical challenges

M.L. Morris [a,*], P.W. Heisey [b]

[a] *Economics Program, International Maize and Wheat Improvement Center (CIMMYT),*
Apdo. Postal 6-641, 06600 Mexico, D.F., Mexico
[b] *Economic Research Service, United States Department of Agriculture (ERS/USDA), Washington, DC, USA*

Abstract

Impact assessment studies consistently show that the benefits generated by plant breeding are large, positive and widely distributed. Numerous case studies have concluded that investment in plant breeding research generates attractive rates of return compared to alternative investment opportunities, that welfare gains resulting from the adoption of modern varieties (MVs) reach both favoured and marginal environments, and that benefits are broadly shared by producers and consumers. But just how reliable are the results of studies that estimate the benefits of plant breeding research? This article reviews methods used to estimate the benefits of plant breeding research and discusses theoretical and empirical issues that often receive inadequate attention in applied impact assessment work. Our objective is not to question the validity of the theoretical frameworks commonly used to estimate the benefits of plant breeding research, but rather to examine problems that can arise when the widely accepted theoretical frameworks are used for empirical analysis. Most of these problems can be grouped into three basic categories: (1) problems associated with measuring adoption and diffusion of MVs, (2) problems associated with estimating benefits attributable to adoption of MVs, and (3) problems associated with assigning credit among the various plant breeding programmes that participated in developing the MVs.
© 2003 Elsevier B.V. All rights reserved.

Keywords: Agricultural research; Agricultural research evaluation; Plant breeding research; Impact assessment; Economic analysis

1. Introduction

Impact assessment studies consistently show that the economic benefits generated by plant breeding are large, positive, and widely distributed. Case studies too numerous to mention have concluded that investment in plant breeding research generates attractive rates of return compared to alternative investment opportunities, that welfare gains resulting from the adoption of modern varieties (MVs) reach both favoured and marginal environments, and that benefits are broadly shared by producers and consumers. Swayed by the large body of empirical evidence that supports these findings, public research organisations, private corporations and international lending agencies have invested millions in plant breeding research. But just how reliable are the results of studies that estimate the benefits of plant breeding research? Are the methods used to conduct such studies theoretically sound? And are the data credible?

This article reviews methods used to estimate the benefits of plant breeding research and discusses issues that often receive inadequate attention in applied impact assessment work. Our goal is not to question

* Corresponding author. Tel.: +52-55-5804-2004;
fax: +52-55-5804-7558.
E-mail address: m.morris@cgiar.org (M.L. Morris).

the validity of the theoretical frameworks commonly used to estimate the benefits of plant breeding research, nor is it to elaborate the many difficult conceptual issues that complicate research evaluation in general. Rather, our objective is to examine problems that may arise when the widely accepted theoretical frameworks are used for empirical analysis. Most of these problems can be grouped into three basic categories: (1) problems associated with measuring adoption and diffusion of MVs, (2) problems associated with estimating benefits attributable to adoption of MVs, and (3) problems associated with assigning credit among the various plant breeding programmes that participated in developing the MVs.

2. Measuring the adoption and diffusion of modern varieties (MVs)

Plant breeding research generates benefits when MVs are taken up and grown by farmers. Modern varieties deliver different types of benefits, including higher yields, improved quality, lower production costs, simplified crop management requirements or shorter cropping cycles. Regardless of the type of benefits, however, their size and value depends on the area planted to MVs. Therefore, the first step in calculating the benefits of plant breeding research is to estimate the area planted to MVs. In principle, this should be easy. In practice, it is often difficult.

2.1. Defining MVs

Estimating the area planted to MVs is complicated by the fact that it is often not clear just what constitutes a 'modern variety'. Conventionally, the term refers to any variety developed by a scientific plant breeding programme. If such varieties were readily identifiable and unchanging, estimating the area planted to MVs would be relatively easy. Unfortunately, varieties produced by scientific plant breeding programmes are not always readily identifiable and unchanging.

MVs are not always readily identifiable because the economically valuable characteristics that are bred into MVs cannot always be detected simply by looking at a standing crop. In some cases, MVs have distinct physical characteristics that are easily visible and that distinguish them from other cultivars

(e.g., plant height, leaf shape, flower colour). In other cases, however, the characteristics that distinguish MVs from 'traditional varieties' may not be readily apparent, at least not to non-expert observers (e.g., resistance to pests or diseases, drought tolerance, heat or cold tolerance, improved storage quality, improved nutritional content).

Even when MVs can be identified visually, they do not remain unchanging through time. Whenever farmers save harvested seed and replant it in a subsequent cropping cycle—a common practice in many developing countries—cultivars undergo genetic changes. Genetic changes may be intentional (as when farmers' deliberately select seed with desired traits) or inadvertent (the result, for example, of unintentional seed mixing, contamination by foreign pollen, or random genetic mutation). Regardless of whether the changes are intentional or inadvertent, over time the characteristics of successive generations of MV plants grown from recycled seed change. Eventually a point is reached at which the latest generation of plants differs from the original generation in one or more key characteristics, so classifying them as MVs becomes problematic.

2.2. Measuring the area planted to MVs

Assuming there is agreement on what constitutes an MV, then it should be possible to estimate the area planted to MVs. Depending on the context, the estimation procedure may involve a static dimension (area planted to MVs at a given point in time) or a dynamic dimension (rate of diffusion of MVs through time).

2.2.1. Adoption of MVs at a given point in time
Three types of data are commonly used to estimate the area planted to MVs at a given point in time: (1) farm-level survey data, (2) seed sales data and (3) expert opinion.

Farm-level survey data: the most reliable way to estimate the area planted to MVs is using farm-level survey data. Unfortunately, such data are rarely available, because surveys are expensive and time consuming to conduct. Even when they are available, the spatial and/or temporal coverage is often incomplete.

Seed sales data. An alternative method for estimating the area planted to MVs involves the use of seed sales data. This method is subject to four potential

problems. First, seed sales data usually do not include data on farm-saved seed or seed produced outside the formal seed sector, so the method will give misleading results if a significant area is planted to farm-saved or 'artisanal' seed. Therefore the method works best for crops grown mainly from commercial seed, which restricts its usefulness in many developing country contexts. Second, even when most seed planted is commercial seed, data on commercial seed sales must be treated with caution, because seed organisations may have incentives to misrepresent their production and sales figures. Third, this method gives incorrect results if there are significant discrepancies between the amount of seed produced, the amount of seed sold, the amount of seed planted, and the proportion of the planted area that is harvested. Fourth, reliable information about farmers' actual planting rates may not be available.

Expert opinion. As a last resort, the area planted to MVs can be estimated based on expert opinion. In most countries, individuals can be found who can 'guesstimate' the MV area planted with a reasonable degree of accuracy. Many researchers, extension agents, and seed industry representatives acquire knowledge of MV adoption patterns through their daily work experiences and have frequent opportunities to observe MV use in the field. While MV adoption estimates based on expert opinion can be quite accurate, a potential danger of relying on expert opinion is that certain individuals may have incentives to provide biased estimates. Therefore, it is advisable to survey several experts and to base the estimate on the consensus.

2.2.2. Diffusion of MVs through time

For some types of impact studies, it is desirable to estimate not only the area planted to MVs at a specific point in time, but also the rate of diffusion of MVs through time. Estimation of MV diffusion rates is particularly important when the objectives of the study include calculating financial measures of project worth, such as the net present value and the internal rate of return.

Modern variety diffusion rates can be expressed in terms of the percentage area planted to MVs or in terms of the percentage of farmers using MVs. For simplicity, here we discuss diffusion in terms of the percentage area planted to MVs. Most studies on MV

diffusion assume that the cumulative proportion of the area planted to MVs follows the S-shaped or 'logistic' pattern first described by Rogers (1962) in his classic study on the diffusion of innovations. Mathematically, the logistic curve is described as

$$Y_t = \frac{K}{1 + e^{-a-bt}}$$

where Y_t is the cumulative percentage of adoption at time t, K the upper bound of adoption (adoption ceiling), a a constant related to the time when adoption begins, and b a constant related to the rate of adoption. Given sufficient observations on Y_t, it is possible to estimate the unknown parameters K, a, and b using non-linear regression methods. In cases where at least three observations on Y_t are available, and assuming that K can be estimated independently, a more practical approach is to use ordinary least-squares regression to estimate a transformed version of the logistic curve equation:

$$\ln\left[\frac{Y_t}{K - Y_t}\right] = a + bt$$

K can be estimated using several different methods. If diffusion is well advanced and adoption rates are known for several points in time, the simplest method is to plot the data and select a level that appears to be the upper bound. An alternative method is to run the regression using several different values for K and select the value that maximises R^2.

As originally described, the logistic diffusion curve was based on a number of assumptions that included the presence of a large, non-homogeneous population of potential adopters who have unequal access to information about innovations and who differ in their willingness to innovate. When this assumption is violated, the probability increases that the diffusion path will diverge from the expected smooth S-shaped function. For this reason, while logistic curves are often appropriate for estimating MV diffusion over an extended period and across a large area, they are not always appropriate for estimating MV diffusion within a short period or in a restricted area.

Another potential problem with the logistic diffusion curve is that it is based on the implicit assumption that technology adoption is non-reversible. For successful innovations, this is generally the case, especially at the aggregate level. But it is not always

the case. Farmers often take up a new technology, experiment with it for some time, and then discontinue using it. With MVs, disadoption can occur for a number of reasons. Most obviously, MVs may turn out to be unprofitable. Examples abound in which MVs have been introduced into areas where they were not well adapted, with disappointing results. Alternatively, changes in external factors may over time erode the profitability of MVs, for example, when rising fertiliser prices reduce the returns to investing in hybrid seed. Finally, a good MV may be eclipsed by a better MV. Given the possibility of disadoption, use of the classic upward-sloping logistic curve may be inappropriate.

3. Estimating the benefits associated with adoption of MVs

The second category of problems that can affect the empirical evaluation of plant breeding research involves the estimation of benefits associated with adoption of MVs.

3.1. Estimating farm-level yield gains

The benefits that result from the adoption of MVs depend on the productivity gains that MVs deliver when they are grown by farmers. For simplicity, productivity gains are usually measured in terms of yield gains. However, no standard method exists for measuring yield gains. Varietal evaluation trials may be conducted on experiment stations, in farmers' fields under researcher management, or in farmers' fields under farmer management. Usually multiple replications are involved, in the same location or in different locations. The maximum yield at one location may be reported, or mean yields across several locations. Each type of varietal evaluation trial can provide useful information, but it is unlikely that any single measure derived from trial results will exactly reflect how a variety will perform in large-scale plantings in farmers' fields. Trial yields will almost always be higher than farmer's yields, so when yield gains associated with MV adoption are calculated based on trial data, the absolute value will often be overestimated. Case study evidence suggests that *absolute* yield gains observed in varietal evaluation trials are often

higher than those observed in farmers' fields, but it is empirically uncertain whether relative yield gains are also higher. If yields realised in farmers' fields increase by the same proportion as in evaluation trials, the relative gain would be the same, even though the absolute gain would be smaller in farmers' fields.

3.2. Accounting for changes in crop management practices

Adoption of MVs is often accompanied by changes in crop management practices. MVs are frequently promoted as part of an improved technology package, so when farmers adopt MVs, often they also adopt complementary inputs such as fertiliser, herbicide and pesticide. Farmers may also change the method or timing of cultural practices, including land preparation, planting, fertilisation and weed and/or pest control. If no allowance is made for changes in crop management practices occurring at the same time as changes in MVs, the benefits attributed to MV adoption may be overestimated. In estimating the benefits attributable to plant breeding research, it is therefore advisable to distinguish between the 'germplasm effect' on productivity and the 'crop management effect' (Fig. 1). This can be very challenging. Improved germplasm and improved crop management practices usually interact, so the productivity gains observed when the two are adopted simultaneously often exceeds the sum of the productivity gains observed when each is adopted independently. Also the relative importance of the two effects can vary. In cases in which MV adoption occurs without any changes in management practices, the entire yield gain can legitimately be attributed to the germplasm effect. But in cases in which MV adoption is accompanied by changes in crop management practices, the germplasm effect may represent a relatively small proportion of the overall yield gain.

3.3. Accounting for non-yield benefits

Our discussion of economic benefits thus far has focused on the value of additional crop production associated with adoption of MVs. Benefits that do not show up in the form of increased crop yields have not been considered. Examples include improved grain quality, improved fodder and straw quality, and reduced crop growth cycles. Non-yield benefits can be
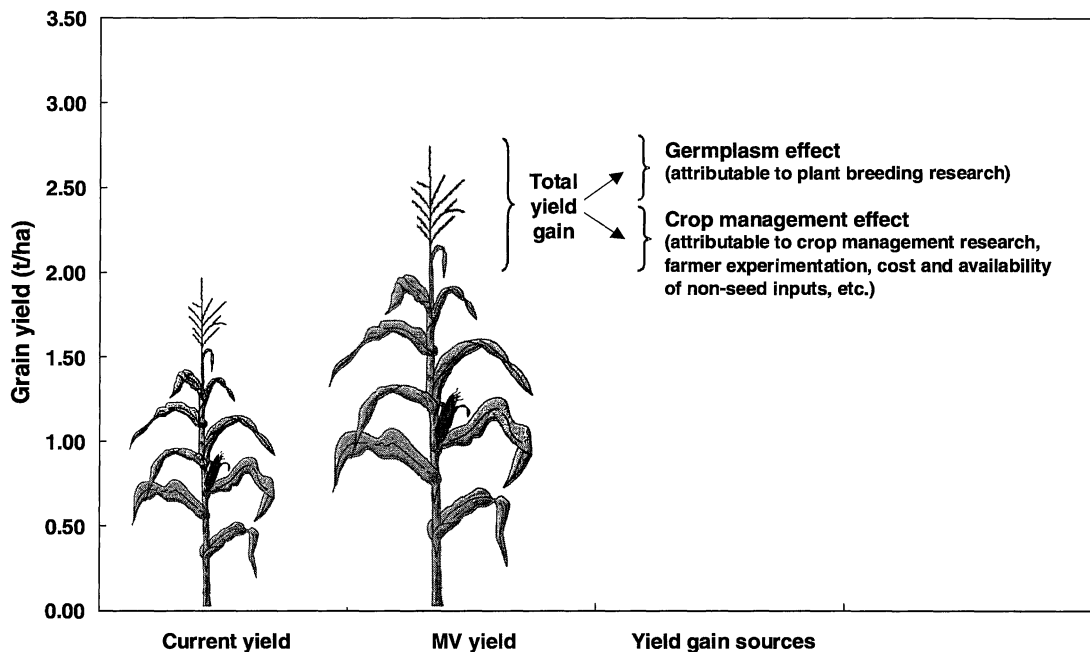
Fig. 1. Yield gain components: germplasm vs. crop management effect.

very important; sometimes they even exceed the value of yield benefits.

The best approach for valuing non-yield benefits depends on the nature of the benefit and the type of cropping system. In commercial agriculture, improvements in the quality of grain, fodder, or straw are often reflected in market price differentials, making valuation of benefits relatively straightforward. In subsistence-oriented agriculture, however, quality improvements are rarely reflected in market price differentials. Quality factors are often cited as having contributed to successful adoption of MVs by non-commercial farmers, but few attempts have been made to quantify and value the benefits associated with quality improvements.

A reduction in the growth cycle of a crop can represent a significant benefit, even without any increases in yield potential. Short-duration varieties are attractive because they can be harvested early, making them less susceptible to weather-related abiotic stresses occurring late in the growing season. Also since short-duration varieties can be planted late or harvested early, they can be accommodated more

easily into multi-crop rotations, which affords farmers with opportunities to increase the productivity of their overall cropping system. Because it is a complex undertaking requiring detailed economic analysis of entire cropping systems, valuation of reductions in crop growth cycles is rarely undertaken.

3.4. Increasing yield potential vs. maintaining current yields

Over time, most successful crop breeding programmes generate genetic gains in yield. Genetic gains in yield have several different components. The most obvious is increased yield potential. Theoretically, increases in yield potential are measured with potential stresses set at non-limiting levels, so they can be thought of as increases in maximum yields.

Another, less obvious component of yield gains is increased stress resistance. In addition to selecting for increased yield potential, many plant breeding programmes select for improved host plant resistance to biotic and abiotic stresses. Evans and Fischer (1999) and Tollenaar and Wu (1999) describe alternative
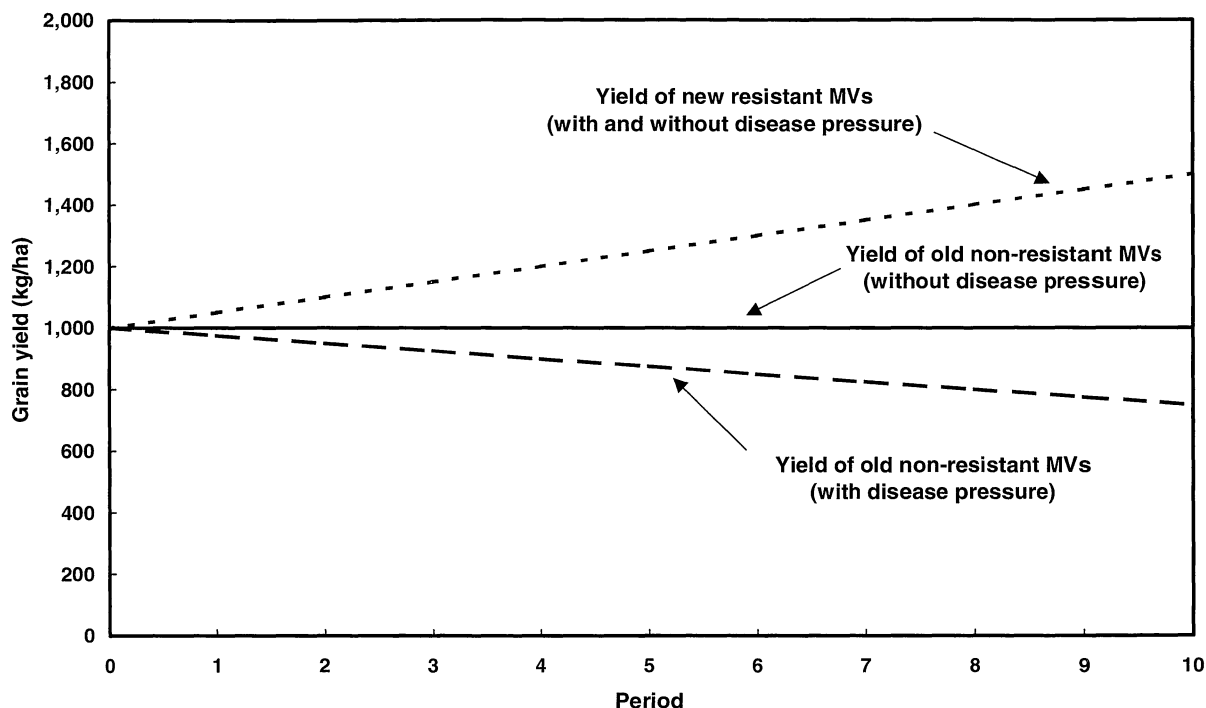
Fig. 2. Yield gains given perfect disease resistance in new MVs.

approaches for distinguishing between increases in yield potential and increases in stress resistance. Most plant breeders appear to be quite comfortable with the distinction, at least conceptually. In practice, they may have difficulty distinguishing between the two, since even well-managed experiments usually are subject to stresses of one kind or another.

Yield gains attributable to increased stress resistance are particularly tricky to measure when stress resistance deteriorates over time. This often happens with disease resistance, because mutations in disease pathogens frequently arise to overcome genetically based resistance in the plant. Fig. 2 depicts a case in which disease resistance breaks down over time. In cases such as this, it may be desirable to disaggregate total gains in disease resistance into gains resulting in improvement in resistance and gains resulting from maintaining resistance at the levels present in previously released varieties at the time of their release.

Research aimed at avoiding losses from deteriorating stress resistance is called *maintenance research.*

Methods for quantifying and valuing the benefits of improved stress resistance are most commonly described in the literature on maintenance breeding (see Brennan et al., 1994; Collins, 1995; Smale et al., 1998; Maredia and Byerlee, 1999; Townsend and Thirtle, 2001; Marasas et al., 2003).

Plant breeders have long argued the importance of maintenance research, but economic analyses of maintenance research are scarce. In principle, if supply with and without maintenance research is carefully estimated, projected total benefits should include the results of both productivity and maintenance research. In practice, ignoring maintenance research may lead to underestimation of benefits (Heim and Blakeslee, 1986; Adusei and Norton, 1990; Marasas et al., 2003). In some cases, it may be desirable to disaggregate total benefits into benefits attributable to productivity-enhancing research and benefits attributable to maintenance research. This requires estimation of two separate 'without research' scenarios.
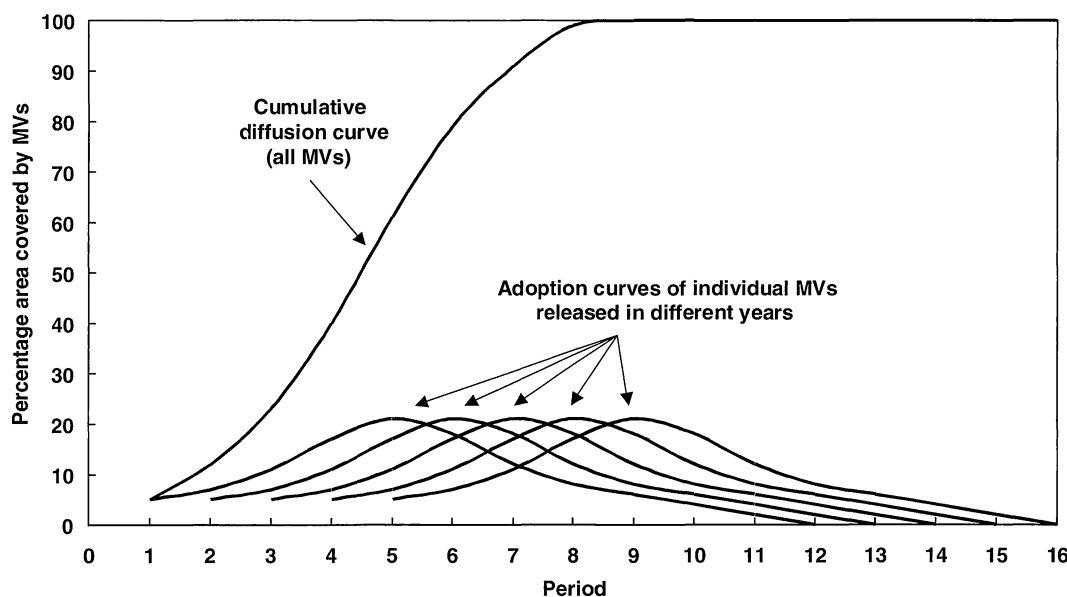
Fig. 3. Cumulative diffusion of MVs released by a plant breeding programme.

3.5. Estimating benefits from programmes releasing streams of varieties

Successful breeding programmes incur costs on an ongoing basis and release streams of varieties over time, with the number and frequency of varieties released varying considerably between crops and regions. Maredia and Byerlee (1999) present a stylised adoption model that accommodates sequential releases of multiple varieties over an extended period (Fig. 3). The model divides the benefits of crop improvement research into Stage I productivity gains (associated with initial adoption of MVs) and Stage II productivity gains (associated with the replacement of older MVs with newer MVs). Stage I gains are often dramatic, because they tend to occur within a brief period. Stage II gains are usually much less dramatic, but over the longer run they can provide most of the benefits from plant breeding research (Byerlee and Moya, 1993; López-Pereira and Morris, 1994; Byerlee and Traxler, 1995; Heisey et al., 2002). In assessing the impact of breeding programmes that have released streams of MVs through time, it is important not to confound Stage I and Stage II effects. If productivity gains associated with the latest-generation MVs are attributed to the entire area planted to MVs during the entire time that MV diffusion occurred, then the research benefits will be vastly overestimated.

3.6. Imagining the 'without project' (counterfactual) scenario

Many plant breeding impact studies implicitly assume that in the absence of the breeding programme being evaluated, the performance of the varieties being grown by farmers would have remained unchanged. This assumption is unrealistic, as usually there are alternative sources of MVs. The relevant comparison is not between current performance and the performance that was being achieved at the time the breeding programme was established, but rather between current performance and the performance that farmers would currently be achieving had the breeding programme being evaluated not been established (the counterfactual). This concept is well known in the project analysis literature, in which it is referred to as the "with and without project" comparison (Gittinger, 1980). In the context of plant breeding research, it has been discussed by Evenson (2000), Marshall and Brennan (2001), Evenson and Gollin (2003) and Morris (2002).

Fig. 4 illustrates this problem using an example in which the benefits of the plant breeding programme
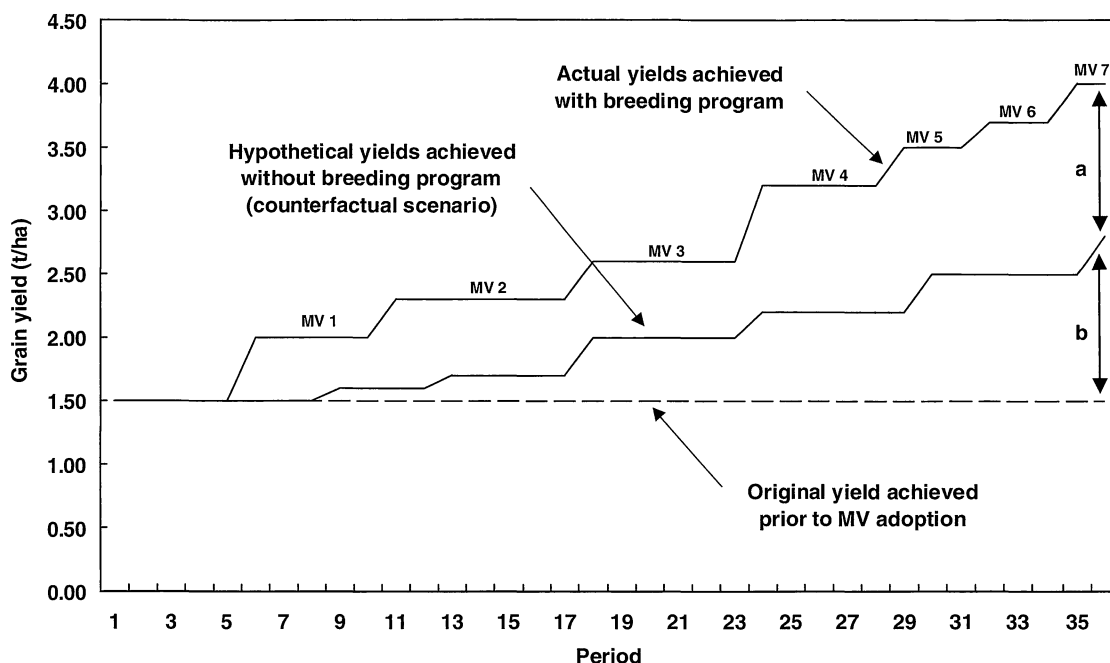
Fig. 4. Estimating MV yield gains: projecting the counterfactual scenario.

are measured in terms of yield gains attributable to adoption of MVs. A common mistake in many impact studies is to assume that the yield gain attributable to the breeding programme is the difference between the farmers' original yield and their current yield, represented in Fig. 4 by the vertical distance $(a+b)$. A more realistic estimate would take into account the fact that yield gains would likely have been realised even in the absence of the breeding programme being evaluated, because farmers would have grown MVs obtained from other sources. The yield gains that would have been achieved are represented by the vertical distance (b). Although it is impossible to know with certainty what would have happened to farmers' yields had the breeding programme not existed, some sort of subjective judgement is needed to account for the yield gains that would have been achieved under the counterfactual scenario.

3.7. Translating farm-level yield gains into aggregate supply response

In many cost-benefit studies of plant breeding programmes, benefits at time t (B_t) are calculated as $B_t =$

$gY_tX_{1t}P_t$, where g is the percentage gain in yields attributable to the breeding programme, Y_t the yield at time t, X_{1t} the land area affected by the breeding programme, and P_t the output price. When X_{1t} is held constant, this simplified approach implicitly assumes a perfectly inelastic supply function, which is reasonable if there is no substitutability among factors of production and if the area planted to each crop does not vary as the result of research-induced changes in profitability (Morris et al., 1994). However, the approach does not allow for factor price effects attributable to plant breeding research that could temper aggregate supply response and affect the size and distribution of research benefits. This can be a problem, because research-induced changes in profitability can lead to changes in factor prices that in turn affect aggregate supply response. For example, during the Green Revolution in South Asia, adoption of rice and wheat MVs led to increased demand for labour (Ruttan, 1977; Jayasuriya and Shand, 1986; Lipton and Longhurst, 1989). So long as labour supply was less than perfectly elastic, increased demand for labour exerted upward pressure on wage rates in local labour markets, tempering aggregate supply response and affecting

the welfare of households in adopting areas for whom agricultural labour was a source of household income.

The impact of new labour-using technology may extend outside of the area in which the technology is adopted, if labourers in non-adopting areas are mobile and if migration of labourers from non-adopting areas occurs. In addition to transferring some of the benefits of the new technology to migrating individuals, labour migration will also put upward pressure on wage rates in non-adopting areas (Quizon and Binswanger, 1986; David and Otsuka, 1994; Renkow, 2000). Most studies that focus specifically on plant breeding research do not take into account impacts in related markets, but in the presence of large-scale Green Revolution-type change, significant welfare impacts in labour markets could be overlooked.

3.8. Dealing with price effects in output markets

Depending on the size and degree of openness of the economy in which a plant breeding programme operates, research that leads to yield gains and supply increases may cause changes in output prices, which also could affect the size and distribution of benefits. A large body of literature discusses the distributional impacts of technological change transmitted through price effects in commodity markets (Ayer and Schuh, 1972; Akino and Hayami, 1975; Renkow, 1994). Over the long run, increases in global crop supplies resulting from international plant breeding research are likely to depress real world prices. Recent empirical work suggests that not only the size but also the distribution of research benefits will be affected by the assumptions made about the price responsiveness of supply and demand (Falck-Zepeda et al., 2000).

3.9. Accounting for policy distortions

Estimating the benefits generated by plant breeding programmes can be complicated in the presence of price controls, production quotas, trading regulations, exchange rate controls, and similar policies. By altering the financial profitability of agriculture, such policies can distort the incentives to adopt MVs and consequently increase or decrease the economic benefits attributable to MV adoption. For this reason, the benefits generated by a given plant breeding programme depend only partly on the performance of the breeding programme; they depend also on policy factors that, in the end, have little to do with research. Can and should anything be done about this problem? Unless the distortion is specific to the commodity in question, probably not. If the policy distortions are expected to remain in place, then to the extent that the benefits associated with MV adoption have been affected, the effect will be real. If, on the other hand, there is an expectation that the policy distortions will be removed, then in rare cases it may be feasible and worthwhile to project the likely impact of their removal on MV adoption rates and to adjust the calculation of benefits accordingly.

4. Assigning credit for plant breeding research

The third category of problems that commonly affect the empirical evaluation of plant breeding research involves the attribution of credit among different breeding programmes.

4.1. Dealing with research spill-overs

Improved germplasm moves easily throughout the global plant breeding system. All professional plant breeders use germplasm that has been improved by others. The existence of research spill-overs increases the overall benefits generated by the global plant breeding system, but it also complicates the task of assigning credit among individual breeding programmes.

Often it is desirable to assess the contribution made by a particular breeding programme that operates as part of a larger network of breeding programmes. Two analytical approaches are possible. The first approach is to frame the problem as a variant of the 'with and without research' problem. Actual benefits and costs are compared with estimated benefits and costs that presumably would have prevailed in the absence of the breeding programme being evaluated. The second approach is to calculate the benefits attributable to the entire network and then apportion them among the individual breeding programmes that make up the network. Pardey et al. (1996) outline

several apportionment rules that can be used for crops whose pedigrees are known. At one extreme, the 'any ancestor' rule allows a breeding programme to claim credit for all MVs having an ancestor from the breeding programme. At the other extreme, the 'last cross' rule attributes all the benefits from a given MV to the breeding programme that made the final cross to produce the MV. In between these two extremes, the 'geometric rule' apportions benefits over several generations of crosses, with later crosses getting more weight than earlier ones.

5. Discussion

Scientists, research administrators and policy makers face increasing pressure to justify continued public investment in agricultural research. As demands proliferate for scarce government funds, better evidence is needed to show that agricultural research generates attractive rates of return compared to alternative investment opportunities. The result has been an upsurge in studies designed to assess the impact of agricultural research.

Few sub-fields within agricultural research have been subjected to as much scrutiny as plant breeding. Interest in the economics of plant breeding emerged after the Green Revolution showed that relatively modest investments in crop genetic improvement could generate enormous benefits at the global level. Supporters of agricultural research seized on the success of the Green Revolution and commissioned a series of studies which predictably concluded that investment in international plant breeding had generated eye-popping returns. These findings were corroborated by numerous follow-up studies which concluded that the benefits of plant breeding research have been not only large, but also broadly distributed. Based on a large body of empirical evidence, the economic attractiveness of plant breeding came to be widely accepted.

But just how reliable are the results of studies that estimate the benefits of plant breeding research? Are the methods used to conduct such studies theoretically sound? And are the data sufficiently complete and accurate?

Questions such as these will seem heretical to some. Within the impact assessment community, evaluation of plant breeding programmes is by now considered routine. Certainly it is easier to document the impact of plant breeding research than it is to document the impact of many other types of agricultural research, since the products of plant breeding programmes are tangible things that can be observed in the field and whose characteristics can be described and measured.

This paper has described problems that can complicate efforts to assess the impact of plant breeding research. Despite the widely held belief that empirical evaluation of plant breeding programmes is now a routine undertaking, documenting and measuring the impact of crop genetic improvement research is subject to many methodological and practical challenges. Failure to recognise and deal effectively with these can lead to incorrect empirical results, possibly leading to inappropriate policy analysis and non-optimal research funding decisions.

To what extent has failure to recognise and resolve the problems described in this paper influenced applied impact assessment studies of plant breeding programmes? To answer this question, it would be necessary to revisit a large number of case studies and systematically review their evaluation methods, something that is beyond the scope of this paper. However, we believe it is more common for research costs to be understated and/or research benefits to be overstated, rather than the inverse, leading to systematic inflation in performance measures. This suggests that returns to investment in plant breeding research are probably not as high as is generally believed. Writing about returns to all types of agricultural research (not just plant breeding), Alston et al. (2000) argue that when greater attention is paid to methodological issues, estimated rates of return are generally lower, rather than higher.

Does this mean that investment in plant breeding is economically unattractive? Certainly not. Even correcting for the methodological errors that appear to have affected many case studies, it is clear that investment in plant breeding often generates significant payoffs. And while the returns to investment in plant breeding may have declined in recent years with increases in research costs, the returns are still attractive relative to most alternative investment opportunities.

Should applied researchers take more care in estimating the benefits of plant breeding research? We believe in many cases they should. We are not

advocating that elaborate measures should always be invoked to address every problem that could conceivably arise, but we do believe that the list of potential problems discussed in this paper can serve as a checklist for those seeking to estimate the benefits of plant breeding research. Although impact studies are undertaken for many different reasons, in the long run the credibility of all impact studies will depend to some extent on the attention paid to methodology in each individual evaluation exercise.

References

Adusei, E.O., Norton, G.W., 1990. The magnitude of agricultural maintenance research in the USA. J. Prod. Agric. 3 (1), 1–6.

Akino, M., Hayami, Y., 1975. Efficiency and equity in public research: rice breeding in Japan's economic development. Am. J. Agric. Econ. 57 (1), 1–10.

Alston, J.M., Chan-Kang, C., Marra, M.C., Pardey, P.G., Wyatt, T.J., 2000. A Meta Analysis of Rates of Return to Agricultural R&D: Ex Pede Herculem? IFPRI Research Report No. 113, September 2000. International Food Policy Research Institute (IFPRI), Washington, DC.

Ayer, H.W., Schuh, G.E., 1972. Social rates of return and other aspects of agricultural research: the case of cotton research in São Paolo, Brazil. Am. J. Agric. Econ. 54 (4), 557–569.

Brennan, J.P., Murray, G.M., Ballantyne, B.J., 1994. Assessing the Economic Importance of Disease Resistance in Wheat. Final Report to the Grains Research and Development Corporation, Australia. NSW Agriculture, Agricultural Research Institution, Wagga Wagga, NSW, Australia.

Byerlee, D., Moya, P., 1993. Impacts of International Wheat Breeding Research in the Developing World, 1966–1990. International Maize and Wheat Improvement Center (CIMMYT), Mexico, D.F., Mexico.

Byerlee, D., Traxler, G., 1995. National and international wheat improvement research in the post-Green Revolution period: evolution and impacts. Am. J. Agric. Econ. 77, 268–278.

Collins, M.I., 1995. The economics of productivity maintenance research: a case study of wheat leaf rust resistance breeding in Pakistan. Ph.D. Thesis. University of Minnesota, St. Paul, MN.

David, C., Otsuka, K. (Eds.), 1994. Modern Rice Technology and Income Distribution in Asia. International Rice Research Institute (IRRI), Los Baños, Laguna, Philippines.

Evans, L.T., Fischer, R.A., 1999. Yield potential: its definition, measurement and significance. Crop Sci. 39 (6), 1544–1551.

Evenson, R.E., 2000. Crop germplasm improvement: a general perspective. Paper presented at the Annual Meeting of the American Association for the Advancement of Science, February 21, 2000, Washington, DC.

Evenson, R.E., Gollin, D. (Eds.), 2003. Impact of the CGIAR on International Crop Genetic Improvement. CAB International, Wallingford, UK (in press).

Falck-Zepeda, J.B., Traxler, G., Nelson, R.G., 2000. Rent creation and distribution from biotechnology innovations: the case of Bt cotton and herbicide-tolerant soybeans in 1997. Agribusiness 16 (1), 21–32.

Gittinger, J.P., 1980. Economic Analysis of Agricultural Projects. World Bank, Washington, DC.

Heim, M.N., Blakeslee, L.L., 1986. Biological adaptation and research impacts on wheat yields in Washington. Paper presented at the Annual Meeting of the American Agricultural Economics Association, Reno, NV.

Heisey, P.W., Lantican, M.A., Dubin, H.J., 2002. Impacts of International Wheat Breeding Research in Developing Countries, 1966–1997. International Maize and Wheat Improvement Center (CIMMYT), Mexico, D.F., Mexico.

Jayasuriya, S., Shand, R., 1986. Technical change and labour absorption in Asian agriculture: some emerging trends. World Dev. 14, 415–428.

Lipton, M., Longhurst, R., 1989. New Seeds and Poor People. Johns Hopkins University Press, Baltimore, MD.

López-Pereira, M.A., Morris, M.L., 1994. Impacts of International Maize Breeding Research in the Developing World, 1966–1990. International Maize and Wheat Improvement Center (CIMMYT), Mexico, D.F., Mexico.

Marasas, C.N., Smale, M., Singh, R.P., 2003. The Global Economic Impact of Breeding for Genetic Resistance to Leaf Rust in CIMMYT-related Spring Bread Wheat. International Maize and Wheat Improvement Center (CIMMYT), Mexico, D.F., Mexico (in press).

Maredia, M., Byerlee, D. (Eds.), 1999. The Global Wheat Improvement System: Prospects for Enhancing Efficiency in the Presence of Research Spill-overs. CIMMYT Research Report No. 5. International Maize and Wheat Improvement Center (CIMMYT), Mexico, D.F., Mexico.

Marshall, G.R., Brennan, J.P., 2001. Issues in benefit-cost analysis of agricultural research projects. Aust. J. Agric. Resour. Econ. 45 (2), 195–213.

Morris, M.L., 2002. Impacts of International Maize Breeding Research in Developing Countries, 1966–1998. International Maize and Wheat Improvement Center (CIMMYT), Mexico, D.F., Mexico.

Morris, M.L., Dubin, H.J., Pokhrel, T., 1994. Returns to wheat breeding research in Nepal. Agric. Econ. 10 (3), 269–282.

Pardey, P.G., Alston, J.M., Christian, J.E., Fan, S., 1996. Hidden Harvest: US Benefits from International Research Aid. Food Policy Report. International Food Policy Research Institute (IFPRI), Washington, DC.

Quizon, J., Binswanger, H.P., 1986. Modeling the impact of agricultural growth and government policy on income distribution in India. The World Bank Econ. Rev. 1, 103–148.

Renkow, M., 1994. Technology, production environment, and household income: assessing the regional impacts of technological change. Agric. Econ. 10 (3), 219–232.

Renkow, M., 2000. Poverty, productivity, and production environment: a review of the evidence. Food Policy 25 (2), 463–478.

Rogers, E.M., 1962. Diffusion of Innovations. Free Press, New York, NY.

Ruttan, V.W., 1977. The Green Revolution: seven generalizations. Int. Dev. Rev. 19 (4), 13–16.

Smale, M., Singh, R.P., Sayre, K., Pingali, P., Rajaram, S., Dubin, H.J., 1998. Estimating the economic impact of breeding nonspecific resistance to leaf rust in modern bread wheats. Plant Dis. 82, 1055–1062.

Tollenaar, M., Wu, J., 1999. Yield improvement in temperate maize is attributable to greater stress tolerance. Crop Sci. 39 (6), 1597–1604.

Townsend, R., Thirtle, C., 2001. Is livestock research unproductive? Separating health maintenance from improvement research. Agric. Econ. 25 (2–3), 177–190.