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The Economic Impact in Developing Countries of
Leaf Rust Resistance Breeding
in CIMMYT-Related Spring Bread Wheat

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Abstract: This study was undertaken to estimate the economic impact of efforts since 1973 by the International Maize and Wheat Improvement Center (CIMMYT) to develop spring bread wheat varieties resistant to leaf rust caused by *Puccinia triticina.* This wheat disease is of major historical and economic importance worldwide. The challenge in estimating the benefits lies in the pathogen's ability to mutate to new races, which may infect previously resistant varieties. Thus, whereas productivity enhancement is often measured in terms of yield gains and increased supply, productivity maintenance is measured in terms of the yield losses avoided through resistance. An economic surplus approach adjusted for maintenance research and a capital investment analysis were applied to estimate the returns on CIMMYT's investment. The results of the analysis suggest an internal rate of return of 41%. When discounted by 5%, the net present value was 5.36 billion 1990 US$, and the benefit-cost ratio 27:1. This implies that every 1990 US dollar invested in CIMMYT's wheat genetic improvement over 40 years has generated at least 27 times its value in benefits from leaf rust resistance breeding in spring bread wheat alone. The findings of the study emphasize the importance of maintenance research in crop breeding programs.

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Executive Summary

Leaf rust caused by *Puccinia triticina* is a wheat disease of major historical and economic importance worldwide. Genetic resistance is the principal means of controlling wheat diseases in developing countries, where fungicides are not often used for this purpose. The objective of this study is to estimate the economic impact on developing country wheat production of efforts by the International Maize and Wheat Improvement Center (CIMMYT) to breed leaf rust resistant spring bread wheat varieties since 1973. The challenge in estimating these benefits is in dealing with the pathogen's ability to mutate to new races, which may infect previously resistant varieties. Various single genes or gene complexes determine the type, level, and longevity of a variety's resistance. Leaf rust resistance breeding is therefore an example of crop maintenance research. Whereas productivity enhancement is often measured in terms of positive yield gains, maintenance is estimated in terms of the yield losses avoided through a given research investment.

Returns were estimated using an economic surplus approach, adjusted for maintenance research, and a capital investment analysis. Gross benefits were modeled as the cost-increasing supply shift avoided through leaf rust resistance. A sample of the major spring bread wheat varieties grown in the developing world was classified by type and level of resistance through trials at CIMMYT. The yield losses occurring in varieties with different resistance levels were compared to the yields that would have been lost had the varieties been fully susceptible. Historical logistic diffusion curves were fitted to the potentially affected study area to estimate the area to which yield savings applied. The analysis was conducted by wheat "mega-environment," a classification developed by CIMMYT to guide its germplasm enhancement activities. The real world wheat price was used to value the production savings. The total cost of wheat genetic improvement by CIMMYT was included. Costs were assumed since 1967 to allow a research lag of six years for varieties released in 1973. A range of investment values was elicited by alternating assumptions on several parameters.

The results suggest that substantial economic returns were generated by CIMMYT's investment in leaf rust resistance breeding since 1967 and projected to 2007. The internal rate of return was 41% under our base scenario and higher research cost assumptions. When discounted by 5%, the net present value was 5.36 billion 1990 US$, and the benefit-cost ratio 27:1. This implies that every 1990 US dollar invested in CIMMYT's wheat genetic improvement over 40 years has generated at least 27 times its value in benefits from leaf rust resistance breeding in spring bread wheat alone. We arithmetically calculated that CIMMYT's investment would still be recovered, even if the average annual yield lost by leaf rust susceptible varieties in mega-environment 1 had been a mere 0.2 to 0.8%. Benefits were primarily generated in mega-environment 1 and by varieties with race-nonspecific leaf rust resistance.

The study underscores the importance of maintenance research in crop breeding programs. As productivity rises, increasing effort is required to maintain previous gains. The continually evolving pest and disease complex has prompted major maintenance efforts over the years. Studies at CIMMYT indicate that progress in protecting wheat yield potential through disease resistance breeding has been greater than advances in yield potential itself. Without constantly upgrading resistance by sustained investment in maintenance research, crop productivity and stability would eventually decline. There are nevertheless comparatively few economic analyses of maintenance research in wheat, particularly for disease resistance breeding. We conclude that the valuation of agricultural research is incomplete without accounting for the losses that would have occurred in the absence of its maintenance component.

The Economic Impact in Developing Countries of Leaf Rust Resistance Breeding in CIMMYT-Related Spring Bread Wheat

C.N. Marasas, M. Smale, and R.P. Singh

Introduction

Leaf rust caused by *Puccinia triticina* Eriks. is a wheat disease of worldwide historical and economic importance. Yield losses to leaf rust are suffered in many wheat-producing areas in most years, and periodic epidemics were common in most decades of the last century. The cultivation of resistant varieties remains the principal control method in developing countries, where fungicides are not often used for this purpose. The major challenge is in dealing with the pathogen's ability to mutate to new races, which may infect previously resistant varieties. Various single genes or gene complexes determine the type, level, and longevity of a variety's resistance. Leaf rust resistance breeding is therefore an example of crop maintenance research. Whereas productivity enhancement is often measured in terms of positive yield gains, maintenance is estimated in terms of the yield losses avoided through the research investment. Though its importance has long been argued, there are comparatively few economic analyses of wheat maintenance research, particularly for disease resistance breeding.

The objective of this study is to estimate the economic impact on developing country wheat production of efforts by the International Maize and Wheat Improvement Center (CIMMYT) to breed leaf rust resistant spring bread wheat varieties since 1973. An economic surplus approach, adjusted for maintenance research, and a capital investment analysis were used to estimate the returns. The yield losses in varieties with different levels of leaf rust resistance were compared to the yields that would have been lost had the varieties been fully susceptible. The total cost of wheat genetic improvement by CIMMYT was included. Costs were assumed since 1967 to allow a research lag of six years for varieties released in 1973. The production savings generated by CIMMYT's investment were then estimated for the period since 1967 and projected to 2007. A range of investment values was elicited by alternating assumptions on several parameters. This report first outlines the background and scope of the study and summarizes previous research related to the economic analysis. The conceptual framework and methodology are then described and results and conclusions presented.

Background

Leaf rust caused by *P. triticina* is a wheat disease of major historical and economic importance worldwide (Howard and Howard 1909; Saari and Prescott 1985; Samborski 1985; Roelfs et al. 1992). It is the most widespread of three types of rusts. The other two are stem rust caused by *P. graminis* and stripe rust caused by *P. striiformis*. The symptoms of leaf rust usually involve brown lesions on the upper leaf surface of the wheat plant. Severe levels of disease can halt growth or even destroy the plant by causing water and nutrient losses through restriction of the photosynthetic area. The economic importance of rusts follows from the extent to which they may reduce grain yield and stability, their ability to spread rapidly and reach epidemic proportions under favorable conditions, and the pathogens' potential to mutate rapidly to overcome the effects of current resistance genes.

Periodic rust epidemics were common in most decades of the last century, and the development of genetic resistance has been a plant breeding objective since the early 1900s (Macindoe and Brown 1968; Lupton 1987). It has also been a priority of CIMMYT's wheat breeding program since its inception. The cultivation of resistant varieties remains the principal control method in developing countries, where farmers use very little fungicide on wheat. Procuring and distributing the large quantities of fungicides that would be needed to combat an unanticipated rust epidemic would not be feasible in many of these countries. Genetic manipulation of resistance genes over the past 40 years has generally resulted in more stable patterns of resistance (Singh and Dubin 1997), but some yield losses to rusts are still suffered in many wheat-producing areas in most years.

Varieties can carry different types and levels of leaf rust resistance. With the discovery of the genetic basis of resistance (Biffen 1905), physiological specialization in rusts (Stakman et al. 1962), and the gene-for-gene hypothesis (Flor 1956), the utilization of race-specific resistance has dominated in wheat improvement (Rajaram et al. 1997). A single gene or a combination of genes having intermediate to major effects controls this type of resistance. Many of these genes are now known and have been catalogued by McIntosh et al. (1995). Depending on the genetic constitution of the host and the pathogen, a variety may be resistant to one isolate of the pathogen, but susceptible to another. Due to the intermediate to major effects conferred by race-specific resistance genes, yield losses may be minimal during the useful life of the cultivar. However, these effects may be overcome within a relatively short period of time. Once a variety's resistance has been overcome by newer pathogens, the reaction to the pathogen becomes essentially susceptible and yield losses may then be large. The longevity of a cultivar with race-specific resistance can range from rapid vulnerability to relative and often deceiving durability (Kilpatrick 1975; Rajaram et al. 1997). However, it is likely that most types of race-specific resistance will eventually succumb to new adaptive pathotypes, if careful deployment is not practiced. In many areas it takes no more than a few years for a new pathogen race to arise. The history of wheat is filled with examples of new virulence genes arising in the rust fungi and increasing to levels rendering previously resistant varieties vulnerable to disease.

The pathogen's ability to mutate rapidly and evolve new physiological races gives rust resistance its continual importance in breeding programs. To avoid the potential for plant disease epidemics caused by uniformity in the genetic base, resistant varieties must be replaced continually with new varieties that possess different resistance genes. Since CIMMYT's establishment in 1966, most wheat lines distributed to national agricultural research programs have carried leaf rust resistance based on race-specific genes. However, CIMMYT wheat breeders soon took an interest in varietal mixtures, multilines, multi-locational testing, and other mechanisms for obtaining diverse, multigenic, and more stable resistance (Borlaug 1965, 1968; Rajaram et al. 1997). A severe leaf rust epidemic in northwestern Mexico in 1976-77 dramatically underscored the need for more durable resistance (Dubin and Torres 1981).

In view of the frequent erosion of race-specific genes, race-nonspecific resistance as theoretically defined by Vanderplank (1963) and applied to rust resistance by Caldwell (1968) has been the dominant wheat breeding strategy at CIMMYT (Rajaram et al. 1988). This type of resistance is usually complex and based on the interaction of a few or several genes having partial to additive effects.[1] The genes are theoretically effective against all races of the pathogen simultaneously and result in varying levels of resistance against them (Singh and Dubin 1997). Disease development in varieties that possess race-nonspecific resistance typically progresses more slowly (Caldwell 1968; Parlevliet 1975). The varieties maintain useful levels of resistance in most years, showing higher infection levels when disease pressure is heavy, but not succumbing. The response to infection is essentially susceptible, and the material shows typical leaf rust symptoms. Some yield losses may occur soon after the release of the variety and may be larger than the losses suffered by varieties with effective race-specific resistance. The race-nonspecific resistance appears to endure longer, however (Johnson 1988). Its path of deterioration, if deterioration occurs, may be more gradual and may not cause devastating losses for many years.

CIMMYT-related germplasm is grown over large areas and exposed to a variety of pathogens under conditions that may favor disease development. Genetic diversity and durability are therefore important features of the rust resistance sought by CIMMYT's global wheat improvement program. CIMMYT scientists breed for race-nonspecific resistance by accumulating diverse, multiple genes from new sources and genes controlling different resistance mechanisms within single varieties (Rajaram et al. 1996). Initially, parents are selected that lack effective major genes and demonstrate moderate to good levels of resistance to the local rust pathogens. The parents of interest should show susceptibility at the seedling stage in the greenhouse and slow rusting as adult plants in the field. Genetic diversity is maintained by using parents with different sets of additive genes in crosses, if the information is available for these genes. If such information is not available, parents of diverse

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[1] There are numerous reports on the race-nonspecific resistance genes and their effects in CIMMYT-related spring bread wheat varieties in various countries. See for example: Singh (1991, 1992, 1993); Singh and Gupta (1991, 1992); Singh and Rajaram (1991, 1992); Singh et al. (1991); Malaker and Singh (1995); Singh and Huerta-Espino (1995, 1997); Singh et al. (1995); Rajaram et al. (1996); Sayre et al. (1998); Singh et al. (1999); and Singh et al. (2000).

origins or pedigrees are selected for crosses. In the breeding nursery, plants are subjected to heavy disease pressure for chosen rust pathotypes, and plants with low to moderate final disease severity are selected. Other morphological markers are also used in selecting plants. Promising advanced lines are tested at multiple locations to select various types of disease resistance and to assess the effectiveness and stability of resistance across environments. This involves shuttling the segregating populations between sites in Mexico, or between Mexico and "hot spot" locations outside the country. Genetic analyses are conducted for the most important advanced lines. This selection strategy has resulted in the development of high-yielding wheat lines containing four to five minor, additive genes and very high resistance levels. Losses from leaf rust in these lines are considered negligible, even under high disease pressure (Singh et al. 2000).

Objective and Scope of the Study

The objective of this study is to estimate the economic impact on developing country wheat production of CIMMYT's efforts since 1973 to develop leaf rust resistant spring bread wheat varieties. The yields lost by varieties of different resistance categories were compared to the yields that would have been lost had the varieties been fully susceptible. The economic value of the wheat yield saved was then calculated. The scope of this study and definition of terms are explained below.

The study encompassed all leaf rust resistance mechanisms carried by CIMMYT-related spring bread wheat. Though CIMMYT emphasizes selection for race-nonspecific leaf rust resistance (Rajaram et al. 1996), a time lag exists between the distribution of an advanced wheat line and the release of a variety selected from it by a national program. Breeders in some countries may prioritize other characteristics. A time period also passes until a variety attains its adoption ceiling and gradually ceases to be grown in farmers' fields. Producers often continue to grow varieties with resistance levels that wheat scientists may no longer consider satisfactory. CIMMYT-related varieties with race-specific and race-nonspecific resistance can therefore be found in farmers' wheat fields today.

This study deals with developing countries, given CIMMYT's mandate to breed advanced lines for the national agricultural research programs in those countries. We focus on spring bread wheat, though winter and facultative habit wheat and durum wheat are included in CIMMYT's breeding efforts and are also grown in the study area. However, spring bread wheat covers about two-thirds of the wheat area in the developing world and comprised an estimated 71.5 million hectares in 1997 (Heisey et al. 2002).

The analysis is conducted by wheat "mega-environment" (ME), a classification developed by CIMMYT to guide its germplasm enhancement activities (Rajaram et al. 1995; van Ginkel et al. 2000). Six MEs have been defined for spring bread wheat (Appendix A). As outlined in the appendix, we focused on the MEs where spring bread wheat is grown at low latitudes—that is, MEs 1, 2, 3, 4a, 4b, 4c, and 5. Mega-environment 1 accounts for 36 million hectares and 54% of the study area of 66.5 million hectares (Appendix A, Table A1).

The term "CIMMYT-related" includes those materials selected from advanced CIMMYT lines by wheat breeders in national agricultural research programs. The varieties included are generally descendants of the first semidwarf wheat varieties released during the late 1960s. These first semidwarfs initially spread throughout the irrigated zones most favorable to wheat production. Later, more widely adapted descendants of these varieties spread into less favorable growing environments, including rainfed areas with relatively modest production potential. The development and diffusion of these materials is accomplished through multilocation testing and the exchange of germplasm between CIMMYT and national programs. CIMMYT sends nurseries, consisting of dozens to hundreds of advanced lines, to partners that request them for testing and selection each year (Fox and Skovmand 1996). From these materials, local scientists choose lines demonstrating the best adaptation to local conditions, select from them, or cross them to elite local germplasm, and submit the resulting materials to national trials. We refer to the varieties then released as "CIMMYT-related."

CIMMYT and CIMMYT-related germplasm play an important role in developing country wheat production. Almost 80% of the spring bread wheat area in developing countries was sown to CIMMYT-related semidwarf varieties in 1997 (Heisey et al. 1999). Wheat breeders in these countries indicated that materials from CIMMYT International Nurseries are the most frequently crossed in pursuit of disease resistance goals (Rejesus et al. 1997). Most CIMMYT bread wheat germplasm, and several of the major wheat varieties grown in the developing world, contain in their pedigrees the ancestral source of the gene combinations believed to confer durable rust resistance. CIMMYT's co-operation with national wheat research programs in developing countries is thus likely to have achieved a broad international flow of germplasm with leaf rust resistance.

Previous Research

Returns on investments in agricultural research have often been estimated assuming that research explains positive productivity growth, and that productivity would remain constant in the absence of research. However, this assumption ignores the losses that may result from physical, biological, and economic changes that could render existing technologies less effective. The gains from previous research may thus not remain static, but may decline as a result of these changes. Whereas productivity enhancement is often measured in terms of positive yield gains, maintenance is estimated in terms of the yield losses that would have occurred in the absence of investments in research.

A certain proportion of new research is known as maintenance research, which is needed to correct the inherent tendency of the usefulness of research products to deteriorate over time. This depreciation has been shown to occur at different rates across various commodity groups (Adusei 1988), and agricultural productivity has been estimated to decrease by 5 to 40% without maintenance research (Araji et al. 1978). By means of a questionnaire distributed to scientists at agricultural experiment stations, Adusei and Norton (1990) showed that 35% of research efforts in the United States of America (USA) are dedicated to maintenance research. The maintenance proportion of total research was shown to vary by type of commodity and was found to be higher for crops than for livestock. The productivity maintenance effort for wheat was estimated at 41%.

The importance of maintenance research in crop breeding programs should be recognized for several reasons (Moseman 1970; Araji et al. 1978; Knutson and Tweeton 1979; Schuh and Tollini 1979; Ruttan 1982; Evans 1983; Peacock 1984; May 1985; Swallow et al. 1985; Plucknett and Smith 1986; Adusei 1988; Pardey and Roseboom 1989; Adusei and Norton 1990; Bohn and Byerlee 1993; Alston et al. 1995). As crop productivity rises, increasing effort is required to maintain previous gains. As yields rise and the yield curve flattens, the proportion of research absorbed by maintenance increases. Gains from improved breeding techniques are typically easier to achieve during the early years, after which intensified efforts are required to maintain similar productivity levels. The continually evolving complex of pests and diseases, and their apparently increased resistance to chemical and other control measures, has prompted the turnover of wheat varieties over time. These circumstances have been a major cause of research depreciation and the resulting need for maintenance to prevent productivity declines and yield fluctuations. Maintenance may be of special importance in tropical regions, where reproduction and evolutionary changes in pests and pathogens are likely to be more rapid, causing resistant mutants to comprise a successively larger proportion of the overall population. Finding new solutions to these problems has been a major objective of research in entomology, plant pathology, weed science, and plant breeding. Without constantly upgrading resistance by sustained investment in maintenance research, the gains in crop productivity and stability achieved over the past decades would eventually decline. Stable and sustainable productivity is as important as raising the yield ceiling of crops.

A further issue relates to early problem identification, and Plucknett and Smith (1986) raise several examples of the broad-based capability and "preventative medicine" typical of sound maintenance research. This is important when considering the lag between the time that research funds are committed and when the results are ready for widespread adoption. The valuation of agricultural research is therefore incomplete without accounting for the losses that would have occurred in the absence of its maintenance component. Clear comprehension of this concept is crucial for enlightened policy decisions in resource allocation and priority setting.

Economic analyses have nevertheless tended to undervalue the productivity losses avoided through agricultural research. Townsend and Thirtle (2001) have illustrated the magnitude of this error by separating the maintenance effects of animal health research from output increases due to improvement research in South Africa. They suggest a minimum underestimation of 50% on returns to livestock research when the negative effects of diseases are not explicitly taken into account. Though their analysis focused on livestock, the findings may also apply to returns estimates for wheat research. Adusei and Norton (1990) in fact showed that maintenance comprised a higher proportion of crop than of livestock research in the USA. As Townsend and Thirtle (2001) also emphasize, we do not suggest that maintenance research is underestimated because of a lack of understanding or effort. Instead, valuation of these benefits is often restricted by data limitations.

Most assessments of the returns on wheat research investments[2] have focused on productivity enhancement. There are comparatively fewer economic analyses of wheat maintenance research, particularly for pest and disease resistance breeding (Doodson 1981; Heim and Blakeslee 1986; Blakeslee 1987; Brennan and Murray 1988; Priestley and Bayles 1988; Brennan et al. 1994; Morris et al. 1994; Collins 1995; Smale et al. 1998; Marasas 1999). However, research at CIMMYT indicates that resistance breeding has generated a substantial proportion of the returns on international wheat research over the past decades (Bohn and Byerlee 1993; Byerlee and Moya 1993; Byerlee and Traxler 1995; Rajaram et al. 1996; Heisey et al. 1999). Analyses of trial results confirmed that progress in protecting yield potential through leaf rust resistance has been greater than advances in yield potential itself (Sayre et al. 1998).

Smale et al. (1998) estimated the returns on CIMMYT's investment in a breeding strategy for race-nonspecific resistance, as compared to one for race-specific resistance, in the Yaqui Valley of northwestern Mexico. A return of 40% was calculated for 1970-1990. The authors assumed average annual yield savings of only 9% and a research-to-adoption lag of five years, which is reasonable for varieties released as close to CIMMYT as the Yaqui Valley. They used detailed information on resistance genes and the longevity of useful resistance for each wheat variety grown since 1968. The Yaqui Valley represents a testing ground for ME1—the major environment in which CIMMYT-related spring bread wheat is grown. However, that study covered only 150,000 of the estimated 66.5 million hectares of spring bread wheat included in this study.

Similar genetic information was not available on a global basis to facilitate our analysis. The actual longevity of useful leaf rust resistance is not known for each variety released in each production environment of the developing world since 1973. The genetic basis of resistance is also not known for all varieties, and the presence of resistance sources in a variety's ancestry does not ensure that it contains the relevant gene. Even if the gene is present, interactions with other genes and the environment eventually determine the variety's resistance level when challenged by pathogens in farmers' fields. Moreover, considering that farmers in developing countries use varieties with various types and levels of leaf rust resistance, our analysis encompassed race-specific and race-nonspecific resistance. The conceptual framework and methodology underlying the economic analysis is explained in the following sections.

Conceptual Framework

The first step in measuring the economic benefits of agricultural research is to compare the situation with research to one with no research, also known as the "with" and "without" scenarios (Gittinger 1982; Alston et al. 1995). Following the background information provided in the previous sections, we assumed that the "with" scenario is represented by resistant varieties with different leaf rust resistance categories, and the "without" scenario by susceptible varieties. Given the pathogen's ability to overcome the effects of previously resistant varieties, we argued that leaf rust resistance breeding is an example of productivity maintenance. An economic surplus approach adjusted for maintenance research and a capital investment analysis were applied to estimate the returns on CIMMYT's investment. The "with" and "without" scenarios are subsequently explained within an economic surplus framework.

In the basic version of the surplus approach, productivity enhancement is often treated as a cost-reducing rightward or downward shift in the aggregate supply function[3] of a commodity, as shown by S_1 in Figure 1. This may result from yield increases or cost savings attributable to the technology. Constant supply is assumed in the absence of

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[2] A review of previous studies, including wheat among other enterprises, can be found in Evenson (1998). Studies more recently conducted in Africa are summarized in Marasas (1999), and impact assessment milestones of the Consultative Group on International Agricultural Research are described by Pingali (2001).

[3] The economic surplus approach for estimating the returns on agricultural research was pioneered by Griliches (1958). The progressive refinements that have since appeared in the literature vary in their complexity and data requirements, and may differ in their functional form, nature of the demand and supply curves, and the nature of the research-induced shifts in the supply curve. These assumptions influence the magnitude of the change in economic surplus, and its distribution between consumers and producers. For examples, which also include adaptations to crop breeding programs, see: Peterson (1967); Schmitz and Seckler (1970); Fishel (1971); Ayer and Schuh (1972); Akino and Hayami (1975); Hayami and Herdt (1977); Lindner and Jarrett (1978); Scobie and Posada (1978); Schuh and Tollini (1979); Rose (1980); Wise and Fell (1980); Norton and Davis (1981); Alston et al. (1988); Byerlee (1990); Voon and Edwards (1991); Brennan (1992); Johnston et al. (1992); Renkow (1993); Morris et al. (1994); Alston et al. (1995); Collins (1995); Anandajayasekeram et al. (1996); and Marasas (1999).

research, as represented by S_0. The area under the demand curve, and between S_1 and S_0, shows the increased economic surplus associated with this shift. However, the assumption of a static supply function does not remain valid in the face of evolving leaf rust pathogens and the resulting depreciation of genetic resistance. Once a variety's resistance has been overcome by newer pathogens, its production gains will not remain constant. They will decline and result in lower output production per unit cost. If not constantly replaced by newly resistant varieties with a similar productivity potential, a leftward or upward shift in the supply curve will occur, as shown by S_2.

Maintenance research within a surplus approach can therefore be defined as the effort required to prevent a cost-increasing supply shift, which results from changes in the physical, economic, or biological environment (Collins 1995). The economic surplus generated by preventing this shift is shown as the shaded area under the demand curve, and between S_0 and S_2 in Figure 1. This framework thus depicts S_0 as the supply with maintenance, but without enhancement research; S_2 as the supply without maintenance or enhancement research; and S_1 as the supply with maintenance and enhancement research. The discussion assumes full adoption and depreciation, though these are clearly dynamic processes.

In our case, we assume that the "with" scenario is the supply (S_0) generated by the CIMMYT-related spring bread wheat varieties with different leaf rust resistance categories since 1973. The "without" scenario is the supply (S_2) that would have prevailed had these varieties been fully susceptible. The benefits are estimated in terms of the productivity losses, or the cost-increasing supply shift from S_0 to S_2, which have been avoided through leaf rust resistance. Positive enhancement gains, depicted by the shift from S_0 to S_1, are not valued.

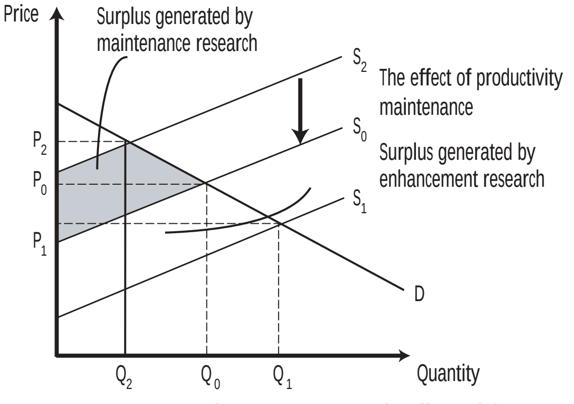

Figure 1. General economic surplus approach adjusted for maintenance research.

Notes: S_0 = Supply with maintenance, but without enhancement research; S_1 = Supply with maintenance and enhancement research; S_2 = Supply without maintenance or enhancement research; S = Supply; D = Demand; P = Price; and Q = Quantity.

Our approach is simplified methodologically in the following ways, due to standard difficulties in estimating the impact of maintenance research, estimating the economic impact of agricultural research in general, and limitations imposed by the available data :

- The costs and benefits of maintenance and enhancement research are often difficult to separate. Our assumptions in this regard are explained in the Methodology section.
- If detailed, historical farm-level data were available for annual yield losses from leaf rust over the millions of hectares of spring bread wheat grown in the developing world, benefits could be calculated directly. In the absence of this information, we use trial data on relative losses for a sample of those varieties. These data are combined with estimates from CIMMYT pathologists of the expected farm-level losses and areas affected by leaf rust.
- We do not know the area sown to CIMMYT-related wheat for each year on the aggregate diffusion curve over the past three decades. We thus estimate the annual areas sown by fitting a logistic function. Point estimates drawn from historical data serve as function parameters and enable us to calibrate the shape of the curve.
- We apply a capital investment analysis to estimate the returns, instead of a fully developed equilibrium model based on a multi-market world economy. One reason is that equilibrium models require supply and demand elasticities for all relevant input and output markets for all affected countries. The benefits in this analysis are aggregated over various relatively small wheat-producing countries in the developing world. Losses to leaf rust might have generated a shift in the short- and long-term wheat supply curve in any one of these countries. However, these changes would not have been substantial enough to affect the world wheat price in the presence of the large volumes traded by wheat-producing countries in the developed world. The demand curve is therefore perfectly elastic at the world wheat price in our version of Figure 1. We measure the supply shift avoided in units on the horizontal axis, valued at the world wheat price, for each year and wheat-producing environment included in the study. The supply curve refers to CIMMYT-related spring bread wheat only.

Methodology

In the capital investment analysis, the research returns were estimated in terms of the net present value, internal rate of return, and benefit-cost ratio, as defined by Gittinger (1982). The net present value of leaf rust resistance breeding in CIMMYT-related spring bread wheat can be most generally expressed as:

$$\text{Net present value} = \sum_{t=1}^{n} \frac{1}{(1+i)^t} [(p_t \lambda y_t a_t) - C_t] \tag{1}$$

Essential parameters are: (1) λ, the average annual farm-level percent yield loss avoided through varieties with different leaf rust resistance categories; (2) y, the average annual farm-level wheat yield per hectare, and (3) a, the area sown to CIMMYT-related spring bread wheat that is potentially affected by leaf rust. The product of these terms represents the production savings by leaf rust resistance category and wheat breeding environment. This is valued by the (4) real world wheat price p. The difference between the gross benefits and the (5) research cost C is calculated for (6) each year t. The benefits start in 1973, the year of release of the first variety (Torim 73) recognized and promoted for race-nonspecific resistance. Costs are assumed since 1967 (t_1) to allow a research lag for the varieties released in 1973. The benefits end n years later in 2007 (t_n), the year the last adoption ceiling predicted in our logistic diffusion curves is reached. The net benefits are discounted since 1967 by the (7) interest rate i to obtain the net present value.

The net present value is an economic indicator of the magnitude of net benefits generated by the investment. By contrast, the internal rate of return expresses the magnitude of net benefits relative to the investment outlay. It represents the maximum interest that can be paid for the resources used if an initiative is to recover its investment. The internal rate of return is estimated by setting the net present value equal to zero in equation (1) and solving for i arithmetically:

$$\sum_{t=1}^{n} \frac{1}{(1+i)^t} [(p_t \lambda y_t a_t) - C_t] = 0 \tag{2}$$

The investment returns can also be expressed as the ratio of benefits generated relative to the funds invested. For this purpose, the benefit-cost ratio is calculated by dividing the present value of the gross benefits by the present value of the research costs:

$$\textit{Benefit-cost ratio} = \sum_{t=1}^{n} \frac{1}{(1+i)^t} \left[\frac{(p_t \lambda y_t a_t)}{C_t} \right] \tag{3}$$

In this report, we first compare the gross benefits by resistance category and wheat breeding environment, since the research costs could not be separated on this basis. The economic returns on CIMMYT's investment in wheat genetic improvement are then calculated. Sensitivity analysis is conducted by varying assumptions related to research costs, the discount rate, and yield losses avoided. Various sources of primary and secondary data were employed, including: (1) the 1990 and 1997 CIMMYT Global Wheat Impacts Surveys; (2) data from the Food and Agriculture Organization (FAO) on annual national wheat yields and areas; (3) data from trials conducted at El Batán, Mexico, in 2000 and previous years; and (4) other CIMMYT publications and estimates. Calculation of each of the parameters in equations (1) to (3) is described next, with details related to data sources and assumptions. A summary of parameter assumptions is presented in Table 1.

Yield losses avoided

Parameter λy_t in equations (1) to (3) is defined as the average annual farm-level yield losses avoided through growing CIMMYT-related spring bread wheat varieties, by genetic resistance category and ME, from 1973 to 2007. This is calculated as the product of: (1) the percent yield loss avoided through resistant relative to susceptible varieties, by resistance category; (2) the average annual farm-level percent yield loss with susceptible varieties, by ME; and (3) the average annual farm-level yield of CIMMYT-related spring bread wheat, by ME from 1973 to 2007. Calculation of each of these terms is explained in the following sections.

Percent yield loss avoided through resistant relative to susceptible varieties. A list of varieties was drawn from CIMMYT's latest Global Wheat Impacts Survey, which provides data on the area sown to the major spring bread wheat varieties grown by farmers in developing countries in 1997 (see Heisey et al. 2002 and summary in Heisey et al. 1999). A similar survey was implemented in 1990 (Byerlee and Moya 1993). In 1997, questionnaires were sent to 41 developing countries where at least 20,000 tons of wheat are

Table 1. Summary of parameters used in this study.

Environment	Mega-environment (ME)	% yield lost to leaf rust[†‡]	% area affected by leaf rust[‡]	Cumulative % area under CIMMYT-related wheats[§] 1977	1990	1997	Adoption lag	Diffusion period
Irrigated	1	6	96	83	99	99	0	15
High rainfall	2	3	92	38	77	81	8	21
Acid soil	3	3	100	0	60	48	12	12
Semi-arid, Mediterranean	4a	2	45	5	23	59	9	25
Semi-arid, Southern Cone	4b	1	100	0	69	91	14	15
Semi-arid, Subcontinent	4c	1	69	0	25	50	14	17
Hot, humid	5a[#]	6	100	83	99	95	0	15

[†] Yields lost by susceptible varieties.

[‡] Average annual estimates obtained from the International Maize and Wheat Improvement Center (CIMMYT).

[§] Estimates of the cumulative percentage area sown to CIMMYT-related spring bread wheat in 1997 were obtained from Heisey et al. (2002), and were assumed as the adoption ceilings in each ME. The diffusion curves were calibrated with the 1977 and 1990 data (CIMMYT 1989; Byerlee and Moya 1993).

[#] The information for ME 5 refers to the area affected by leaf rust, that is ME 5a (see Appendix A for details).

produced annually.[4] Responses were received from 36 countries that account for almost 99% of developing world wheat production. Spring bread wheat areas were reported for 34 of these countries.[5] Area estimates were based on special surveys conducted at the regional or country level, annual government surveys and seed sales in some countries, and estimates by wheat researchers. Information was elicited on the name, pedigree, origin, and area sown to individual varieties.

The database lists 1997 area estimates for 441 spring bread wheat varieties. Of these, 123 varieties of known CIMMYT origin, released since 1970, planted on more than 500 hectares, and for which seed was available in the CIMMYT gene bank were grown in a field trial at El Batán, Mexico, in 2000. Five grams of seed of each variety was planted and grown without fungicide protection. Leaf rust epidemics were established by inoculating susceptible spreader rows planted adjacent to the trial material. The trial varieties were scored three times during their growth period for disease severity in comparison to susceptible check varieties, following the modified Cobb Scale (Peterson et al. 1948) (Table 2). This procedure provided a definition of the effectiveness of each variety's resistance to leaf rust in the field. The varieties were also evaluated as seedlings in the greenhouse with selected *P. triticina* races to assess the presence of effective race-specific genes. The varieties were then classified by type and level of genetic resistance to the current Mexican leaf rust population. Trial data were obtained for 117 of the 123 varieties. For an additional 67 varieties, supplementary data were available from previous trials conducted by CIMMYT over several years in a similar manner as described above. This resulted in a total sample of 184 varieties.

For several of these cultivars, the field symptoms of leaf rust were known in their respective areas from regional or international trial data. For those cultivars where information was not known, the

Table 2. Definition of the leaf rust resistance categories used in this study.[†]

Category	% leaf rust infection relative to susceptible check	Type of resistance
1	80 - 100	Susceptible
2	50 - 79	Race-nonspecific, low resistance
3	30 - 49	Race-nonspecific, moderate resistance [‡]
4	10 - 29	Race-nonspecific, high resistance [‡]
5	less than 10	Race-nonspecific, high resistance [‡]
6	less than 5	Effective race-specific resistance

[†] Based on the modified Cobb Scale (Peterson et al. 1948).

[‡] Race-nonspecific categories 3 to 5 should survive most leaf rust epidemics.

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[4] The nations of Central Asia and the Caucasus were not yet included in these surveys, because they were not yet included in CIMMYT's mandate area.

[5] Of the 36 countries, Lebanon reported no spring bread wheat and no areas were reported for Libya.

likely behavior was predicted based on the presence or absence of effective race-specific genes from the greenhouse tests and behavior in the field trials. We assumed that most lines were likely to be classified into similar resistance categories in other environments. Though some exceptions in each direction may occur, the varieties were evaluated under very high disease pressure in the trials in Mexico. It is therefore more likely that we may have underestimated the level of protection from race-nonspecific resistance over the area included in this study.

Subsequently, the midpoint of the percent leaf rust infection relative to the susceptible check varieties (Table 2) was subtracted from 100 percent to represent the percent yield loss avoided by each resistance category. This was multiplied by the average expected farm-level loss in susceptible varieties by ME, as described in the following section.

Average annual farm-level percent yield lost with susceptible varieties. Historical farm-level data on the average annual yields lost to rust were not available over the extensive spring bread wheat producing areas of the developing world included in this study. Nor were global data on weather, management practices, or spatial distributions of pathogen and resistance types available to allow prediction of the annual disease pressure or the duration of resistance. In the absence of these data, we used estimates of expected losses from secondary sources. For this purpose, we initially considered various sources of trial data and historical accounts from the literature.

The grain yield losses associated with various types of leaf rust resistance have been compared under experimental conditions in studies conducted by CIMMYT (Singh et al. 1991; Singh and Huerta-Espino 1997). However, these estimates do not necessarily represent the annual yields lost in farmers' fields over all the production areas included in this study. Small-plot evaluations have also been shown to overestimate disease losses (Saari and Prescott 1985; Roelfs et al. 1992). Sayre et al. (1998) estimated the effects of genetic resistance on yield losses from leaf rust by regression analysis. Fifteen CIMMYT bread wheats released between 1966 and 1988 were grown under farmers' management conditions in the Yaqui Valley of Mexico in six trials for four seasons, with and without fungicide. The trial results indicated the difference in percent yield loss from rust between bread wheats with race-specific and race-nonspecific resistance, once race-specific genes are no longer effective, and under conditions of heavy disease pressure. These data were combined with information on the known or predicted longevity of race-specific resistance, and they were used to estimate the time path of resistance and the economic benefits of race-nonspecific leaf rust resistance in the Yaqui Valley (Smale et al. 1998). However, even in that study, actual annual disease losses in farmers' fields were not known. Though the trial data from Sayre et al. (1998) used to estimate the yield savings represented farmers' management practices fairly closely, the disease pressure in the trials was heavier than that experienced in producers' fields in most years. The Yaqui Valley estimates also do not necessarily represent the conditions in all wheat MEs included in this study.

CIMMYT data from the International Spring Wheat Yield Nurseries (ISWYN) were also initially considered as a source of information. These annual trials are conducted at locations in several MEs worldwide. They provide historical data on yield and other information—including rust infection scores—for the varieties included over different sites. We would have been interested in the effect of rust resistance on the yields of varieties grown at the same site over several years. However, trial entries change annually as new materials are developed, so the same varieties are rarely used for more than two or three years. The only exception is the variety Siete Cerros, a reference check that is included in all ISWYN trials in all years and at all sites. There are also some problems in working with the ISWYN data. First, not all information has been reported, which especially includes rust scores, and not all trial sites have been used for all ISWYN years. Second, the ISWYN information represents data from experiment stations, whereas we were concerned with farm-level data. Third, when using these data, it is difficult to control for the effects on farm-level yield of factors other than rust, such as annual weather variation, changes in trial management, other biotic and abiotic stresses, and degradation of the resource base of the research station. These factors may also affect the yield of the control variety (Collins 1995; unpublished observations by CIMMYT 1996). We therefore could not obtain global estimates of average annual farm-level yield losses to leaf rust from the ISWYN data.

There are various historical accounts of the economic importance of wheat rusts, and the cereal rusts have been described as fungal diseases with "worldwide" occurrence characterized by "frequent severe epidemics" and "huge annual losses" (Agrios 1997). However, the number and significance of recorded rust epidemics vary widely. Estimated production losses have typically been reported anecdotally for the developing world (Saari and Prescott 1985; Smale et al. 1998). Even when occurrence of the disease may be recorded, it is seldom accompanied by data on yield losses or the relationship to wheat prices, output levels, or imports. There are also problems when measuring rust losses in practice (Saari and Prescott 1985; Roelfs et al. 1992). Losses of less than 10% are difficult to measure statistically under most circumstances. Consequently, disease development must be severe to measure losses more accurately. It is also difficult to disaggregate rust-occasioned losses from those due to other biotic and abiotic stresses. These may often occur simultaneously and contribute to observed losses.

Accounts in the literature of leaf rust losses for the Asian subcontinent include Barclay (1892), Howard and Howard (1909), Nagarajan and Joshi (1975, 1985), Joshi (1980), Joshi et al. (1980), Nagy (1984), Joshi et al. (1985), Bajwa et al. (1986), and Khan (1987). Accounts for Mexico include Borlaug (1954, 1968), Dubin and Torres (1981), and Smale et al. (1998), and for the Southern Cone, Kohli (1985). For Africa and other developing countries, as well as developed countries in Asia, Europe, North America, and Oceania, see Chester et al. (1951), Stakman and Harrar (1957), Saari and Prescott (1985), Roelfs and Bushnell (1985), and Oerke et al. (1994). In the accounts mentioning them, the estimated yield losses from leaf rust range between environments and years, and by the scale of the area covered.

Table 3 shows examples of the yield loss estimates reported in the literature, and these examples are raised to demonstrate the importance of the area and time period represented. The disease loss encountered for any variety in any year is generally higher in zones of high disease pressure, such as in localized "hot spots." Estimated losses are also much higher in epidemic years, especially in areas where losses cannot be averted by chemical control. Farm-level yield losses averaged over several years, large areas, and various production environments are clearly smaller. Such annual losses vary from a trace to usually less than 10% (Roelfs et al. 1992), and they rarely exceed 15% (Singh et al. 1991). Oerke et al. (1994:272) estimate that the global average, including developed and developing countries, of actual losses caused by all wheat diseases (excluding pests and weeds) over the three-year period from 1988 to 1990 was 12.4%. This means that on a global basis, annual losses averaged over a longer time period for leaf rust alone should be less.

Comprehensive annual yield loss data at the state level in the USA were obtained from the Cereal Disease Laboratory (http://www.cdl.umn.edu) for a period of 25 years from 1976 to 2000. The average annual losses to leaf rust for the USA in total ranged between traces in some years, up to 2.7% (Table 3), but they differed between locations and years. These data demonstrate the point that annual losses averaged over large areas are smaller. However, these estimates do not represent the production conditions and disease pressure prevailing in all spring bread wheat environments included in this study. They also do not represent the situation in most developing countries, where few farmers use fungicides to control leaf rust. Previous estimates by CIMMYT (1985) suggest an area-weighted average annual yield loss of 3.7% to leaf rust, when calculated over a ten-year period for 22 developing countries producing more than 100,000 hectares of wheat. This information was, however, not attached to MEs.

In view of all these considerations, we based our upper-bound estimates of the average annual farm-level percent yield loss in susceptible varieties on those provided by the CIMMYT Wheat Program by wheat-producing environment (Table 1). Estimates in all MEs are less than 10% and thus in line with the general global guideline of less than 10% (Roelfs et al. 1992:2). The estimates are moreover based on yield losses in susceptible varieties in environments where a mosaic of resistant and susceptible cultivars is used. This reduces the build-up and spread of rust over large areas. Losses exceeding 25%, as reported in northwestern Mexico by Dubin and Torres (1981), might occur in most regions classified as ME 1 and ME 5 if only susceptible cultivars were used. This is because water and nitrogen, which favor disease development, are usually not limiting in these production regions. Wheat could not be grown without using fungicides under this scenario. Higher average annual losses than those assumed in Table 1 would therefore have been likely if all cultivars sown in the developing world were in fact fully susceptible.

In addition to using these estimates to solve equations (1) to (3), we performed a sensitivity analysis by arithmetically calculating the minimum average annual yield that would have had to have been lost by susceptible varieties in ME 1 to recover CIMMYT's wheat breeding investment since 1967.

Table 3. Estimated yield losses from leaf rust for various regions and years, from various sources.

Country or region	Years	Yield loss (%)	Source
Africa:			
Algeria	Ten years	2-5	CIMMYT (1985)
Egypt	1976-78[†]	15-20	CIMMYT (1978)
		10-20[‡]	Saari and Prescott (1985)
		Minor[§]	
	Ten years	1-2	CIMMYT (1985)
Ethiopia	Ten years	5-6	CIMMYT (1985)
Kenya	Ten years	1-3	CIMMYT (1985)
Libya	Ten years	2	CIMMYT (1985)
Morocco	Ten years	4-10	CIMMYT (1985)
Tunisia	Ten years	1	CIMMYT (1985)
Zimbabwe	1978[†]	25 of area	Saari and Prescott (1985)
America:			
Argentina	Ten years	1-3	CIMMYT (1985)
Brazil	Ten years	4-15	CIMMYT (1985)
Chile	Ten years	1	CIMMYT (1985)
Mexico (Yaqui Valley)	1978[†]	25-40	Dubin and Torres (1981)
	Ten years	5-7	CIMMYT (1985)
	Annual	9	Smale et al. (1998)
Peru	Ten years	2	CIMMYT (1985)
Uruguay	Ten years	1-2	CIMMYT (1985)
United States of America	1976-2000	Traces (<0.002) –2.7	Cereal Disease Laboratory (http://www.cdl.umn.edu)
Asia:			
Bangladesh	Ten years	2	CIMMYT (1985)
China	Ten years	1-4	CIMMYT (1985)
India (Punjab)	1971-73	5-10	Joshi et al. (1980)
(Northern)	1973[†]	6	Saari and Prescott (1985)
	1972[†]	3	
(Uttar Pradesh)	1986	5-10	Byerlee and Moya (1993)
(Various regions)	Ten years	1-6	CIMMYT (1985)
	Early 1900s	1-10	Howard and Howard (1909)
Nepal	Ten years	2-3	CIMMYT (1985)
Pakistan (Punjab)	1978[†]	10-20	Nagy (1984); CIMMYT (1978)
		5-10[§]	Saari and Prescott (1985)
(Various regions)	Ten years	2-3	CIMMYT (1985)
Syria	Ten years	Traces	CIMMYT (1985)
Turkey	Ten years	1-10	CIMMYT (1985)

Notes: [†] represents epidemic years, [‡] losses from yield trials in epidemic years, and [§] national losses in epidemic years. The CIMMYT (1985) estimates represent the national, unweighted range in average losses estimated for the different production regions within a country. The remaining estimates represent average annual losses.

The calculation was limited to ME 1 to render the estimates more conservative, though this environment accounted for the major proportion of the study area.

Average annual farm-level yields. Time series of the average annual farm-level yield of CIMMYT-related spring bread wheat varieties by ME were generated by combining data from the 1990 CIMMYT Global Wheat Impacts Survey with annual national wheat yields reported by FA0 (http://faostat.fao.org). The 1990 CIMMYT data provide point estimates of spring bread wheat yield and area by production zones within countries and the wheat-producing environments. Since national boundaries and edges of MEs typically overlap, the CIMMYT database records areas and yields by zones, or portions of MEs, within countries. The FAO data provided time series of national average yields from 1973 to 1998, including all wheat types, and not CIMMYT-related spring bread wheat only.

First, we smoothed the FAO national wheat yield series using three-year moving averages. Next, we calculated a national average 1990 spring bread wheat yield, by dividing the sum of the zone-level areas by the sum of the zone-level production for each country from the CIMMYT data. A spring bread wheat yield series was generated for each zone and country, by multiplying the ratio of 1990 zone-level yields to the national average with the FAO national average yield in each year from 1973 to 1998. Zone yields were then multiplied by zone areas for estimates of production by zone, which were aggregated over all the zones by country included in each ME. This production estimate was divided by the corresponding area estimate to calculate a zone-adjusted, area-by-country weighted average spring bread wheat yield by ME, from 1973 to 1998 (Figure 2).[6]

Average yield levels thus estimated were the highest in MEs 1, 2, and 5, and they have increased in all MEs since 1973. Annual yield fluctuations were evident in MEs 3 and 4b. Trend regressions were fitted to the data to project yields to 2007. Embedded in these calculations is the assumption that, though overall average yields have changed over time, the ratio of spring bread wheat yield by production zone to national average has remained constant within countries.

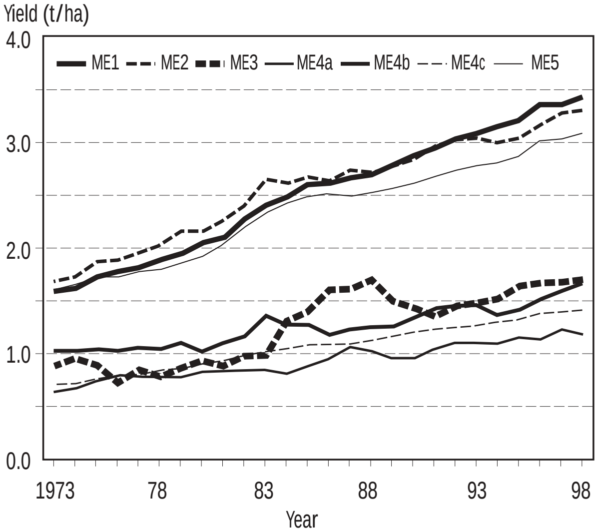

Figure 2. Average annual spring bread wheat yield by CIMMYT mega-environment from 1973 to 1998.

With the parameter λy_t we thus measure the losses avoided through leaf rust resistance as a proportion of the observed yield of CIMMYT-related spring bread wheat. However, these yields (y_t) and the growth in annual wheat yields observed in Figure 2 have resulted from both maintenance and enhancement research over the years. This complicates the estimation of the supply with maintenance research but net of enhancement research (S_0) in Figure 1, and it demonstrates the difficulties in separating the two components. No data or other systematic methods were available to separate these inherent effects over all production areas and years included in this study. Since S_0 is in fact never observed, it is difficult to estimate. We thus chose to apply the available data to estimate λy_t, even though the production savings from maintenance research may be overestimated. This would cause less distortion in the results than arbitrarily attempting to disentangle the maintenance and enhancement effects in the yield series. The percent yield loss avoided (λ) through leaf rust resistance is furthermore likely to remain the critical parameter in the conceptual framework depicted in Figure 1.

However, we included a sensitivity analysis to assess the magnitude by which the production savings were overestimated in the base scenario. For this purpose, the enhancement and other effects were eliminated from the yield series in ME 1 by drawing on CIMMYT trial data for northwestern Mexico (Sayre et al. 1998). This favorable wheat production area has heavy disease pressure and represents a testing ground for the major environment in which CIMMYT-related spring bread wheat is grown (ME 1). Considering that these trial results were available only over a relatively limited area and time period, however, we chose to apply them in a sensitivity test rather than in our base scenario.

The data by Sayre et al. (1998) were generated from replicated trials including 15 popular CIMMYT-related bread wheat cultivars released between 1966 and 1988 in the Yaqui Valley of northwestern Mexico. This set of cultivars provided an almost 30-year historical perspective of germplasm improvement at CIMMYT. The genetic progress in reducing grain yield losses through leaf rust resistance breeding was subsequently estimated over this time period. The

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[6] The 1997 yield by ME estimates obtained with this approach were compared to the 1997 point estimates of spring bread wheat yields independently estimated by Heisey et al. (2002). The latter are reported to be consistent with FAO estimated yields. We calculated the 1997 area-weighted average yield over the study area at 2.85 t/ha, which was comparable to the area-weighted average of 2.46 t/ha estimated by Heisey et al. (2002). Though slightly higher in most MEs, our yield estimates were within a similar range, and the minor difference will not affect the overall results.

results showed that the annual progress in grain yield potential achieved through resistance breeding, averaged over six trials, was 0.48% for fungicide protected plots and 2.21% for plots not protected by fungicide. Thus, although the grain yield potential of CIMMYT-related cultivars has improved significantly over the past 30 years, the progress in protecting this yield potential through rust resistance breeding was estimated to be at least four times greater. The trial data imply that leaf rust resistance has accounted for 82% of the average annual progress in grain yield potential between 1966 and 1988 in northwestern Mexico. This estimate was used to adjust the average annual yield series for ME 1. The following loglinear model was used for this purpose:

$$ln\,(y_t) = \alpha + \beta X + \varepsilon \qquad (4)$$

The parameters are: $ln\,(y_t)$, the natural logarithm of y_t, the average annual farm-level yield of CIMMYT-related spring bread wheat in ME 1; α, a constant; β, the average annual yield growth rate; X, time in years from 1973 to 1998; and ε, the error term.

The loglinear $ln\,(y_t)$ of the original ME 1 yield series y_t was regressed to estimate the coefficient on time β, representing the average annual percent growth in yield from 1973 to 1998. The coefficient was adjusted by 82% to include only the proportion of growth attributable to leaf rust resistance breeding, as estimated from the CIMMYT trial data by Sayre et al. (1998). This resulted in a new coefficient $\hat{\beta}$, which was used to generate a new loglinear yield series $ln(\hat{y}_t)$. The antilog resulted in a yield series $(\hat{y}_t)$ including only the growth attributable to leaf rust resistance, net of yield enhancement and other research effects, and thus corresponding to around 82% of the original series y_t. As before, we regressed the data to project yields to 2007, and repeated the analysis by substituting y_t with $\hat{y}_t$ in equations (1) to (3).

Area to which yield savings apply

Parameter a_t in equations (1) to (3) represents the average annual area to which yield savings apply, by genetic resistance category and ME, from 1973 to 2007. This is calculated as the product of: (1) the percent area grown to CIMMYT-related spring bread wheat by ME since 1973; (2) the average annual percent area potentially affected by leaf rust by ME; (3) the percent distribution of area by genetic resistance category and ME; and (4) the average annual area sown to CIMMYT-related spring bread wheat by ME, from 1973 to 2007.

Percent area grown to CIMMYT-related spring bread wheat. The proportion of area sown to CIMMYT-related spring bread wheat varieties since 1973 was estimated by diffusion curves with a logistic function (Griliches 1957; CIMMYT 1993). The logistic function produces an S-shaped curve representing the cumulative proportion of adoption over time. This assumes slow initial growth in the use of the new technology, followed by a more rapid increase and then a slow rate of increase as adoption approaches a ceiling asymptotically. Since Griliches' study of hybrid maize adoption in 1957, the S-shaped logistic curve has often been used in studies of seed technology adoption. The function is expressed as:

$$P = \frac{K}{1+e^{-(a+bt)}} \qquad (5)$$

Parameters are: P, the cumulative percent area representing the cumulative path of adoption; K, the ceiling or upper bound of adoption; t, time; b, a constant related to the slope or rate of adoption; and a, a constant related to the time when adoption begins.

Historical CIMMYT Global Wheat Impacts Survey data from 1977, 1990, and 1997 on adoption levels and adoption lags were used to solve for the logistic function parameters algebraically (Table 1). This enabled the estimation of cumulative adoption rates in intervening years. Estimates of the cumulative percent area planted to CIMMYT-related spring bread wheat by ME in 1997 (Heisey et al. 2002) were assumed as the adoption ceiling in each environment. The 1997 estimates were combined with 1977 (CIMMYT 1989) and 1990 (Byerlee and Moya 1993)[7] data to calibrate the diffusion curves at three points in time, and subsequently to estimate the total time period of diffusion in each ME. The same sources were used to estimate the adoption lag, or the period from varietal release until its initial adoption by farmers, in each ME. We assumed that

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[7] Adoption reported in ME 3 for 1997 (Heisey et al. 2002) is lower than for 1990 (Byerlee and Moya 1993). This is explained by the relatively high number of improved tall varieties that continued to be released and sown in Brazil. Since they are tall, they were not accounted for in the adoption estimates for semidwarf varieties by Heisey et al. (2002). However, they probably often contain improved and/or CIMMYT germplasm, and could still be considered as CIMMYT-related material. For all wheat production environments other than MEs 2 and 4a, there is fairly strong evidence that adoption ceilings have been reached, unless major genetic changes are accomplished, such as for drought tolerance.

CIMMYT-related varieties released since 1973 followed similar aggregate adoption paths as those beginning to diffuse in 1966. The year 2007 thus proved to be the latest year predicted by the logistic curves. Figure 3 shows the fitted diffusion curves by ME from 1973 to 2007.

The earliest release dates for the spring bread wheat varieties drawn from the 1997 CIMMYT Global Wheat Impacts Survey data and classified by genetic resistance category are consistent with our assumptions regarding the initial years of diffusion. The most susceptible varieties in genetic resistance categories 1 and 2 were released the earliest, in 1970. This was before the initial year (1973), in which we have assumed the deliberate change in CIMMYT's breeding strategy to focus on race-nonspecific resistance. The varieties with moderate to high levels of race-nonspecific resistance in categories 3 to 5 were released thereafter, beginning in 1973, 1974, and 1979, respectively. Varieties with effective race-specific resistance in category 6 were released from 1983 onward, which seems to indicate that farmers are rapidly turning over the varieties. Most of these varieties were grown in MEs 3 (acid soils) and 4b (dry), which have the longest adoption lags (Table 1). Based on this information, it seems reasonable to assume that varieties with race-nonspecific resistance began to spread among farmers from 1973.

Percent area potentially affected by leaf rust. The analysis included only the average annual percent area potentially affected by leaf rust in each ME. Estimates were drawn from the CIMMYT Wheat Program (H.J. Dubin, personal communication; Table 1) by reviewing a list of production zones corresponding to the MEs in the countries included in the Global Wheat Impacts Surveys. The potentially affected area varied by ME, but was assumed to be constant over the period of analysis.

Percent area by genetic resistance category and mega-environment. We calculated 1997 point estimates of the percent distribution of area to which yield savings applied, by genetic resistance category and ME. Information on the resistance categories from the sample of varieties tested in trials was combined with the areas sown to each variety, as recorded in the 1997 CIMMYT Global Wheat Impacts database. However, the 1997 database reports the area accruing to each variety by country rather than ME. We therefore partitioned the area per variety among MEs in the same proportion as the country's total spring bread wheat area is distributed among MEs, as indicated by the 1990 database. The sample variety areas were then summed for each resistance category and ME, and expressed as the percent of the total area of sample varieties.

Table 4 indicates that 80% of the sample area was protected by genes conferring race-nonspecific resistance (categories 2 to 5), while only 10% of the area accrued to race-specific resistance (category 6). A further 10% of the area was sown to varieties classified as almost fully susceptible (category 1) in Table 2. These findings correspond with the observations by Smale et al. (1998) that varieties with race-specific resistance occupied a generally

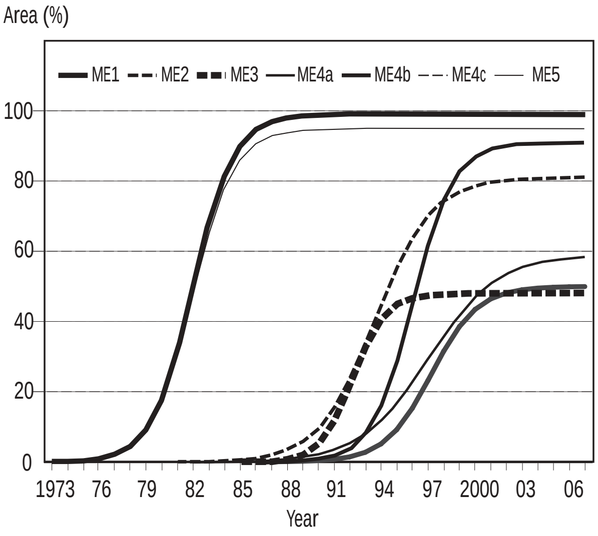

Figure 3. Percent area in post-1972 CIMMYT-related spring bread wheat releases by mega-environment from 1973 to 2007.

Table 4. The percent area by genetic resistance category and mega-environment in the sample of major CIMMYT-related spring bread wheat varieties grown in the developing world in 1997.

	Genetic resistance category †					
Mega-environment	1	2	3	4	5	6
1	11.8	6.6	37.7	36.1	4.1	3.7
2	1.0	8.0	37.8	19.4	0	33.8
3	8.7	0	7.9	11.1	0.3	72.0
4a	1.1	2.9	53.6	25.2	0	17.2
4b	0	0	1.6	1.2	0	97.2
4c	8.7	5.0	36.8	41.4	4.3	3.8
5a	13.0	8.5	33.2	40.9	2.5	1.9
Sample area (000 ha)	3,694	2,342	13,679	12,723	1,222	3,694
Percentage	10	6	37	34	3	10

† Genetic resistance categories are defined in Table 2.

decreasing percentage of the bread wheat area in the Yaqui Valley of Mexico.

When specific environments were considered, Table 4 shows that more than 80% of the area in MEs 1, 4a, 4c, and 5a were planted to varieties with race-nonspecific resistance. However, most of the area in MEs 4b (97%) and 3 (72%), and a substantial area in ME 2 (34%), accrued to race-specific resistance. Characteristics other than race-nonspecific leaf rust resistance might be more important in MEs 2, 3, and 4b. For example, diseases such as septoria leaf blotch or fusarium head scab are important in MEs 2, 3, and 4b, and aluminum toxicity in ME 3. These MEs also appeared more prone to annual yield and area fluctuations (Figures 2 and 4). Susceptible varieties comprised the minor proportion in all of the MEs, but nevertheless occupied over 10% of the area in MEs 1 and 5.

We assumed that the share of each resistance category remained constant throughout the estimated diffusion paths for all CIMMYT-related spring bread wheats from 1973 to 2007. We also assumed that CIMMYT-related varieties released after 1973 followed cumulative diffusion paths similar to those of varieties that began to diffuse in 1966 (Figure 3). Together, these assumptions imply that in each year of the diffusion path of these varieties, beginning in 1973 in MEs 1 and 5 and later in other MEs, the area was distributed by resistance type as shown in Table 4. For the overall area across all MEs, it was thus assumed that around 10% was planted to susceptible varieties, 10% to varieties with effective race-specific resistance, and 80% to varieties with varying levels of race-nonspecific resistance.

However, in 1974 the only areas with germplasm exhibiting race-nonspecific resistance were found in MEs 1 and 5.[8] Thereafter, the area planted to varieties with race-nonspecific resistance increased relatively rapidly in these environments, since over 80% of a sharply rising cumulative adoption rate comprises a large area. No area was planted to varieties with race-nonspecific resistance in other MEs until many years later (Table 1). In the environments with lower cumulative adoption ceilings and slower diffusion, the resulting areas were considerably smaller. In MEs 2, 3, and 4b, the percent area planted to varieties with race-nonspecific resistance was also assumed smaller throughout their diffusion paths, based on the area estimates shown in Table 4.

Average annual area in CIMMYT-related spring bread wheat. Time series of the average annual area sown to CIMMYT-related spring bread wheat by ME, from 1973 to 2007, were generated following an approach similar to that used for the average annual yield calculations shown in Figure 2 (i.e., by combining 1990 CIMMYT Global Wheat Impacts Survey data with FAO data obtained from http://faostat.fao.org). The ratio of the 1990 zone-level area to the national area in spring bread wheat was multiplied with the FAO national average area from 1973 to 1998, and aggregated over zones to obtain the corresponding series by MEs (Figure 4). Trend regressions were used to project areas to 2007. As for the yield series, the procedure assumed that the ratio of the ME segments within a country to the national area sown to spring bread wheat did not change over time. ME 1 clearly accounted for the major proportion of the study area. The average annual area estimated by this approach increased in most MEs since 1973, but decreased in MEs 4a and 4b. Annual area fluctuations were evident in MEs 3 and 4b.

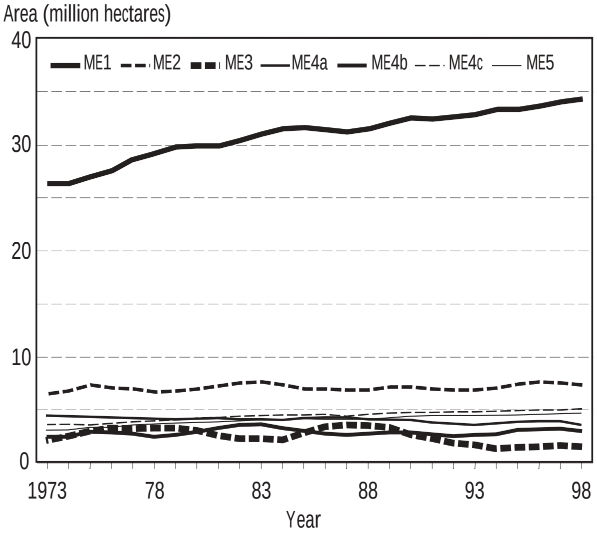

Figure 4. Average annual spring bread wheat area by CIMMYT mega-environment from 1973 to 1998.

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[8] We have assumed 1973 as the year of CIMMYT's deliberate change in breeding strategy to emphasize race-nonspecific leaf rust resistance. This is because the first variety recognized and promoted for race-nonspecific resistance was released in this year (Torim 73). However, as outlined in the background to this study, CIMMYT breeders had in fact taken an interest in selection methods favoring diverse, multigenic resistance before 1973. Most CIMMYT lines bred at that time probably already carried race-nonspecific resistance, though they might not have been specifically recognized for this characteristic. Our adoption estimates are therefore conservative.

The real world wheat price

The real world wheat price, or p_t in equations (1) to (3), was used to value the production savings from 1973 to 2007 and to estimate the gross benefits. Wheat is the most traded of the world's three major cereals and is therefore valued at the world price equivalent. Most developing country wheat producers are on average net importers or self-sufficient in the crop, which implies that the opportunity cost of their wheat is the import parity price. However, it would be exceedingly difficult to estimate accurate reference points reflecting the geographical distribution of production and consumption activities for each of the countries included in this study, or to aggregate them into an average import parity price by ME. In more complete partial equilibrium models of research impact, prices are endogenously determined by wheat supply and demand. In our case, we argued that though the supply shift avoided through leaf rust resistance breeding may have been substantial in a number of wheat-producing countries in the developing world, these changes would in most cases not affect the world wheat price.

The world wheat price based on Hard Red Winter Wheat No. 2 was therefore applied in the analysis. This price was used because the USA exports the largest volume of wheat and hard red winter is its dominant market class. We applied the base scenario of a series developed by the International Food Policy Research Institute (IFPRI) from United States hard red winter wheat prices obtained from the World Bank (IFPRI IMPACT, calculated from: World Bank 2000). The 1998 IFPRI prices were converted to 1990 real prices to correspond with the research cost series described in the subsequent section. A long-term downward trend in the real wheat price was observed from 1973 onwards, but the price fluctuated annually (Figure 5).

Research costs

CIMMYT's real research investment from 1967 to 1999, expressed in 1990 US$ and estimated for higher and lower cost scenarios, was obtained from Heisey et al. (2002). Costs were assumed since 1967 to allow a six-year research lag for varieties released in 1973. A five-to six-year research development period for a new wheat variety should be a reasonable assumption in view of CIMMYT's shuttle breeding program, outlined in the background to this study.

The cost series by Heisey et al. (2002) was developed on the basis of several assumptions. In all cases, the objective was to estimate the economic impact of CIMMYT's total wheat improvement effort. First, it was assumed that CIMMYT's entire budget was devoted to genetic improvement of wheat and maize. Though this has been CIMMYT's primary focus since its inception, some research products over the years might not have been confined to crop genetic improvement only, such as farming systems, natural resources, and economics research. Second, it was assumed that the entire Wheat Program staff, including reasearchers involved in plant breeding, pathology, agronomy, physiology, and other disciplines, was focused on genetic improvement. This partly reflects the organization of CIMMYT's wheat breeding program.

Heisey et al. (2002) considered three approaches to calculate the research costs, of which we employed the highest and the lowest. In the higher cost scenario, it was assumed that CIMMYT's entire budget, including resources invested in other programs[9] and administration, could be charged to crop genetic improvement. CIMMYT's budget was allocated between wheat and maize by the proportion that the Wheat Program budget comprised of the total budget. The set of figures

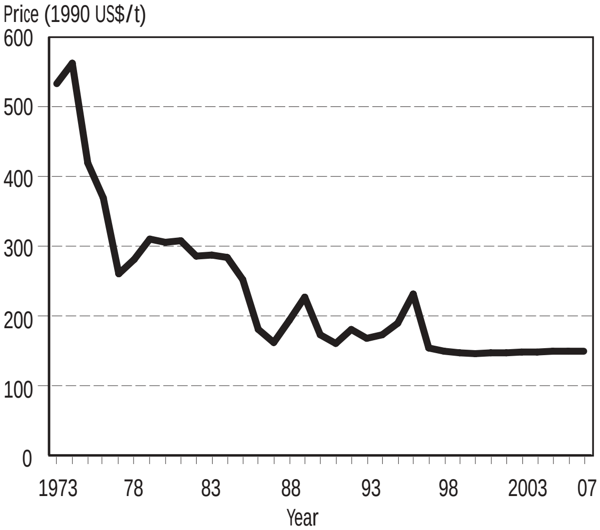

Figure 5. The annual and projected real world wheat price from 1973 to 2007.

Source: Adapted from IFPRI IMPACT (calculated from: World Bank 2000)

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[9] At the time this study was undertaken, five research programs existed at CIMMYT: Wheat, Maize, Economics, Applied Biotechnology, and Natural Resources.

arising from this assumption may be an overestimate of the true investment since it incorporated many activities not directly related to wheat genetic improvement. In the lower cost scenario, CIMMYT's total budget was allocated to wheat genetic improvement by the proportion that Wheat Program senior staff comprised of all senior staff at CIMMYT, including those in other research programs, external relations, and administration. This assumption may represent an underestimate of the true investment in wheat genetic improvement, since it ignores the infrastructural, technical, and administrative support required to ensure the functioning of the program.

The integrated nature of enhanced germplasm production complicated the separation of maintenance research from other objectives and activities. Wheat genetic improvement at CIMMYT involves infrastructure, knowledge, and support extending across different disciplines and programs. Leaf rust resistance cannot be separated from other wheat breeding objectives such as yield, adaptation, and resistance to other pests and diseases. Rather than attempting to disentangle the expenses on wheat pathology from wheat breeding in total, we applied the full cost of CIMMYT's wheat genetic improvement since 1967. With regard to valuing maintenance research, this assumption demonstrates the difficulty in separating various pathology, agronomy, and physiology activities in the production of enhanced germplasm.

The annual estimates included the costs of shipments through international nurseries and testing costs borne by CIMMYT. Only the investments by national programs, such as local screening for rusts and other tests, were excluded. As with the other time series data we have employed, costs were projected to 2007. However, the trend in the series was more quadratic than linear in form. CIMMYT's real investment in wheat genetic improvement increased steadily from 1967 until its peak in 1988, after which it declined substantially (Figure 6). The long-term real investment in wheat genetic improvement has therefore decreased, and the real investment in the 1990s has approximately returned to the level prevailing in the 1970s. The real investment by the low research cost scenario decreased slightly earlier, because the numbers of non-crop program staff relative to crop program staff increased since the mid-1980s. Costs fluctuated annually, probably due to variations in budgets and funding cycles. Rather than predicting either an upward shift or continued downward pattern, we chose to hold CIMMYT's investment constant at the 1999 level. The research costs (C_t) in equations (1) to (3) were subtracted from the gross benefits to estimate the net benefits.

Discount rates

The discount factor allows estimation of the present value of an amount to be received or paid at some time in the future (Gittinger 1982). This requires multiplication of the future value with the discount factor, where i is the interest rate and t the year in equations (1) to (3). The acceptability of the economic returns on a research program is influenced by the way the investment is viewed. The returns are particularly sensitive to the level of the interest rate (i), or assumptions about how money is valued over time. The appropriate rate is the subject of extensive debate in the applied and theoretical economics literature (Gittinger 1982; Ray 1986; Alston et al. 1995). The debate centers on which concept of the value of capital to use.

If i is the "opportunity cost of capital" in an economy, it represents the return on the marginal investment that uses the last of the available capital. This i is meant to reflect "the choice made by the society as a whole between present and future returns, and hence, the amount of total income the society is willing to save" (Gittinger 1982). Furthermore, Dixit and Pindyck (1994) consider investment expenditures as sunk costs and irreversible when

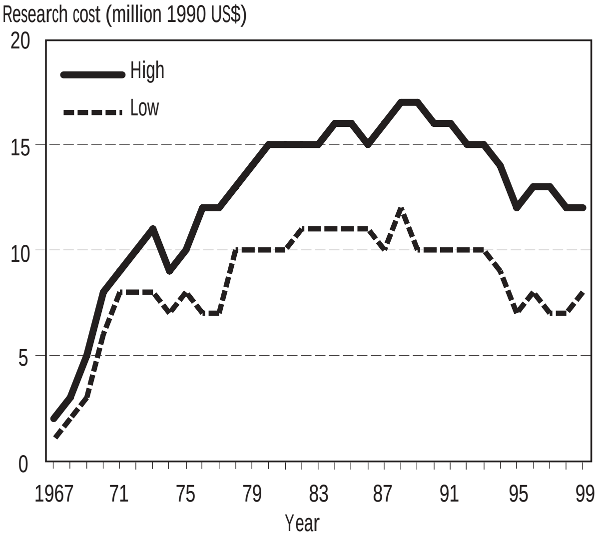

Figure 6. Real CIMMYT expenditures on wheat genetic improvement for the high and low research cost scenarios from 1967 to 1999.

Source: Heisey et al. (2002)

they are firm or industry-specific. In our case, it could be argued that the decision to invest in leaf rust resistance breeding might have eliminated other options. Private investors such as the World Bank usually incorporate risks or irreversibility in the opportunity cost of capital used to evaluate project investments. A range of 8 to 15% in real terms is often assumed for developing countries.

However, the investment could also be considered from the viewpoint of a public investor with a longer-term "social time preference rate." This reflects the idea that society has a longer time horizon than individuals. It implies the use of a lower *i* for publicly funded projects, or those oriented to the production of public goods to generate benefits for society in general.

The nature of the benefits produced by the investment thus influences the choice of interest rate. In our case, we argued that genetic disease resistance is in part a private and in part a public good (Heisey et al. 1997). That is, sowing genetically resistant cultivars can provide benefits to individual farmers and to society by reducing the costs of controlling epidemics. Applying a discount rate focusing on private goods only would therefore underestimate the total benefits of leaf rust resistance breeding. It may also be reasonable to assume a public investment perspective for the public sector funds invested in wheat breeding at CIMMYT.

Given this debate on choosing appropriate discount rates, we assumed interest rates of 1%, 5%, and 15% to represent different perspectives on the investment decision. These included a public investment viewpoint with a longer term "social time preference rate" (1%); an intermediate rate corresponding to the current real interest rate, such as the average interest rate charged by the United States Federal Reserve Bank over the past 15 years (5%); and the perspective of a private investor such as the World Bank, with risks or irreversibility incorporated in the interest rate (15%). The payback period was viewed from the beginning of the research investment. This was assumed to start in 1967 (year t_0) to allow a six-year research lag for varieties released in 1973. The benefits were assumed to start in 1973 (year t_6), and to continue to 2007 (year t_{40}), the year the last adoption ceiling was reached in our predicted diffusion curves. An intermediate 5% discount rate was first assumed in the base scenario. This was then varied by discount rates of 1 and 15%.

Results

The economic impact of the CIMMYT-related spring bread wheat varieties with various leaf rust resistance categories, grown in the developing world since 1973, is discussed in the subsequent sections. First, the present value of real gross benefits by genetic resistance category and wheat-producing environment is discussed, because research costs could not be separated on the same basis. An intermediate discount rate of 5% was assumed. Research costs were then included, and the investment returns are presented in terms of the net present value, internal rate of return, and benefit-cost ratio. All resistance categories and MEs were included, and the results are reported for the high and low research cost scenarios. A 5% discount rate was first assumed in estimating the net present value and benefit-cost ratio. The sensitivity of the analysis to alternative assumptions on the discount rates and yield losses avoided through leaf rust resistant varieties was subsequently assessed.

Discounted gross benefits by resistance category and mega-environment

When including all resistance categories and MEs, the discounted gross benefits from 1973 to 2007 amounted to 7.46 billion 1990 US$ (Tables 5 and 6). Varieties with race-nonspecific resistance (categories 2 to 5) accounted for 91% of the benefits. Varieties with race-specific resistance accounted for 7%, whereas those classified as almost fully susceptible represented only 2% of the benefits. Though comparatively smaller, the benefits generated by race-specific and almost susceptible categories were still of considerable magnitude.

Table 5. Discounted gross benefits of genetic leaf rust resistance in CIMMYT-related spring bread wheat from 1973 to 2007, by resistance category.

Genetic resistance category	Gross benefits † (million 1990 US$)	Category as percentage
1	138	1.9
2	324	4.3
3	2,648	35.5
4	3,418	45.8
5	403	5.4
6	530	7.1
All categories	7,461	100.0

† Estimates include CIMMYT mega-environments 1 to 5 in each resistance category. The gross benefits were discounted by 5%.

Table 6. Discounted gross benefits of genetic leaf rust resistance in CIMMYT-related spring bread wheat from 1973 to 2007, by mega-environment and resistance type.

	Gross benefits by resistance type [†] (million 1990 US$)			Gross benefits by mega-environment	
Mega-environment	Race-nonspecific	Race specific	All [‡]	Percentage	1990 US$ per hectare [§]
1	5,913.1	357.4	6,391.5	85.7	177.5
2	139.9	108.6	248.9	3.3	31.1
3	4.2	20.8	25.3	0.3	12.7
4a	5.4	1.6	7.0	0.1	1.2
4b	0.4	18.3	18.7	0.3	6.2
4c	6.5	0.4	7.0	0.1	2.8
5	723.6	22.7	762.4	10.2	84.7
All	6,793.1	530.0	7,460.9	100	112.2

[†] The gross benefits were discounted by 5%.

[‡] "All" includes varieties with race-nonspecific resistance (categories 2 to 5), race-specific resistance (category 6), and those classified as almost fully susceptible (category 1), as defined in Table 2.

[§] Year 2000 area estimates by mega-environment were assumed, as shown in Appendix A Table A1. All resistance types were included.

Race-nonspecific resistance generated the major proportion of benefits in MEs 1, 2, 4a, 4c, and 5. Benefits in MEs 3 and 4b accrued largely to race-specific resistance. These findings reflect the assumptions on the percent cumulative area by ME sown to CIMMYT-related varieties with different resistance categories (Table 2) and the level of yield savings assigned (Table 1). Greater representation of varieties with race-specific resistance was indicated in MEs 3 and 4b (Table 4), and these environments were also characterized by larger annual yield and area fluctuations over time (Figures 2 and 4). Considerations other than leaf rust might be more important in these areas, such as septoria leaf blotch, fusarium head scab, or aluminum toxicity. The benefits of leaf rust resistant varieties depend on the magnitude of the yield losses avoided in comparison to losses in susceptible varieties in a given environment and year. In environments where yields lost by susceptible varieties are lower, the advantage of leaf rust resistance should also be lower.

ME 1 accounted for 6.4 billion 1990 US$—86% of the gross benefits by ME (Table 6)—for various reasons. This large environment represented 54% of the study area, and new wheat varieties have historically been shown to spread rapidly in ME 1 (Figure 3). About two-thirds of this favorable wheat growing environment is found in the irrigated zones of the Asian subcontinent. Since both average yields and potential losses from disease are higher in these areas, the production savings from resistance are also greater.

Returns on the research investment

Following the inclusion of research costs, the results demonstrate that CIMMYT's investment in wheat genetic improvement since 1967 has generated substantial economic returns (Table 7). An intermediate discount rate of 5% was first assumed to calculate the net present value and benefit-cost ratio. Under the lower research cost scenario, the internal rate of return was 44%, the net present value 5.43 billion 1990 US$, and the benefit-cost ratio 39:1. When higher research costs were assumed, the rate of return was 41%, the net present value 5.36 billion 1990 US$, and the benefit-cost ratio 27:1. Though the magnitude of research investments matters, the analysis was not too sensitive to the two research cost scenarios.

Table 7. Returns on the investment in leaf rust resistance breeding in CIMMYT-related spring bread wheat from 1967 to 2007, for low and high research cost assumptions. [†]

Research costs	Internal rate of return (%)	Net present value (billion 1990 US$)	Benefit-cost ratio
Low	44	5.43	39:1 (5,567:141 million 1990 US$) [‡]
High	41	5.36	27:1 (5,567:205 million 1990 US$) [‡]

[†] The net present value and benefit-cost ratio were calculated with a 5% discount rate.

[‡] The estimates in brackets indicate the ratio of the present value of gross benefits to the present value of the research costs.

The benefit-cost ratio implies that every US dollar invested in CIMMYT's wheat genetic improvement since 1967 has generated at least 27 times its value in benefits from leaf rust resistance breeding in spring bread wheat alone. All other wheat breeding benefits are considered as pure benefits, such as the increases in yield potential and resistance to other biotic and abiotic stresses. The internal rate of return of over 40% implies that every US dollar invested in CIMMYT's wheat genetic improvement since 1967 has generated a return of at least 40 cents to society, after paying the full cost of the program. The net present values, exceeding 5 billion 1990 US$ after paying the full research cost, are clearly of considerable magnitude. The returns on CIMMYT's total investment in wheat genetic improvement were thus competitive, even when only the benefits of leaf rust resistance in spring bread wheat varieties grown at low latitudes were considered.

As for the gross benefits, most of the net benefits were realized in ME 1 (Table 8). CIMMYT's entire investment in wheat genetic improvement since 1967 was charged against the gross benefits in ME 1 alone. Under the higher research cost scenario, the internal rate of return was 39% and the net present value 4.56 billion 1990 US$. When the higher research investment was charged in a similar manner against the combined gross benefits for MEs 2, 3, 4a, 4b, 4c, and 5, the rate of return was 17% and the net present value 0.6 billion 1990 US$. Though substantial returns were generated in these MEs, they were much lower than those realized in ME 1. Given the cost estimates we have employed, this implies that CIMMYT's entire investment in wheat genetic improvement over 40 years was more than justified by the benefits from leaf rust resistance breeding in ME 1 alone.

Table 9 shows the effect of the investment perspective on the economic returns. As could be expected, the net present value decreased when discounted by higher interest rates. However, even when a stringent 15% interest rate was assumed, a positive and substantial net present value of 0.62 billion 1990 US$ was generated under the higher research cost scenario.

Investment returns generated by a yield series net of enhancement and other effects

This sensitivity analysis explores the magnitude of distortion caused by the difficulties in eliminating enhancement and other research effects from the yield series (y_t) used to estimate the supply shift avoided from S_0 to S_2 in Figure 1. When assuming that leaf rust resistance has accounted for 82% of the average annual progress in wheat yield potential in ME 1, the overestimation of production savings in

Table 8. Returns on the investment in leaf rust resistance breeding in CIMMYT-related spring bread wheat from 1967 to 2007, by mega-environment (ME) and research cost scenario. †

Research costs and MEs	Internal rate of return (%)	Net present value (billion 1990 US$)
Low research cost		
ME 1	43	4.63
MEs 2 to 5	20	0.66
All MEs	44	5.43
High research cost		
ME 1	39	4.56
MEs 2 to 5	17	0.59
All MEs	41	5.36

† Gross benefits in ME 1 were charged the full research cost. Gross benefits for MEs 2, 3, 4a, 4b, 4c, and 5 were combined and charged the research investment in a similar manner. The net present value was calculated with a 5% discount rate.

Table 9. Net present value of the investment in leaf rust resistance breeding in CIMMYT-related spring bread wheat from 1967 to 2007, for various discount rates and research cost scenarios.

	Net present value at different discount rates (billion 1990 US$)		
Research costs	1%	5%	15%
Low	15.40	5.43	0.64
High	15.26	5.36	0.62

Table 10. Returns on the investment in leaf rust resistance breeding in CIMMYT-related spring bread wheat from 1967 to 2007 in mega-environment 1, for different yield series and research cost assumptions. †

Yield and research cost scenarios	Internal rate of return (%)	Net present value (billion 1990 US$)
Yield series with enhancement, maintenance to leaf rust, and other effects:		
Low research cost	43	4.63
High research cost	39	4.56
Yield series with maintenance to leaf rust, but net of enhancement and other effects:		
Low research cost	41	4.00
High research cost	38	3.93

† The net present value was discounted by 5%. Leaf rust resistance was assumed to account for 82% of the average annual progress in wheat yield potential since 1973.

our base scenario was minimal (Table 10). The internal rate of return generated from the yield series net of enhancement and other effects ($\hat{y}_t$) was 38% under the higher research cost scenario. The net present value at the 5% discount rate was 3.93 billion 1990 US$. Although the CIMMYT trial data by Sayre et al. (1998) used to adjust the yield series were not available over the total study area, ME 1 clearly accounted for the major proportion of the benefits (Table 8). Nevertheless, we would be cautious to assume that 82% of all growth in yield potential in farmers' fields over all environments and years included in this study could be attributed to leaf rust resistance breeding alone, as in the trials in northwestern Mexico. We thus confined the estimates to a sensitivity analysis rather than the base scenario.

Minimum yield savings necessary to recover CIMMYT's investment

The investment returns in Table 7 were calculated by employing estimates of the expected average annual yields that would have been lost, had all CIMMYT-related spring bread wheat varieties been susceptible (Table 1). These in turn determined the yield losses avoided through varieties with various leaf rust resistance categories. Within our conceptual framework, the results are likely to be most sensitive to this assumption. Yet this parameter was the most difficult to estimate reliably over the large geographical areas included in this study. Rather than using *ad hoc* methods to identify a lower yield loss scenario to compare with our original assumptions, an alternative approach was adopted in the sensitivity analysis. We arithmetically calculated the minimum average annual percent yields that would have had to have been lost to leaf rust by susceptible varieties in ME 1 to recover CIMMYT's investment in wheat genetic improvement since 1967. The calculation was limited to ME 1 to render the estimates more conservative, though this environment clearly accounted for the major share of the benefits (Table 8).

The minimum yields that would have had to have been lost to recuperate the investment ranged between 0.2 and 0.8% under various assumptions on the discount rates, research costs, and yield series applied (Table 11). These minimum estimates were a mere fraction of those assumed in Table 1, and they would be unusually low for this important wheat disease in this high-yielding zone with heavy disease pressure. The investment returns presented in Table 7 should therefore be fairly robust. By generally used standards, the returns were profitable even under our most stringent assumptions.

Discussion

An era characterized by a global decline in agricultural research investments increasingly emphasizes the efficient allocation of scarce resources. This study demonstrates the substantial economic impact on developing country production of efforts by CIMMYT to breed leaf rust resistant spring bread wheat varieties since 1973. The estimated yield losses by varieties of different leaf rust resistance categories were compared to the yields that would have been lost had the varieties been fully susceptible. An economic surplus approach, adjusted for maintenance research, and a capital investment analysis were used to estimate the returns. A range of investment values was elicited by alternating assumptions on various parameters. The internal rate of return over 1967-2007 was 41% under our base scenario and higher research cost assumptions. When discounted by 5%, the net present value was 5.36 billion 1990 US$, and the benefit-cost ratio 27:1. Benefits were primarily generated in ME 1 and by varieties with race-nonspecific resistance. The full cost of CIMMYT's wheat genetic improvement effort since 1967 was included. In contrast, the benefits accounted only for the yield losses avoided through leaf rust resistance in CIMMYT-related spring bread wheat varieties grown at low latitudes since 1973.

This implies that every 1990 US dollar invested in CIMMYT's wheat genetic improvement over 40 years has generated at least 27 times its value in benefits from leaf rust resistance breeding in spring bread wheat alone. All other wheat breeding benefits are considered as pure benefits, such as the increases in yield potential over time (Figure 2, Byerlee and Moya

Table 11. The minimum average annual percent yield that would have had to have been lost by susceptible varieties in mega-environment 1 to recover CIMMYT's investment in wheat genetic improvement from 1967 to 2007, for various discount rates, research costs, and yield series scenarios.

Yield series and research costs	Minimum yield loss (%) 5% discount rate	15% discount rate
Yield series with enhancement, maintenance to leaf rust, and other effects:		
Low research cost	0.18	0.48
High research cost	0.26	0.66
Yield series with maintenance to leaf rust, but net of enhancement and other effects:		
Low research cost	0.21	0.55
High research cost	0.30	0.76

1993; Rajaram and van Ginkel 1996; Rajaram et al. 1997), and resistance to other biotic and abiotic stresses.[10] We generally understated the areas to which benefits were accrued, because we focused only on the MEs where spring bread wheat is grown at low latitudes (Appendix A). This excluded winter and facultative habit bread wheat and durum wheats, and the spring bread wheat grown in ME 6, even though these areas are also affected by leaf rust. Whereas the numerical values of the estimated benefits are sensitive to assumptions about underlying parameter values, they remain substantial enough to satisfy stringent investment criteria, even under conservative cost and benefit assumptions.

Within the conceptual framework of this analysis, the results are likely to be most sensitive to assumptions regarding the extent of yield losses avoided through leaf rust resistant cultivars. This was partly dictated by the relative magnitude of the expected yields that would have been lost by susceptible varieties in a given environment and year. This has two implications. First, in environments where yield losses in susceptible varieties are lower, the benefits of leaf rust resistance should also be lower. This may partly explain why farmers in 1997 still used varieties that were almost fully susceptible, or carried race-specific resistance, albeit on the minor proportion of the study area (Table 4). Second, even though leaf rust resistance is an important consideration, yield remains a critical breeding objective. Yield levels, either saved through maintenance or gained through enhancement research, remain a vital factor affecting the economic value of pest and disease resistance in wheat (Smale et al. 1998; Marasas 1999). Assumptions on yield parameters exert a major influence on the magnitude of the supply shifts associated with research investment in an economic surplus approach, such as that depicted in Figure 1.

Yet the yield loss in susceptible varieties was the most difficult parameter to estimate reliably over the large geographical areas included in this study. We therefore arithmetically calculated the minimum average annual yields that would have had to have been lost by susceptible varieties in ME 1 to recover CIMMYT's wheat breeding investment since 1967. The calculation was limited to ME 1 to render the estimates more conservative, though this environment clearly accounted for the major share of the benefits. The minimum yield loss estimates ranged between 0.2 to 0.8%, which would be extremely low for this important wheat disease in this high-yielding zone with heavy disease pressure.

ME 1 accounted for 86% of the gross benefits by ME. When the full burden of the higher research cost scenario was charged against these gross benefits, the internal rate of return was 39% (Table 8). When the research costs were charged against the combined benefits for MEs 2, 3, 4a, 4b, 4c, and 5 in a similar manner, the rate of return was 17%. Though still of considerable magnitude, the returns were lower than those reported for ME 1. The results indicate that CIMMYT's investment in wheat genetic improvement could be justified by the benefits from leaf rust resistance breeding in ME 1 alone. Several characteristics of this immense wheat-producing environment are likely to determine favorable investment returns. It accounted for 54% of the study area, and historical patterns have shown that new wheat varieties spread rapidly in ME 1. This favorable wheat-growing environment is also favorable for disease. Since average yields are higher, the production savings from genetic resistance are also greater.

Varieties with race-nonspecific resistance accounted for 91% of the gross benefits and for the major share of the benefits generated in MEs 1, 2, 4a, 4c, and 5. Varieties with race-specific resistance and those classified as essentially susceptible accounted for 7 and 2% of the benefits, respectively (Table 5). Though comprising a minor share of the total, the benefits from these varieties were not insignificant in absolute magnitude, and they increased the returns on CIMMYT's wheat improvement effort. Varieties with race-specific resistance appeared to be associated with specific environments and accounted for the major proportion of benefits generated in MEs 3 and 4b. Considerations other than race-nonspecific leaf rust resistance might be more important in these areas, such as septoria leaf blotch, fusarium head scab, or aluminum toxicity. These environments also demonstrated larger annual yield and area fluctuations over time (Figures 2 and 4). In environments where yields lost by susceptible varieties are lower, the advantage of leaf rust resistance should also be lower.

Albeit on the minor proportion of the study area, and mostly in areas where leaf rust might be of less importance, some farmers appeared to continue growing varieties assumed to lack durable leaf rust

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[10] Appendix A Table A1 shows examples of other CIMMYT wheat breeding objectives for spring bread wheat.

resistance. It is conceptually and practically difficult to assess the total utility farmers would compromise by reducing the area sown to susceptible varieties, or in this case, varieties lacking durable resistance. Various factors not necessarily related to resistance affect farmers' choice of cultivars and their rate of varietal replacement (Heisey 1990; Brennan and Byerlee 1991; Heisey and Brennan 1991; Brennan et al. 1994; Marasas 1999). Farmers do not necessarily grow wheat cultivars with the socially desirable level of rust resistance (Heisey et al. 1997). For example, some cultivars with race-nonspecific resistance could carry slight yield penalties in disease-free environments, even though their use in leaf rust prone areas could provide substantial protection to grain yield and other traits (Singh and Huerta-Espino 1997). Farmers may therefore continue to grow varieties with levels of resistance that wheat scientists may no longer consider satisfactory. Furthermore, neither breeders nor farmers necessarily know *ex ante* the specific type of resistance, and its durability, in a variety when it is released. Proof of durability comes only after widespread, successful cultivation of the variety in an environment favorable to leaf rust. The historical performance of resistances in fact helps breeders to identify durable sources for future use.

Due to the variability of the rust pathogen and its ability to evolve, it is assumed that breeding efforts will continue to address possible mutations. Because race-nonspecific resistance appears to last longer, CIMMYT's emphasis on this type of resistance seems justified. If incremental costs were calculated for race-nonspecific compared to race-specific resistance, the breeding costs for race-specific resistance are likely to be greater than those for race-nonspecific resistance (Smale et al. 1998). Assuming that new resistance genes are increasingly scarce, the cost of searching for them in wheat materials rises over time. Once the frequency of effective race-specific genes diminishes in advanced materials, genes will have to be sought in other materials such as landraces and wild relatives. The cost of transferring resistance from these materials into advanced lines is higher. In the meantime, the changing pattern of rust races will necessitate the continued allocation of research resources to search for and incorporate resistance. This could absorb much of the research effort and slow progress in improving other characteristics (Borlaug 1968). Instead, pursuing race-nonspecific forms of resistance usually implies working within advanced lines for new partially effective genes and gene complexes. New sources of partially effective resistance are accumulated in elite lines carrying known sources of resistance.

Several features of plant diseases in developing countries suggest that our calculations have understated dimensions of benefits from leaf rust resistance that are difficult to measure but important to recognize (Smale et al. 1998). Output losses from rust include both incremental annual losses and the major losses incurred by epidemics. The consequences of *not* having resistance could be catastrophic (Lakhanpal 1989). How socially important these losses are depends not only on their absolute magnitude, but also on the role of wheat production in the national economy, the attitude of that society towards risk, the time horizon, and other considerations influencing the valuation of the yield loss. For some farmers and societies, the true costs of these losses, especially in epidemics, can be great because of the extent to which they rely on the wheat crop. Large crop losses may imply price increases, which are passed on to consumers, or unforeseen imports purchased at world market prices, which may not be favorable. Epidemics may require treatment with fungicide and large-scale, well-coordinated mobilization campaigns, as was the case in northwestern Mexico during the wheat leaf rust epidemic in 1976-77 (Dubin and Torres 1981). However, this option might not be feasible for many farmers and societies in the developing world.

An estimated two-thirds of ME 1 is on the Asian subcontinent, where vast historic devastation from rust epidemics has been reported. Though it is well accepted that famines are caused by the loss of entitlements to food rather than food supply, it is not known for certain what the effects of greater production instability would have been on particular social groups, such as small-scale farmers and rural consumers. It would also be difficult to estimate the monetary and health costs of the alternative to genetic resistance, which is to treat the problem by chemical methods. Some farmers and societies therefore place a premium on avoiding disasters. Genetic leaf rust resistance changes the yield distribution by reducing the probability that yields will occur within the lower range and thereby reduces the probability of disaster.

Furthermore, some diseases defined as public risk diseases (Brennan et al. 1994) can readily spread from one farm to another. Farmers who grow cultivars susceptible to these diseases not only place their own production at risk, but also increase the likelihood of other farmers suffering losses. A particular form of loss is the increased probability that a new physiological race of a pathogen may evolve, which may overcome the effects of cultivars resistant at the time. Rusts are in the high risk category considering their history of variation, polycyclic nature, and the ability of their primary and secondary inoculum to be transmitted over long distances.

This study underscores the importance of maintenance research in crop breeding programs. Substantial economic returns were estimated by valuing the yield losses avoided through leaf rust resistance and assuming all other wheat breeding benefits as pure benefits. The findings support research at CIMMYT indicating that part of the progress in wheat yield gain over the years has been achieved by protecting this yield potential through disease resistance breeding (Bohn and Byerlee 1993; Byerlee and Moya 1993; Byerlee and Traxler 1995; Rajaram et al. 1996; Sayre et al. 1998; Smale et al. 1998; Heisey et al. 1999). Analyses of trial results imply that genetic leaf rust resistance contributed 82% of the average annual growth in yield potential in northwestern Mexico (Sayre et al. 1998). Maintaining disease resistance can potentially contribute more to the benefits of these cultivars than gains in yield potential alone.

As crop productivity rises, increasing effort is required to maintain previous gains. The constantly evolving pest and disease complex has continued to prompt the turnover of wheat varieties, and finding new solutions to these problems has been a major objective of research in entomology, plant pathology, weed science, and plant breeding. Without sustained investment in maintenance research, crop productivity and stability would eventually decline. The valuation of agricultural research is therefore incomplete without accounting for the losses that would have occurred in the absence of its maintenance component (Moseman 1970; Araji et al. 1978; Knutson and Tweeton 1979; Schuh and Tollini 1979; Ruttan 1982; Evans 1983; Peacock 1984; May 1985; Swallow et al. 1985; Plucknett and Smith 1986; Adusei 1988; Pardey and Roseboom 1989; Adusei and Norton 1990; Bohn and Byerlee 1993; Alston et al. 1995).

Most assessments of the returns on wheat research investments have nevertheless focused on productivity enhancement (Evenson 1998). There are comparatively fewer economic analyses of the value of pest and disease resistance in wheat (Doodson 1981; Heim and Blakeslee 1986; Blakeslee 1987; Brennan and Murray 1988; Priestley and Bayles 1988; Brennan et al. 1994; Morris et al. 1994; Collins 1995; Smale et al. 1998; Marasas 1999). Economists may thus have tended to undervalue the productivity losses avoided through wheat research. Townsend and Thirtle (2001) have illustrated the magnitude of this error, and suggest a minimum underestimation of 50% on the returns on livestock research when the negative effects of diseases were not explicitly taken into account. These findings may also apply to returns estimates for wheat research, especially considering that maintenance has been reported to comprise a higher proportion of crop than of livestock research in the USA (Adusei and Norton 1990).

As Townsend and Thirtle (2001) also emphasize, we do not suggest that maintenance research is underestimated because of a lack of understanding or effort. Instead, valuation of the benefits from maintenance research is often restricted by data limitations and by the difficulties in separating the costs and benefits of maintenance from enhancement research. However, we conclude that rate of return estimates which assume that crop breeding explains only positive productivity growth, and that productivity would remain unchanged in the absence of research, are bound to be understated.

Increases in population, income, and urbanization in developing regions necessitate continued growth in cereal productivity (Borlaug 1965; Pingali and Heisey 2001). The genetic progress necessary to sustain the required growth will be forthcoming only if sufficient investments in agricultural research and education are maintained. In contrast, long-term declines in world cereal prices and structural adjustment in developing countries have often resulted in decreasing research investments in recent years. At CIMMYT, the real investment in wheat genetic improvement has declined substantially since the late 1980s (Figure 6, Heisey et al. 2002). Models of the world food economy show that the wheat sub-sector of developing nations is expected to suffer annual welfare losses of nearly 7 billion 1990 US$ by the year 2020, if further annual reductions in public investments in research and infrastructure are assumed (Rosegrant et al. 1995). These global funding constraints increasingly underline the need to ensure that research programs generate attractive economic returns, such as those demonstrated for leaf rust resistance breeding in CIMMYT-related spring bread wheat. Strongly sustained investment in agricultural research is needed, not only to maintain past productivity gains, but also to meet demands for further growth. This calls for a clear comprehension of the total utility of agricultural research, including its maintenance component, to facilitate enlightened policy decisions regarding resource allocation and priorities.

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Appendix A

Definition of CIMMYT mega-environments included in this study

The analysis presented in this report was conducted by wheat breeding mega-environment (ME). The ME classifation was developed by the CIMMYT Wheat Program to guide germplasm enhancement activities in various target production environments. A mega-environment is defined as a broad, not necessarily contiguous area occurring in more than one country and frequently transcontinental. It is characterized by similar biotic and abiotic stresses, cropping-system requirements, consumer preferences, and for convenience, by volume of production (Rajaram et al. 1995). Germplasm generated for a given mega-environment is useful throughout the defined area and accommodates major stresses, though possibly not all significant secondary stresses. Within MEs, CIMMYT thus addresses millions of hectares with a certain degree of homogeneity as it relates to wheat. Responsibility for micro level agro-ecological domains within the ME remains with the respective national crop improvement programs. Table A1 provides descriptive information on the MEs defined for spring bread wheat production.

Since the 1990 Global Wheat Impacts Survey there has been a new definition of wheat MEs, particularly in the case of the former MEs 5a and 5b (Rajaram et al. 1995; van Ginkel et al. 2000). The newly defined ME 5 comprises 9 million hectares (van Ginkel et al. 2000), which is almost 2 million hectares more than the former 7.1 million hectares for MEs 5a and 5b (Rajaram et al. 1995). The calculations in this study are based on area shares allocated among MEs within countries as represented in the 1990 classification. However, changes in total area should not affect the results of the analysis. Though 100% of the area in ME 5a could potentially be affected by leaf rust (Table 1), diseases in ME 5b are considered almost non-existent (Rajaram et al. 1995). Our calculations for ME 5 were confined to the area previously known as ME 5a, because this was the only part of ME 5 affected by leaf rust. We refer to ME 5 in the text, which should be understood as the former ME 5a.

Leaf rust is potentially a problem in all wheat-growing areas. It causes production losses in all spring bread wheat environments, except for the former ME 5b (Rajaram et al. 1995). Spring bread wheat is also grown in ME 6, and an estimated 80% of this large area of 20 million hectares, could potentially be affected by leaf rust. However, ME 6 in the developing world includes only China, Mongolia, North Korea, and some Central Asian states, if assuming that these are presently classified as "developing" rather than "former Soviet Union." Relatively limited historical data on wheat variety adoption in these countries are available at CIMMYT. Some countries were not included in either the 1990 or 1997 CIMMYT Global Wheat Impacts Surveys, although the data improved between the two surveys. Additionally, the higher latitude requires the wheat grown in these areas to carry a certain level of photoperiod sensitivity, unlike that in all other spring bread wheat MEs. The CIMMYT spring bread wheat program has thus had limited direct impact in these regions.

This study therefore focused on the MEs where spring bread wheat is grown at low latitudes, and included MEs 1, 2, 3, 4a, 4b, 4c, and 5. According to year 2000 estimates, this comprised a study area of around 66.5 million hectares (Table A1).

Table A1. Selected characteristics of CIMMYT spring bread wheat mega-environments (MEs).

ME	Description	Major breeding objectives	Representative locations / regions	1990 Estimated area (000 ha)	2000 Estimated area (000 ha)
1	Favorable, low rainfall irrigated, temperate, low latitude	Resistance to lodging, LR, SR, YR[†]	Yaqui Valley, Mexico; Indus Valley, Pakistan; Gangetic Valley, India; Nile Valley, Egypt	31,875	36,000
2	Favorable, high rainfall, temperate, low latitude	Resistance to lodging, LR, SR, YR, *Septoria* spp, *Fusarium* spp, sprouting	North African coast; Highlands of East Africa; Andes; Mexico	7,476	8,000
3	Acid soil, high rainfall, temperate, low latitude	Acid soil tolerance, resistance to lodging, LR, SR, YR, *Septoria* spp, *Fusarium* spp, sprouting	Passo Fundo, Brazil	1,680	2,000
4a	Semi-arid, low rainfall, winter dominant, temperate, low latitude	Resistance to drought, *Septoria* spp, YR	Aleppo, Syria; Settat, Morocco	5,404	6,000
4b	Semi-arid, low rainfall, summer dominant, temperate, low latitude	Resistance to drought, *Septoria* spp, *Fusarium* spp, LR, SR	Marcos Júarez, Argentina	3,145	3,000
4c	Semi-arid, mostly residual moisture, hot, low latitude	Resistance to drought, and heat in seedling stage	Indore, India	4,340	2,500
5a	Warm, irrigated, high rainfall, humid, low latitude	Resistance to heat, *Helminthosporium* spp, *Fusarium* spp, sprouting	Joydepur, Bangladesh; Londrina, Brazil	3,890	9,000 [†‡] (ME 5a and 6)
5b	Warm-dry, irrigated, low humidity, low latitude	Resistance to heat, and SR	Gezira, Sudan; Kano, Nigeria	3,170	
6	Moderate rainfall, summer dominant, temperate, high latitude	Resistance to LR, SR, *Helminthosporium* spp, *Fusarium* spp, sprouting, photoperiod sensitivity	Harbin, China	4,830	20,000[‡]
			Total estimated area	65,810	86,500

[†] LR = leaf rust, SR = stripe rust, and YR = yellow rust.

[‡] The year 2000 estimates of spring bread wheat area in ME 6 are around 15 million hectares more than the 1990 estimates. This major area increase was related to the inclusion of Central Asian countries of the Former Soviet Union now being classified as developing countries.

Sources: Byerlee and Moya (1993); Rajaram et al. (1995); van Ginkel et al. (2000); the 1990 CIMMYT Wheat Impacts database.

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