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The economic impact of productivity maintenance research: breeding for leaf rust resistance in modern wheat[☆]

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Abstract

This paper reports the results of a study undertaken to estimate the economic impact in developing countries 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 lies in the pathogen's ability to mutate to new races, which may infect previously resistant varieties. Genetic resistance, rather than fungicide application, is the principal means of controlling leaf rust in developing countries. Whereas productivity enhancement is often estimated in terms of yield gains and increased supply, productivity maintenance is measured in terms of the yield losses avoided by the research investment. The internal rate of return on CIMMYT's research investment was estimated at 41%. When discounted by 5%, the net present value was US$ 5.36 billion in 1990 dollars, and the benefit–cost ratio was 27:1. These findings emphasise the economic importance of maintenance research in crop breeding programs.

Keywords: Economic impact; Productivity maintenance research; Leaf rust; Rate of return analysis; Developing countries; Wheat

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1. Introduction

The 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. This assumption ignores the losses that may result from the physical, biological or economic changes that could render existing technologies less effective. Whereas crop productivity enhancement is often measured in terms of positive yield gains, productivity maintenance is estimated in terms of the yield losses that would have occurred in the absence of research investment. Most assessments of the returns on wheat improvement programs have focused on productivity enhancement (Evenson, 1998). There are comparatively fewer economic analyses of the value of pest and disease resistance (Doodson, 1981; Heim and Blakeslee, 1986; 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 by research. Townsend and Thirtle (2001) illustrated the magnitude of this

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error by separating the maintenance effects of animal health research from output increases due to improvement research in South Africa. They suggested 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 United States of America (USA) (Adusei and Norton, 1990).

Studies at the International Maize and Wheat Improvement Center (CIMMYT) have indicated that resistance breeding has generated a considerable proportion of the returns on international wheat research over the past decades (Byerlee and Moya, 1993; Byerlee and Traxler, 1995; Smale et al., 1998; Heisey et al., 2002). Analyses of trial results confirmed that progress in protecting yields through leaf rust resistance has been greater than advances in yield potential itself (Sayre et al., 1998). The valuation of agricultural research is therefore incomplete without accounting for the losses avoided by its maintenance component (Araji et al., 1978; Knutson and Tweeton, 1979; Plucknett and Smith, 1986; Adusei and Norton, 1990).

This paper reports the results of a study undertaken to estimate the economic impact in developing countries of CIMMYT's efforts to breed leaf rust resistant spring bread wheat varieties since 1973. The returns were estimated using a simplified economic surplus approach, adapted to maintenance rather than productivity enhancement research. We first outline the background and scope of the study, before presenting the conceptual framework, methodology, results and conclusions.

2. Background and scope

Leaf rust, caused by *Puccinia triticina*, is a wheat disease of major historical and economic importance worldwide (Roelfs et al., 1992). It is the most widespread of three types of wheat rusts. The other two are known as stem and stripe rust, caused by *P. graminis* and *P. striiformis*, respectively. Yield losses to rusts 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 method to control leaf rust in developing countries, where fungicides are not often used for this purpose. The major challenge for wheat breeding is in dealing with the pathogen's ability to mutate to new races, which may infect previously resistant varieties.

Wheat varieties may carry different types and levels of leaf rust resistance. Race-specific resistance is conferred by a single gene, or by a combination of genes, producing intermediate to major reactions against specific pathogen races. However, these effects may be overcome within a relatively short time, as demonstrated by a severe leaf rust epidemic in northwestern Mexico in 1976/1977 (Dubin and Torres, 1981). Race-nonspecific resistance is conferred by a few or several interacting genes, which have partial to additive effects against several pathogen races simultaneously. This results in varying levels of resistance. Although the percentage infection associated with race-nonspecific resistance may be higher compared to varieties with effective race-specific resistance, it appears to endure longer.

This study focuses on the modern spring bread wheat grown in developing countries. Spring bread wheat covers about two-thirds of the wheat area in the developing world, with the remainder sown to durum, winter and facultative wheat. Since CIMMYT's establishment in 1966, the mandate of its wheat program has been the development of advanced lines for wheat breeding programs in developing countries. CIMMYT routinely sends nurseries containing progeny of various parental combinations to national agricultural research programs, where they are selected for local adaptation or crossed with elite local germplasm. By 'CIMMYT-related' we refer to these materials, which are descendants of the first 'modern', semi-dwarf wheat types released during the late 1960s. CIMMYT-related semi-dwarf varieties comprised 78% of the spring bread wheat area in developing countries in 1997. The remaining area was planted to other semi-dwarf types, landraces, tall wheat types released by national breeding programs, or varieties of unknown ancestry (Heisey et al., 2002).

The development of leaf rust resistance has been a priority of CIMMYT's wheat breeding program since its inception, and emphasises the selection for race-nonspecific rather than race-specific resistance. In a 1997 survey, wheat breeders in developing countries indicated that materials from CIMMYT International Nurseries were the most frequently crossed in pursuit of disease resistance goals (Rejesus et al., 1997). Smale et al. (1998) previously estimated the returns on CIMMYT's investment in breeding for race-nonspecific as compared to race-specific resistance in northwestern Mexico. The authors utilised detailed data on the type and longevity of resistance for each wheat variety grown during the study period. However, their study covered only 150 000 hectares of the estimated 66.5 million hectares of spring bread wheat included in our analysis. Similar genetic information was not available on a global basis, and such a narrow comparison would be of limited use within the larger context of this study.

Modern wheat varieties with either race-specific or race-nonspecific resistance can be found in wheat fields of developing countries today. National partners in some countries may lend greater priority to traits other than leaf rust resistance; farmers often continue to grow varieties with resistance levels that wheat scientists may no longer deem satisfactory; and the genetic type and longevity of a variety's resistance is not necessarily known at the time of its release. This study therefore compares the estimated yield losses from all types of leaf rust resistance carried by CIMMYT-related wheat to the losses that would have occurred had the varieties been fully susceptible.

The analysis is conducted by wheat breeding mega-environment (ME), a classification developed by CIMMYT to guide its germplasm enhancement activities (Rajaram et al., 1995). Six MEs have been defined for spring bread wheat. We focused on the environments where spring bread wheat is grown at low latitudes, including MEs 1–5. ME 1 accounts for 36 million hectares and 54% of the study area of 66.5 million hectares.

3. Conceptual framework

The first step in measuring the economic benefits of agricultural research is to compare the situation with research to its counterfactual in the absence of research, also known as the 'with' and 'without' scenarios. The framework we used is a partial equilibrium, economic surplus approach, in which the definition of the 'counterfactual' is the unique ingredient. In the economic surplus approach, productivity enhancement is often treated as a yield-increasing or cost-reducing, rightward or downward shift in the commodity supply function (Griliches, 1958; Alston et al., 1995). The counterfactual is often assumed as a constant supply in the absence of research.

However, the supply function is not static in the face of evolving leaf rust pathogens and depreciating genetic resistance. Once a variety's resistance has been overcome by newer pathogens, its yield advantage over previous releases will decline, resulting in lower production per unit cost. Unless wheat varieties that lose their resistance are continually replaced by newly resistant varieties with similar productivity potential, the 'correct counterfactual' would instead be represented by a leftward or upward shift in the supply curve. 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, biological or economic environment (Collins, 1995). The economic surplus thus generated is shown as the shaded area in Fig. 1. This framework 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, the 'with' scenario is assumed as the actual wheat supply (S_0) generated by the modern CIMMYT-related spring bread wheat with different leaf rust resistance categories since 1973. The 'without' scenario is the wheat supply (S_2) that would have prevailed had these varieties been fully susceptible. The benefits are estimated as the productivity losses, or supply shift from S_0 to S_2, that were averted through leaf rust resistance breeding. The yield gains from productivity enhancement, depicted by the shift from S_0 to S_1, are not valued.

The approach is simplified 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. We applied 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

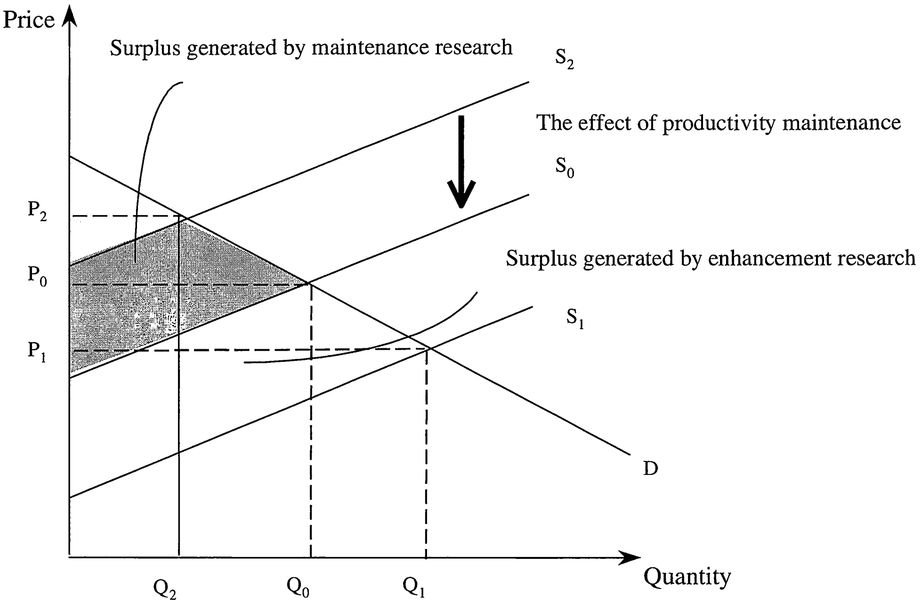

Fig. 1. General economic surplus approach adapted to maintenance research. Note: S_0 is the supply with maintenance, but without enhancement research; S_1 the supply with maintenance and enhancement research; S_2 the supply without maintenance or enhancement research; S the supply; D the demand; P the price; and Q the quantity.

require supply and demand elasticities for all relevant input and output markets, for all affected countries. The benefits are aggregated over a large number of 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, the changes might 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. If they had been, the benefits would be greater than estimated here, since the supply would have contracted and prevailing prices would have been higher. The demand curve is therefore perfectly elastic at the world wheat price in our version of Fig. 1.[1] We measure the shift in wheat supply avoided through leaf rust resistance breeding 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.

4. Methodology

The net present value, internal rate of return, and benefit–cost ratio were used as criteria to estimate the returns on the research investment (Gittinger, 1982). The net present value of breeding leaf rust resistant modern wheat varieties can be most generally expressed as:

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

Essential parameters are: λ, the average annual farm-level percentage yield loss avoided by growing varieties with different categories of leaf rust resistance; y, the average annual farm-level wheat yield; and a, the area to which yield savings apply. The product of these terms represents the production savings by leaf rust resistance category and wheat breeding environment. These are valued by the real wheat

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[1] Another general equilibrium effect not considered here is that, in the absence of resistant varieties, farmers might have responded to the disease pressure by increasing other inputs devoted to wheat (e.g., land, labour, or even fungicides) to mitigate losses from rust disease. There are other dimensions to the 'correct counterfactual' that may be important to consider, though they complicate the analysis considerably, rendering it more speculative.

price p. The difference between the gross benefits and the research cost C is calculated for each year t. The benefits start in 1973, the year in which the first variety recognised and promoted for race-nonspecific resistance was released (Torim 73). Costs are included since 1967 (t_1) to account for the development of 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 interest rate i to obtain the net present value.

The internal rate of return is estimated by setting the net present value equal to zero in Eq. (1) and solving for i arithmetically:

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

The benefit–cost ratio is calculated by dividing the present value of the gross benefits by the present value of the research costs:

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

Estimation of each of the parameters in Eqs. (1)–(3) is described next, and a summary of parameter assumptions is presented in Table 1.

4.1. Yield losses avoided

The yield losses avoided (λy_t) in Eqs. (1)–(3) were estimated as the product of three terms. First, the percentage infection compared to a susceptible check variety was used to estimate the percentage yield loss avoided by resistance category. This was based on trial data for a sample of the major spring bread wheat varieties grown in the developing world, as drawn from CIMMYT's 1997 Global Wheat Impacts Survey (unpublished data summarised in Heisey et al., 2002). Varieties with known CIMMYT origin, released since 1970, planted to more than 500 hectares, and for which seed was available in the CIMMYT genebank, were grown without fungicide protection in a field trial in El Batán, Mexico. Leaf rust epidemics were established by inoculating susceptible spreader rows planted adjacent to the trial material. The varieties were scored three times during their growth stage for disease severity compared to susceptible check varieties, following the modified Cobb scale (Peterson et al., 1948). This provided a definition of the effectiveness of their resistance in the field. Seedling evaluation tests with selected *P. triticina* races were conducted in the greenhouse 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.[2] These data were combined with supplementary information from previous CIMMYT trials over several years to obtain a sample of 184 varieties.

The second term used in the estimation is the average annual farm-level percentage yield lost with susceptible varieties by ME. This involves farm-level losses averaged over several years, large areas, and various production environments in developing countries. These yield losses are clearly lower than those estimated in zones of high disease pressure or those reported in epidemic years. As described in detail in Marasas et al. (2003), we searched various sources of trial data and historical accounts from the literature for estimates of expected losses. However, experimental estimates were not available for all production regions in the study area, and information from small-plot evaluations tends to overestimate disease losses. Data on weather conditions, management practices, and spatial distributions of pathogen and resistance types were also not available to allow prediction of the annual disease pressure or the duration of resistance. The number and significance of recorded rust epidemics vary, and production losses have typically been reported anecdotally for the developing world. 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 and imports.

We therefore based the upper-bound estimates of the average annual farm-level percentage yield lost by

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[2] For several of the sample varieties, the field symptoms of leaf rust are known in their respective regions from regional or international trial data. For varieties where information was not known, we predicted the likely behaviour based on the absence or presence of effective race-specific genes from the greenhouse tests and from behaviour in the field trials. We assumed that most lines are likely to have a similar resistance category 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 the level of protection from race-nonspecific resistance may have been underestimated over the area included in this study.

Table 1
Summary of the parameters used in this study

Environment	ME	Percentage yield lost to leaf rust[a,b]	Percentage area affected by leaf rust[b]	Cumulative percentage area sown to CIMMYT-related wheats[c]			Adoption lag	Diffusion period
				1977	1990	1997		
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[d]	6	100	83	99	95	0	15

[a] Yields lost by susceptible varieties.

[b] Average annual estimates obtained from CIMMYT.

[c] Estimates of the cumulative percentage area planted 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).

[d] The information for ME 5 refers to the area affected by leaf rust, i.e., ME 5a.

susceptible varieties on those provided by the CIMMYT Wheat Program (Table 1). These were less than 10% in all MEs, and in line with the general global guideline of less than 10% (Roelfs et al., 1992). The estimates were moreover based on the yields lost by susceptible varieties in environments where a mosaic of resistant and susceptible cultivars is used. Higher average annual losses might have been likely if farmers were in fact sowing only susceptible cultivars. We also conducted a sensitivity analysis to calculate the minimum average annual yield that would have had to been lost by susceptible varieties in ME 1 alone to recover CIMMYT's wheat breeding investment since 1967.

The third term is the average annual farm-level yield of CIMMYT-related spring bread wheat varieties by ME from 1973 to 2007. The series were generated by combining data on the wheat type and environment from the 1990 and 1997 CIMMYT Global Wheat Impacts Survey with the annual national wheat yields reported by the Food and Agriculture Organization (FAO) from 1973 to 1998 (http://www.faostat.fao.org). A trend regression was used to project yields to 2007.

Since these series of observed yields have resulted from both maintenance and enhancement research over the years, it complicated our attempt to measure S_0 in Fig. 1. Sayre et al. (1998) have used trial data to separate the effects of leaf rust resistance from enhancement and other maintenance research. Their results indicated that leaf rust resistance accounted for 82% of the average annual progress in grain yield potential between 1966 and 1988 in northwestern Mexico. However, this estimate would not be reliable for all production environments and years included in our study. We thus chose to apply the available yield series data to estimate y_t, rather than arbitrarily attempting to disentangle the inherent maintenance and enhancement effects. Nevertheless, we employed the estimates by Sayre et al. (1998) to generate a new yield series net of enhancement and other effects for ME 1, the growing environment best represented by northwestern Mexico. This was used as a sensitivity test to assess the magnitude by which the production savings were overestimated in our base scenario.

4.2. Area

Parameter a_t in Eqs. (1)–(3) was calculated as the product of four terms. The first is the percentage area sown to CIMMYT-related spring bread wheat by ME since 1973. Logistic diffusion curves were fitted for this purpose (Griliches, 1957). Function parameters were obtained from 1977, 1990 and 1997 CIMMYT Wheat Impacts data (Table 1). We assumed that CIMMYT-related varieties released since 1973 followed similar aggregate adoption paths to those that began to diffuse in 1966. The year 2007 thus proved to be the latest year predicted by the logistic diffusion

Table 2
The percentage area by genetic resistance category and ME in the sample of major CIMMYT-related spring bread wheat varieties grown in the developing world in 1997

ME	Genetic resistance category[a]					
	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	0.0	33.8
3	8.7	0.0	7.9	11.1	0.3	72.0
4a	1.1	2.9	53.6	25.2	0.0	17.2
4b	0.0	0.0	1.6	1.2	0.0	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)	3694	2342	13679	12723	1222	3694
Percentage	10	6	37	34	3	10

[a] Genetic resistance categories are based on the modified Cobb scale (Peterson et al., 1948) and are defined in terms of the percentage leaf rust infection relative to a susceptible check variety: (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); and (6) less than 5% (effective race-specific resistance).

curves. The second term is the average annual percentage area potentially affected by leaf rust in each ME, as estimated by the CIMMYT Wheat Program (Table 1).

The third term is the percentage area to which yield savings apply, by resistance category and ME. This was calculated as a proportion of the cumulative percentage adoption in each year of diffusion. 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. Table 2 indicates that 80% of the sample area was protected by genes conferring race-nonspecific resistance (categories 2–5), 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). Over 80% of the areas in MEs 1, 4a, 4c and 5 were planted to varieties with race-nonspecific resistance. Most of the areas in ME 4b (97%) and ME 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.

The fourth term is the average annual area sown to CIMMYT-related spring bread wheat by ME. As for the average annual yields, these series were generated by combining 1990 and 1997 CIMMYT Global Wheat Impacts Survey and FAO data from 1973 to 1998 (http://www.faostat.fao.org). A trend regression was used to project areas to 2007.

4.3. Price

The real world wheat price, or p_t in Eqs. (1)–(3), is the base series for US hard red winter wheat used in the Global Impacts Model of the International Food Policy Research Institute (IFPRI), which represents actual data for past prices and projected data for future prices (Rosegrant et al., 2001).

4.4. Costs

Costs were included since 1967 to account for the development of varieties released from 1973. Real research investments from 1967 to 1999, expressed in 1990 US dollars, were obtained from unpublished data summarised in Heisey et al. (2002). The authors considered three approaches to measure these costs, of which we employed only the highest in the analysis reported here. The cost series by Heisey et al. were developed on the basis of several assumptions. In all cases, their 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 have not 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 researchers involved in plant breeding, pathology, agronomy, physiology and others, was focused on genetic improvement. In the series applied in our analysis, CIMMYT's budget was allocated between wheat and maize according to the proportion of the total budget accuring to the wheat program. The series overestimates not only the investment in wheat improvement, but also the investment in leaf rust resistance breeding.

This assumption demonstrates the difficulty in separating maintenance research from other genetic improvement objectives. The integrated nature of enhanced germplasm production involves infrastructure, knowledge and support extending across different disciplines and programs at CIMMYT. Leaf rust resistance cannot be separated from wheat breeding objectives such as yield, adaptation and resistance to other pests and diseases. Rather than attempting to disentangle the expenses of wheat pathology from wheat breeding in total, we applied the full cost of CIMMYT's wheat genetic improvement since 1967. This includes the costs of shipments through international nurseries, and testing costs borne by CIMMYT. The only costs excluded from this analysis are those borne by national programs, such as local screening for rusts and other tests.

As with the other time series data we employed, costs were projected to 2007. However, the trend in this series is 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. Rather than predicting either an upward shift or continued downward pattern, we chose to hold costs constant at their 1999 level. The research costs (C_t) were subtracted from the gross benefits to estimate the net benefits.

4.5. Discount rate

Given the debate in the economics literature on choosing appropriate discount rates, we applied various interest rates to represent different perspectives on the investment decision. These included the long-term 'social time preference rate' (1%); 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 interest rate including risks and irreversibility, representing the perspective of a private investor or the World Bank (15%).

5. Results

5.1. Discounted gross benefits by resistance category and ME

Results are first presented as discounted real gross benefits by resistance category and ME, because research costs could not be separated on the same basis. The intermediate discount rate of 5% was assumed. Including all resistance categories and MEs, the gross benefits since 1973 amounted to US$ 7.46 billion in 1990 dollars (Table 3). Varieties with race-nonspecific resistance (categories 2–5) accounted for 91% of the benefits. Varieties with race-specific resistance accounted for only 7%, while those classified as almost fully susceptible represented only 2% of the benefits. Race-nonspecific resistance generated the major share of the benefits in MEs 1, 2, 4a, 4c and 5, while most of the benefits in MEs 3 and 4b resulted from race-specific resistance. This reflects the methods used to calculate the area distribution by resistance category within production environments (Table 2).

ME 1 accounted for 86% of the gross benefits by ME for various reasons. This large environment represented 54% of the study area, and new wheat varieties have historically been shown to spread at more rapid rates in ME 1. About two-thirds of this favourable wheat-growing environment is located 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.

5.2. Returns on the research investment

Table 4 indicates the substantial economic returns generated by CIMMYT's research investment. The internal rate of return was 41%. When discounted by 5%, the net present value was US$ 5.36 billion in 1990 dollars, and the benefit–cost ratio was 27:1.

Table 3
Discounted gross benefits of genetic leaf rust resistance in CIMMYT-related spring bread wheat from 1973 to 2007, by ME and resistance type

ME	Discounted (5%) value of gross benefits by resistance type (million US$)[a]			Environment as percentage
	Race-nonspecific	Race-specific	All[b]	
1	5913.1	357.4	6391.5	85.7
2	139.9	108.6	248.9	3.3
3	4.2	20.8	25.3	0.3
4a	5.4	1.6	7.0	0.1
4b	0.4	18.3	18.7	0.3
4c	6.5	0.4	7.0	0.1
5	723.6	22.7	762.4	10.2
All	6793.1	530.0	7460.9	100.0

[a] 1990 US$.

[b] Includes varieties with race-nonspecific and race-specific resistance, and those classified as almost susceptible, as defined in Table 2.

This implies that every US$ invested in CIMMYT's wheat genetic improvement since 1967 has generated at least 27 times its magnitude in benefits from leaf rust resistance in spring bread wheat alone. All other wheat breeding benefits are considered as pure benefits, such as increases in yield potential and resistance to other biotic and abiotic stresses. The net present value decreased when discounted by higher interest rates. However, a substantial net present value of US$ 0.62 billion was still generated, even when a stringent 15% interest rate was assumed.

When the full research cost was allocated to ME 1, the internal rate of return was 39% and the net present value at the 5% discount rate was US$ 4.56 billion. This implies that CIMMYT's investment in wheat genetic improvement over 40 years was justified by the benefits from leaf rust resistance breeding in ME 1 alone.

Table 4
Returns on the investment in leaf rust resistance breeding in CIMMYT-related spring bread wheat from 1967 to 2007

Criterion	Value
Internal rate of return (%)	41
Net present value (billion US$)[a]	
1% interest rate	15.26
5% interest rate	5.36
15% interest rate	0.62
Benefit–cost ratio[b]	27:1

[a] 1990 US$.

[b] The benefit–cost ratio was calculated using a 5% discount rate.

We also explored the magnitude of distortion caused by using the series of observed yields (y_t) in estimating the supply shift avoided from S_0 to S_2 in Fig. 1. When a yield series net of enhancement and other effects was generated and employed under the assumptions in this study, the internal rate of return declined only from 39 to 38% in ME 1. The net present value at the 5% discount rate declined from US$ 4.56 to 3.93 billion. Although the trial data used to adjust the yield series were not available over the total study area, ME 1 clearly accounted for the major share of the benefits.

5.3. *Minimum yield savings necessary to recover the investment*

The investment returns in Table 4 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). Given the difficulties in reliably estimating this parameter over the large geographical areas included in this study, a further sensitivity analysis was performed. We arithmetically calculated the minimum average annual percentage yields that would have had to 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 accounted for the major share of the benefits. The minimum yields that would have had to been lost to recuperate the investment ranged between 0.3 and 0.8% under various assumptions on discount rates and yield series applied. These minimum estimates are a mere fraction of those assumed in Table 1, and would be unusually low for a disease that is as important as leaf rust is in ME 1. The investment returns presented in Table 4 should therefore be fairly robust.

6. Conclusions

The global decline in agricultural research investment increasingly emphasises the efficient targeting of scarce resources. This study demonstrates the substantial economic benefits generated by leaf rust resistance in CIMMYT-related spring bread wheat since 1973. The full cost of CIMMYT's wheat genetic improvement since 1967 was included. The internal rate of return was 41% over the period 1967–2007. When discounted by 5%, the net present value was US$ 5.36 billion in 1990 dollars, and the benefit–cost ratio was 27:1. This implies that every US$ invested in CIMMYT's wheat genetic improvement over 40 years has generated at least 27 times its magnitude in benefits from leaf rust resistance breeding in spring bread wheat alone. Benefits were primarily generated in ME 1 and by varieties with race-nonspecific resistance to leaf rust.

Within the conceptual framework of this analysis, the results are likely to be most sensitive to assumptions on the yield losses avoided by leaf rust resistant varieties. Yet this parameter was the most difficult to reliably estimate over the large geographical areas included in this study. We therefore arithmetically calculated the minimum average annual yield losses to leaf rust that would have had to been offset by resistant varieties in ME 1 to recover CIMMYT's wheat breeding investment since 1967. The minimum yield loss estimates ranged between 0.3 and 0.8%. This would be unusually low for such an important wheat disease in this high yielding zone with heavy disease pressure. However, even these minimum yield savings would have justified the entire CIMMYT wheat program budget over the past 40 years.

Several features of plant disease in developing countries suggest that our calculations have understated dimensions of benefits from leaf rust resistance that are difficult to measure but important to recognise. In addition to incremental annual losses, major losses may be incurred by epidemics. The social consequences from *not* having resistance could be catastrophic for farmers and societies who extensively rely on their wheat crop, and for whom large-scale fungicide treatment may not be feasible. Producers growing varieties susceptible to diseases that can rapidly spread between farms may risk their own production and that of others.

This study emphasises 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. As crop productivity rises, increasing effort is required to maintain previous gains. The continually evolving pest and disease complex has prompted 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 constantly upgrading resistance by 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.

Most assessments of the returns on wheat research have nevertheless focused on productivity enhancement, and may have tended to ignore the productivity losses avoided by maintenance research. As also emphasised by other authors (Townsend and Thirtle, 2001), 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 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.

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