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Rates of yield gain and returns to investment in wheat breeding research are estimated for Pakistan's Punjab for the period since the introduction of semidwarf varieties. Analysis of two comprehensive data sets indicates that wheat breeders have maintained a rate of yield gain in newer releases of semidwarf varieties of about 1 percent per year. Improved disease resistance of newer varieties may have also prevented a yield decline of the order of 0.25 percent per year. Yield gains on farms may be less (0.6 percent per year) because of slow diffusion of new varieties. Given costs of wheat research, returns to investment in wheat breeding have been above 20 percent and are over 15 percent even if all research costs at the national and international level are included. However, more rapid diffusion of new varieties in the Punjab could considerably increase returns to wheat research.

INTRODUCTION

The introduction of semidwarf wheat varieties associated with the Green Revolution in the 1960s had a spectacular impact on wheat yields in Mexico, India, Pakistan, and other countries. Given that semidwarf wheats grown using moderate fertiliser doses on irrigated farms are estimated to have yielded 40 percent more than the older tall varieties, it is not surprising that economic studies estimate very high returns to investment in wheat research in these countries (of the order of 40 percent or more) [Ardito-Barletta (1971); Nagy (1984)]. More recently, semidwarf wheat varieties have been widely adopted in rainfed areas [Penna *et al.* (1983); Brennan (1989); Nagy (1984)], and although yield gains under rainfed conditions have been more modest [10 – 20 percent, Brennan (1989)], the returns to breeding programmes for rainfed wheat have also been high [Brennan (1989a)].

Since the first semidwarf varieties were released in the mid-1960s, and then

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widely adopted, wheat breeders have sharply increased the rate of release of new wheat varieties. In India, for example, nearly 200 new varieties, nearly all semidwarfs, were released from 1966 to 1990; and in Pakistan over 50 new varieties were released over this same period. Although these newer varieties have been developed to serve a number of objectives, especially to maintain disease resistance, an important objective has been to ensure a continuous increase in wheat yields. To date, little evidence is available on the rate of yield gain and improved disease resistance due to the release of newer varieties in this post-Green Revolution period.¹ Some evidence from Mexico suggests that the rate of yield gain in *newer semidwarf* varieties has averaged about 1 percent per year [Waddington *et al.* (1986); Ortiz-Monasterio *et al.* (1990)], but similar evidence is not available from other post-Green Revolution settings. Likewise, studies have not examined the extent to which high rates of return to investment in wheat research have been maintained in the post-Green Revolution period.

This paper aims to estimate the rate of yield gain which can be attributed to the release of newer semidwarf varieties in the province of the Punjab in Pakistan and to compute an average rate of return to wheat breeding research in Punjab Province for the period 1970–87. The Punjab is the main wheat-producing province of Pakistan, accounting for over 70 percent of Pakistan's total wheat output, most of it grown under irrigation. The Pakistan Punjab was one of the first beneficiaries of the Green Revolution, when the semidwarf variety, Mexipak, was widely adopted in the late 1960s. In the two decades from 1965 to 1985, 27 new wheat varieties were released (all but one a semidwarf) compared to only nine varieties that had been released in the previous 50 years (Table 1).

Table 1

Release of New Wheat Varieties in the Punjab, 1955-85

Period	Total Number of Varieties Released	Irrigated Normal Planting	Irrigated Late Planting	Rainfed Areas
1955–59	2	2	0	0
1960–64	0	0	0	0
1965–69	1	1	0	1
1970–74	9	8	2	4
1975–79	9	7	3	1
1980–85	6	3	2	2
Total	27	19	7	8

Note: Some varieties are recommended for more than one category (e.g., optimal and late planting or irrigated and rainfed areas); hence the total of the columns is greater than the actual number of varieties released.

¹The term "post-Green Revolution" refers to the period after the first semidwarf varieties had been widely adopted.

Estimating the progress in wheat breeding is important in Pakistan, since some policy-makers perceive that little, if any, gain has been made in developing new wheat varieties with higher yield potential than Mexipak.² The evidence in this paper will show that, in fact, steady progress has been made by wheat breeders in increasing yields and improving disease resistance, which has provided continuing high returns to investment in wheat research.

METHODS OF ANALYSIS

A Simple Model of Returns to Plant Breeding

The most widely used methodology for the computation of returns to agricultural research has been the economic surplus approach, where the streams of benefits and costs over time associated with a research programme are discounted to compute the internal rate of return to the research investment [Norton and Davis (1981)].³ In the case of a wheat breeding programme, the research investment is an ongoing programme which continuously releases a stream of new varieties. Hence, to facilitate calculations it is easier to simplify the benefits (i.e., producer surplus) and costs of the wheat breeding programme, following Brennan (1989a, b) as:⁴

$$\begin{aligned}
 B &= (g W A Y) - K \\
 R &= (B/C)^{1/n} - 1, \dots \dots \dots \dots \dots \dots \dots \dots \quad (1)
 \end{aligned}$$

where:

- B* = Annual average benefits from the research;
- g* = Annual average rate of yield gain due to the research;
- W* = The price of wheat;
- A* = The area of wheat affected by the research;
- Y* = The average wheat yield;
- K* = The annual costs to farmers of adopting newer varieties;
- R* = The internal rate of return to the research investment;
- C* = The average annual costs of the research programme; and
- n* = The average lag between the peak research expenditures and the time to peak adoption of a new variety.

²However, it is widely recognised that yields of Mexipak are now lower because it has lost its resistance to prevailing rust pathogens.

³Aggregate production function approaches have also been widely used; however, such approaches are less appropriate for computing returns to research on specific commodities in developing countries because of the lack of time-series data on inputs for each commodity.

⁴All prices are expressed in real (deflated) terms.

This specification of the returns to research has a number of underlying restrictive assumptions. First, it assumes a perfectly elastic demand curve so that all benefits are appropriated by producers. For tradeable commodities, such as cereals in an open economy, this is a reasonable assumption. Whether Pakistan's wheat economy qualifies as an open economy is debatable. Certainly, the Government of Pakistan has actively intervened in the wheat market with a variety of objectives. However, over the long term, it seems that the trend in domestic wheat prices parallels the long-run trend in world prices [Renkow (1991)], and no major bias in this analysis is introduced in assuming a perfectly elastic demand curve.

Second, this specification assumes that outward shifts of the supply curve are due to increasing yields rather than area. To the extent that newer varieties cause the area sown to increase, the returns to research are underestimated. Finally, the rate of yield gain due to breeding research may interact strongly with crop management and hence yield gains may be conditional on changes in crop management. This was certainly the case when semidwarf varieties were first released; they were much more responsive to fertiliser than the older taller varieties. In the present study, which examines the newer semidwarfs that are replacing older semidwarfs, variety \times management interactions are expected to be much smaller.

Most of the parameters of the above model can be readily estimated from secondary sources. The most critical parameter and the one requiring careful analysis is g , the annual rate of gain in yield due to the breeding programme. The following section develops methods for estimating this parameter.

Estimating Yield Gains Due to New Varieties

A number of methods are available for measuring yield gains due to new varieties [see Godden (1988) for a review]. Ideally, a varietal trial, in which important commercial varieties released over the period of interest are grown under representative farmer practices (e.g., date of planting, fertiliser rate, etc.) over a number of representative years and sites, is needed to record yield gains due to breeding. In practice, such data are rarely available, and other less satisfactory approaches must be used.

In this paper, yield data from varietal yield testing trials conducted over years were used to estimate the rate of genetic gains in yields. As with most trials to estimate yields of new varieties, varieties included in the trials vary from year to year. Hence, following Godden and Brennan (1987) and Godden (1988), a multiple regression analysis was used to estimate a vintage model of the form:

$$Y_{it} = a + \sum b_i D_i + \sum e_j D_j + u_i, \quad \dots \quad \dots \quad \dots \quad \dots \quad (2)$$

where Y_{it} is yield of variety i in year t (as above), D_i is a set of dummy variables

(0,1) for each experimental year t , D_j is a set of dummy variables (0,1) for the "vintage" or period of release of a variety, and u_t is the error term. Godden and Brennan divided D_j into five-year periods, which allows for non-linear yield increases over time in newly released varieties. In the present study, the main interest is the long-term average rate of increase in yield gains, and the specification of the vintage function was simplified to the following two alternative forms:

$$Y_{it} = a + \sum_i b_i D_i + gV_i + u_t, \quad \dots \quad \dots \quad \dots \quad \dots \quad (3)$$

and

$$\ln(Y_{it}) = a + \sum_i b_i D_i + gV_i + u_t, \quad \dots \quad \dots \quad \dots \quad \dots \quad (4)$$

where $\ln(Y_{it})$ is the natural log of Y_{it} , and V_i is the year in which variety i was released. The linear specification (Equation 3) provides an estimate of the absolute yield increase due to new varieties in absolute terms (i.e., g measures kg/ha/yr yield gains) while the logarithmic specification in Equation 4 gives the relative yield increase ($100 d[\ln(Y_{it})]/dV_i = 100g$ measures the percent per year yield gain). Both specifications were tried but the logarithmic specification was preferred since it generally gave as good or better fit and since we were most interested in relative yield gains.

The specification of Equation 4 measures *both* yield gains due to the release of newer varieties as well as yield declines of older varieties due to the breakdown of disease resistance. The breakdown of resistance is especially important in wheat, for rust pathogens continually mutate and the expected longevity of a wheat variety in terms of rust resistance is only five to seven years [Brennan and Byerlee (1991)]. However, since disease epidemics occur only in some years, one way of separating yield gains of new varieties from yield losses of old varieties is by re-estimating (4) as:

$$\ln(Y_{it}) = a + \sum_{i^*} b_{i^*} D_{i^*} + g^*V_i + u_t, \quad \dots \quad \dots \quad \dots \quad \dots \quad (5)$$

where i^* is the subset of years in which rust epidemics did *not* occur. In this case, g^* is the estimated annual rate of gain in yield potential of new varieties, net of the effects of improved disease resistance.

DATA SOURCES

For the analysis of yield gains in the Punjab, two comprehensive data sets were employed. The first is the results of the International Spring Wheat Yield Nursery (ISWYN) which has been sent by CIMMYT (The International Maize and

Wheat Improvement Centre, Mexico) to many countries annually since the early 1960s to measure yield performance and other varietal characteristics such as disease resistance over a wide range of environments. This nursery has been grown at Faisalabad, Punjab, since 1965, and data are published by CIMMYT in the ISWYN reports for all years except 1977. Methods and practices used in the ISWYN trials have varied over the years, but the materials included in the trials have always been grown under relatively high management on small plots, although without fungicide applications to control diseases. Over the years, 10 widely and commercially grown wheat varieties of the Punjab, released since 1965, have been included in the ISWYN trials. In addition, the early ISWYN trials included the old tall variety C271, released in 1957, which allows an estimate of yield gains from 1957 through the Green Revolution period. Overall, 21 years of ISWYN trial data from 1965 to 1986 (excluding 1977) were available.

The second data set consists of the results of a variety by date of planting trial conducted annually at the Khanewal Seed Farm in southern Punjab for seven years from 1980 to 1986. This replicated trial uses relatively large plot size, is grown under commercial conditions, and has tested 13 popular varieties, including all major varieties released since 1970.⁵ Of these 13 varieties, nine are classified as normal season and recommended for optimum planting in November; four are early-season varieties recommended for late planting after 1st December. Blue Silver, an early-maturing variety, is a common check variety over all years. Furthermore, each variety is grown at four dates of planting, typically ranging from 1st November to early January, and the date of planting was included as an independent variable in Equation 4.⁶ The performance of varieties over planting dates enables yield gains to be estimated under conditions more representative of farmers' conditions, since late planting has become increasingly more common in the Punjab as cropping intensity has increased [Byerlee *et al.* (1987)]. Nonetheless, the trials are planted with higher levels of inputs than farmers use, especially fertiliser, so the yields are considerably above farmers' levels.

RESULTS

Estimates of Gains in Yields in the Released Varieties

Results of the vintage models are reported in Tables 2 to 4. Since the number of dummy variables for each year of experiments (D_t) is as high as 20 in the case of the ISWYN trial, only the F -ratio for including D_t as a group of variables to test the

⁵The trials also include three varieties released for rainfed areas which were excluded from the analysis.

⁶However, the first date of planting (1st Nov.) is outside of the normal range of dates of planting followed by farmers and was dropped from the analysis.

hypothesis that $D_1 = D_2 = \dots = D_n = 0$ is reported. In most cases, this F -ratio is highly significant, indicating considerable year-to-year variation in average yields.

The analysis of the ISWYN data reported in Table 2 using Equation 4 indicates that the rate of yield gain for semidwarf varieties released since 1965 is 1.25 percent per year and highly significant. This includes also the effects of yield declines in older varieties due to loss of disease resistance. The effect of yield gains due to the release of newer varieties alone was estimated by Equation 5 by removing three years which were scored as severe rust years – 1973, 1976, and 1978 – when the older variety Mexipak was given a leaf rust rating of 60S (S = susceptible) or higher on a scale of 0–100S.⁷ When these rust years are excluded, the estimated rate of yield gain falls from 1.25 percent to 1.02 percent, and this difference

Table 2

Regression Results for Vintage Model for ISWYN Data; Faisalabad, 1965-86^a

	Semidwarf Varieties only (All Years 1965-86)	Semidwarf Varieties only (Excluding Rust Years 1973, 76, 78)	All Varieties Since 1957 ^b (All Years 1965-86)
Independent Variables^a			
Year of Variety Release	0.0125*** (3.72)	0.0102*** (2.73)	0.0187*** (6.07)
Dummy Variables for Year, D66 – D86 ^c	F=8.54***	F=3.06***	F=8.63***
Constant	7.564	7.715	7.068
n	61	50	78
R^2	0.83	0.68	0.81

Note: t -values in brackets. *** denotes significance at the 1 percent level.

^aDependent variable is the natural log of yield (in kg/ha).

^bIncludes tall variety C271 released in 1957.

^cThe number given is the F -ratio to enter the set of dummy variables for the year of experiment.

⁷The ISWYN data record rust scores for each variety and also often provide an overall disease rating for the nursery of slight, moderate, or severe infection. The fact that yields of Mexipak were more variable than yields of newer varieties is evidence of a breakdown of disease resistance in this variety.

is statistically significant at the 5 percent level, as indicated by a Chow test. These estimates suggest that 0.23 percent per year of the overall yield gain is attributable to a decline in yields of the old varieties due to increased disease susceptibility. This figure is only a rough guide and is probably an underestimate, since natural rust infestations in small yield plots, surrounded by resistant varieties, are expected to be lower than in large fields of the same variety.

Finally, to compare yield gains in the semidwarf varieties with the overall rate of yield gain that includes the effect of the introduction of semidwarfs, the vintage model for the ISWYN data was run again, including the tall variety C271 released in 1957. The overall increase in yield in this specification averages 1.87 percent per year, considerably above that in the post-Green Revolution period.

The Khanewal Seed Farm data include 123 observations of variety \times planting date \times year. Table 3 summarises estimated regression parameters for various groups of varieties and dates of planting. The estimates for normal season varieties suggest

Table 3

Regression Results for Vintage Model for Normal Season Varieties, Khanewal Seed Farm, Variety by Planting Date Trial, 1980- 86

	All Dates (20 Nov., 10 Dec., and 3 Jan.)	Optimum Date (20 Nov.)	Late Planting (10 Dec. and 3 Jan.)
Independent Variables^a			
Year of Variety Release	.0094*** (2.52)	.0083* (1.89)	.0099*** (2.03)
Days Planted after 1 November	-.0128 (20.2)***		-.0144 (12.0)***
Dummy Variables for			
Year, D81 – D86 ^b	F=2.35**	F=4.08***	F=1.86*
Constant	8.03	7.80	8.10
<i>n</i>	123	41	82
<i>R</i> ²	0.79	0.56	0.70

Note: *t*-values in brackets. *, **, *** denote significance at the 10, 5, and 1 percent level, respectively.

^aDependent variable is the natural log of yield (in kg/ha).

^bNumber given in the *F*-ratio to enter the set of dummy variables for year of experiment.

statistically significant yield gains of about 1.0 percent per year, regardless of planting date. This estimate is very comparable to that of the estimate derived from ISWYN data. Note also that the effect of planting date on yields is highly significant. The coefficients for planting date suggest a yield decline of about 1.3 percent per day's delay in planting – a result consistent with other estimates [e.g., Hobbs (1985)].

The results for early maturing varieties reported in Table 4 present a very different picture. There appears to have been no gain in yield potential of the early maturing varieties over Blue Silver, released in 1971. In fact, for two of the regressions, including that for late planting, the rate of yield gain is negative and statistically significant. Although the rate of yield loss for delayed planting is less for early maturing varieties than for normal varieties (as indicated by the smaller coef-

Table 4

Regression Results for Vintage Model for Early Maturing Varieties, Khanewal Seed Farm, Variety by Planting Date Trial, 1980-86

	All Dates (20 Nov., 10 Dec., and 3 Jan.)	Optimum Date (20 Nov.)	Late Planting (10 Dec. and 3 Jan.)
Independent Variables^a			
Year of Variety Release	-.0057 (2.20)**	-.0014 (.46)	-.0078 (2.18)**
Days Planted after 1 Nov.	-.0096 (14.06)***		-.0102 (7.34)**
Dummy Variables for			
Year, D81 – D86 ^b	F=2.92**	F=2.11	F=1.94
Constant	9.040	8.496	9.250
<i>n</i>	48	16	32
<i>R</i> ²	0.85	0.61	0.73

Note: *t*-values in brackets. *, **, *** denote significance at the 10, 5, and 1 percent level, respectively.

^aDependent variable is the natural log of yield (in kg/ha).

^bNumber given in the *F*-ratio to enter the set of dummy variables for year of experiment.

ficient for date of planting), when planted late, normal season varieties such as Pak 81 yielded better than early maturing varieties such as Blue Silver and Faisalabad 83 [Hobbs (1985)].

Whichever data set is used, the estimated rates of gain reported here compare favourably with those reported for wheat in other countries, such as Mexico [Fischer and Wall (1976); Waddington, *et al.* (1986)] and the U.K. [Godden (1988); Silvey (1981)]. Including the introduction of the semidwarf varieties, the rate of gain has averaged close to 2 percent per year, and since the release of the first successful semidwarf, the rate of yield gain has been about 1 percent per year. Improved disease resistance may have added another 0.25 percent per year yield advantage to using newer varieties.

Impact of New Varieties at the Farm Level

In order to have genetic gains in yields measured in experiments translated into gains to farmers, two conditions are required: first, that varieties released by the research system have been adopted by farmers; second, that yield gains observed by farmers in new varieties are comparable to those measured in experiments.

Of the 24 new wheat varieties that have been released since 1965 for the irrigated areas of the Punjab, only 13 have been commercially adopted (defined as covering at least 1 percent of the wheat area in one or more years). Statistics on farm-level use of semidwarf wheat varieties are available from 1978, and show that Yecora replaced the original Green Revolution varieties, Mexipak and Chenab 70, in the 1970s; and WL711, Punjab 81, and Pak 81 have steadily diffused in the 1980s although there has usually been a long lag between the time of varietal release to the time of farmers' adoption (Figure 1).

To see whether the adoption of these varieties would lead to a similar rate of yield gain as estimated above for all released varieties, an Index of Varietal Improvement was constructed following Brennan (1984). This Index, I_t , is derived from r_i , the yield of variety i relative to the check (constructed from the experimental data), and p_{it} , the proportion of area sown to the variety in year t . That is:

$$I_t = \sum p_{it} r_i \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad (6)$$

Using Equation 6 and estimates of r_i , I_t increased from 100 in 1968 to 120 in 1987 or an average rate of growth in yields in farmers' fields due to adoption of newer varieties of 0.6 percent per year, somewhat less than that observed in the analysis of experimental data. The slow rate of diffusion of newer semidwarf varieties, especially recently released higher yielding varieties such as Pak 81, has

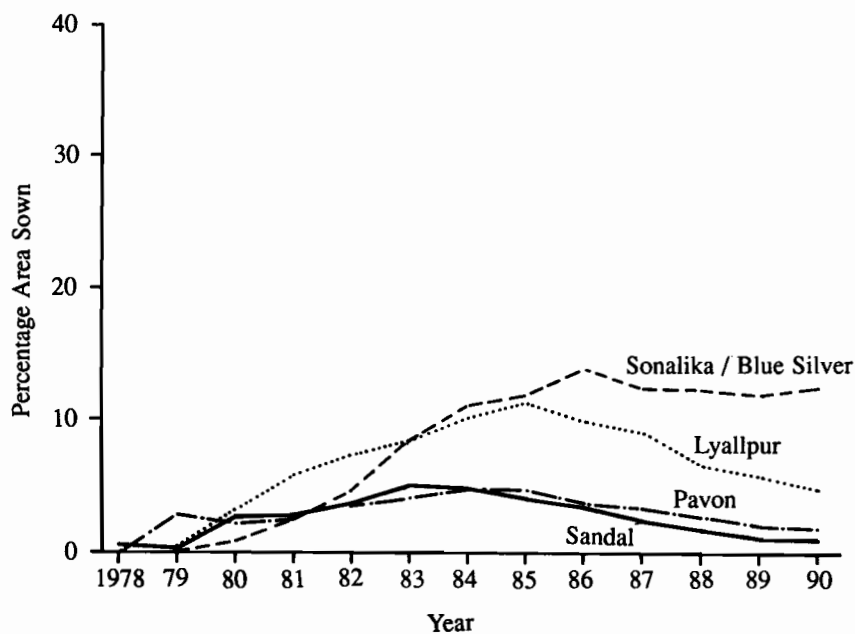
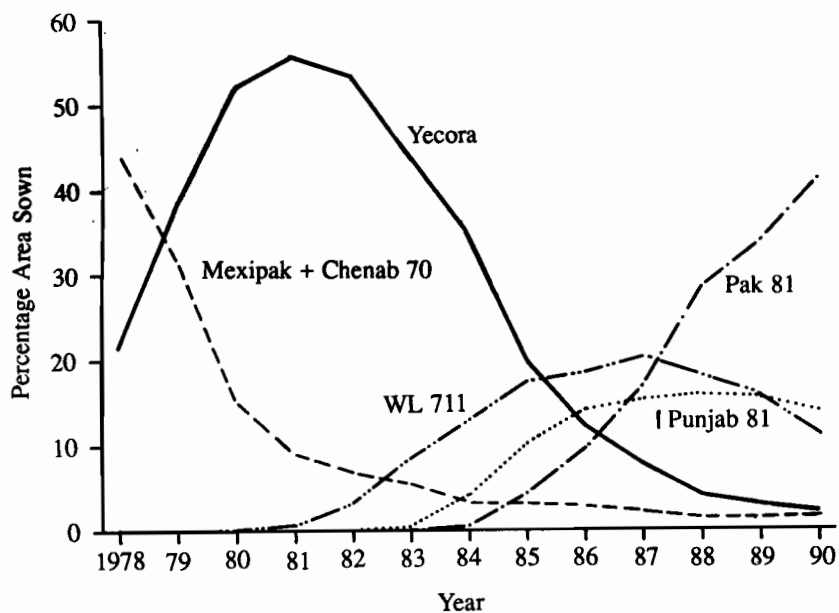


Fig. 1. Percentage Wheat Area Sown to Different Varieties Punjab, Pakistan, 1978 - 90.

undoubtedly been one factor explaining this difference.⁸

Finally, this analysis assumes that *relative* yields observed in experiments reflect the expected *relative* yield gain under farmers' management. There is some evidence to support this assumption. Data from on-farm trials Aslam *et al.* (1989) clearly show the yield superiority of newer varieties such as Pak 81, and analysis of survey data in farmers' fields also supports this evidence of yield superiority [Byerlee *et al.* (1984); Akhter *et al.* (1986)]. Furthermore, farmers overwhelmingly stated that their major reason for adopting the newer varieties was their yield advantage, and eventually farmers did widely adopt the newer varieties [Heisey (1990)].

Economic Returns to Wheat Breeding Research

In addition to the rate of yield gain attributed to wheat breeding, computation of economic returns requires estimates of the parameters A , Y , W , n , and K in Equation 1. From published statistics, the average area planted to semidwarf varieties in the Punjab, A , has increased from about 2 million ha in 1968 to over 5 million ha in 1987, with an average over the period of 3.65 million ha and an average yield, Y , of 1.7 t/ha.

The lag parameter n can be divided into two components: (1) the time from peak expenditures in breeding a variety to the time of varietal release, and (2) the time from varietal release to farmer adoption. The first of these lags has been estimated by Brennan (1989a) for a similar wheat breeding programme to be seven years. The second lag has been estimated for Pakistan's Punjab to be about 10 years [Brennan and Byerlee (1991)]. This is high relative to other countries, partly because there is a long lag in Pakistan from the time a variety is released until it is initially adopted, and partly due to a slow rate of diffusion after initiation of adoption.

The average cost of wheat research in the Punjab was estimated from data on wheat research expenditures in the 1980s at the provincial and federal levels (Q. Tauquir, personal communication). For various years from 1972 to 1988, data were available for the Wheat Research Institute, Faisalabad, PARC, and the Nuclear Institute of Agricultural Biology [Nagy (1984)]. The PARC expenditures were for all provinces and a proportion of these expenditures was applied to Punjab irrigated wheat according to its share in national production (72 percent). For all research expenditures, a 33 percent overhead was added for the experiment station and

⁸Pak 81 represented a major increment in yield potential over previously released varieties. By 1987, this variety had been adopted on less than 20 percent of the area, and hence accounted for a relatively small proportion of the benefits measured in this analysis. However, it is estimated that since 1987 Pak 81 has spread to occupy over half of the total irrigated wheat area in the Punjab, including both small and large farms. This is also evidence that the yield gains measured in experiments are being realised by farmers under their own management.

administrative costs.

These costs include expenditures for all wheat research – both breeding and non-breeding. From annual research reports, it is estimated that breeding experiments make up about half of the total experiments on wheat research in the Punjab [Byerlee and Heisey (1987)]. Assuming that breeding and non-breeding experiments have the same per-unit costs, the cost of wheat breeding research can be estimated. This cost was deflated to 1988 rupees and then converted to U.S. dollars at the official 1988 exchange rate to obtain the annual average cost of wheat breeding in 1988 dollars of US\$ 250,000. However, it can be argued that the research costs of CIMMYT, where many of the successful varieties originated, should be included. Allocating CIMMYT wheat research expenditures in proportion to Punjab wheat production as a share of total wheat production in the Third World (excluding China), gives annual research costs of US\$ 320,000. Hence total annual costs of wheat breeding research might be as high as US\$ 570,000. The fact that CIMMYT's expenditures are higher than Pakistan's total expenditures on wheat breeding research is evidence of the very low overall investment in agricultural research in Pakistan. The wheat research budget is less than 0.02 percent of the value of wheat production, and even considering wheat's share of non-commodity research budgets, such as soil fertility research, the total expenditure on wheat research is surely less than 0.1 percent of the value of wheat production – considerably below the average of 0.4 percent for all developing countries [Pardey *et al.* (1991)]. It can also be argued that from Pakistan's point of view, CIMMYT products are free goods, and a local breeding programme is needed to test and adapt CIMMYT materials. Hence, the following calculations are made with and without the CIMMYT expenditures.

To compute *social* returns on investment in wheat research, the appropriate price of wheat is the border-equivalent price. Since Pakistan was neither a consistent wheat exporter nor importer over the period under analysis, the border-equivalent price falls between the CIF and FOB price. To employ a conservative assumption, the FOB price based on a world FOB price (U.S. Gulf Ports) was taken as the wheat price. Averaged over the period and expressed in 1988 real dollars (using the U.S. wholesale price index), this price was very close to US\$ 200/t.

Finally, the cost, K , of farmers adopting new varieties was assumed negligible since the large majority of farmers obtained seed of new varieties from other farmers on an exchange basis or at prices similar to commercial grain prices [Heisey (1990)].

Using these estimated parameters, the annual rate of return to investment in wheat breeding by research institutes in Pakistan in the post-Green Revolution period is 22 percent with an annual discounted stream of benefits of over US\$ 1.0 million (Table 5). If the CIMMYT expenditures are included, the returns to

Table 5

Estimated Returns to Wheat Breeding Research, Punjab, Pakistan, 1978-87

	Base Run	Including CIMMYT Research Costs	Including Effect of Maintenance of Disease Resistance	With Shorter Adoption Lag	Based on Current Production of HYVs
Assumptions					
Annual Cost of Research (US\$ 000)	250	570	250	250	250
Adoption Lag (Years) ^a	17	17	17	14	17
Average Wheat Production (Million Tons)	6.2	6.2	6.2	6.2	10.4
Rate of Yield Gain (%/Yr) ^b	0.60	0.60	0.85	0.60	0.60
Returns					
Discounted Annual Benefits (US\$ 000)	1,084	1,084	1,536	1,524	1,636
Internal Rate of Return (%)	22	16	25	27	25
Breakeven Yield Gain to Pay Research Costs (%/Yr)	0.14	0.32	0.14	0.10	0.09

^aLag from peak research expenditure to farmer adoption.

^bAverage rate of yield gain is 0.60 percent per year. Including the decline in yield of old varieties, due to loss of disease resistance, the yield gain is 0.85 percent per year.

research are still over 15 percent per year. While these estimated returns are quite reasonable, they are somewhat below those of Nagy (1984), who considered only the impact of switching from tall to semidwarf varieties. The present study considers only gains from *replacement of the original semidwarfs by newer varieties* and ignores the continuing adoption of semidwarfs on the area still sown to tall varieties (about 33 percent of the wheat area in 1975). The choice to ignore the benefits of newer varieties in increasing the total wheat area sown to improved varieties suggests that the overall estimated rate of return is underestimated.⁹

⁹As an example, the newer varieties such as Pak 81 have enabled improved wheat varieties to move into drier areas, where they appear to have an advantage over local varieties that was not present in the earlier generations of semidwarf wheats [Ahmad *et al.* (1991)].

Nonetheless, while these rates of return are impressive, they could be even higher for two reasons. First, without the release and adoption of the newer varieties, the yield of the original semidwarfs would almost certainly have declined as disease resistance broke down. Using the estimated rate of decline of 0.25 percent per year from above (a likely underestimate), the returns from releasing new varieties with higher yield potential and better disease resistance increase to US\$ 1.5 million, or an internal rate of return of 25 percent on the investment in wheat research (Table 5). Second, it has been noted above that the rate of varietal replacement in farmers' fields in the Punjab is very slow by world standards – the average delay from varietal release to full adoption by farmers is about 10 years. If this delay could be reduced to a world average of seven years [Brennan and Byerlee (1991)], the discounted returns from wheat breeding could be increased by US\$ 0.45 million per year (Table 5). This is probably sufficient to justify further investment to increase the rate of multiplication of seed and the promotion of seed sales of new varieties.

The final column in Table 5 represents an expected current return to investment in wheat breeding research. Since semidwarf varieties are now planted on practically all irrigated wheat area in the Punjab, the returns to wheat breeding in the future should be higher than in the past. These calculations assume that similar gains in yields can be achieved for the same level of real research expenditures and, hence, varietal replacement over a larger area with a given yield gain has a greater overall effect.¹⁰

CONCLUSIONS

This paper has presented simple approaches to estimating the rate of yield gains and the economic returns to investment in plant breeding research, for a mature breeding programme that is continuously releasing a stream of new varieties. Application of these methods indicates that wheat breeders in Pakistan have continued to make steady gains in yield potential in the period since the Green Revolution had its major impact. Even using conservative assumptions, it appears that these gains have been sufficient to ensure a high rate of return on investment in wheat research in Pakistan. In fact, the evidence would suggest that Pakistan underinvests in agricultural research even in wheat, its basic food staple.

Despite evidence that the momentum of the Green Revolution has been maintained at a steady though slower rate, some cautionary notes emerge from this analysis, at least with regard to varietal development. First, although several early maturing varieties have been released for late planting, the evidence suggests that

¹⁰It is also assumed that world wheat prices continue their downward trend in real terms at 1 percent annually.

no progress has been made in increasing the yield potential of these varieties. Since late planting has increased enormously in recent years with the increase in cropping intensity, this represents a partial failure of wheat breeding programmes. Fortunately, the new varieties recommended for optimal planting also yield relatively well for late planting. Farmers have generally taken advantage of this fact and planted normal-season varieties at both optimal and late planting dates, despite the recommendations of researchers and extension. Nonetheless, given that substantial resources are invested in developing early-maturing varieties, there is a need to establish an appropriate strategy for varietal development for late planting.

Finally, despite the frequent release of newer higher yielding varieties, their rate of adoption has been relatively slow in Pakistan, both because of lags in multiplying seed of new varieties and because of a slow rate of diffusion of new varieties after the initiation of adoption. This slow rate of varietal diffusion not only substantially reduces the returns to research but also exposes the country to the risk of a disease epidemic, because of the risk that the resistance of new varieties to rust will have broken down by the time they are widely adopted by farmers. If policies on seed multiplication and marketing and extension are changed, the impact of wheat breeding research in Pakistan could be even higher in the future [Heisey (1990)].

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