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**Sources of Growth in Wheat
Yields in Pakistan's Punjab, 1965-2000:
Is There a Sustainability Issue?**

Derek Byerlee^{*} and Akmal Siddiq^{}**

*** Economist, International Maize and Wheat Improvement Center (CIMMYT), Mexico.**

**** PhD candidate, Department of Agricultural Economics, University of Illinois, USA.**

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Executive Summary

Wheat yields rose rapidly in the Punjab of Pakistan during the Green Revolution decade, 1966-76, but the rate of growth has been significantly slower in the decade that followed. Official statistics indicate that the yield of *semidwarf varieties* in irrigated areas has hardly changed since 1970. Slower growth in yields contrasts strongly with the rapid growth of inputs, especially irrigation water from tubewells and fertilizer use, which reached 120 kg nutrient/ha for irrigated wheat in the mid-1980s. Farm survey data from different periods also indicate that between 1970 and 1985 late planting of wheat has become much more common (because of increased cropping intensity), tractor use has replaced animal power, and the use of organic manure seems to have fallen sharply.

A simple model is used to disaggregate the effects on yields of three factors: 1) the conversion of rainfed land to irrigated land, 2) the adoption of high-yielding varieties (HYVs), and 3) the increasing yields of HYVs resulting from the release of newer HYVs and increased fertilizer application. Applying the model to the period 1971-73 to 1984-86 indicates that, given the change in inputs, irrigated wheat yields should have increased by at least 725 kg/ha. Yields in fact increased by only 375 kg/ha, reflecting the presence of long-term negative influences on yields. The stagnation in yields of HYVs in the 1970s and 1980s is contrary to earlier projections based on extensive on-farm experimentation.

The results suggest that important sustainability issues must be resolved if wheat yields in Pakistan's Punjab are to be maintained. These issues appear to relate to 1) increased cropping intensity, which leads to delayed planting of wheat, 2) use of poor quality tubewell water, 3) increased weed and disease problems, and 4) low efficiency of fertilizer use. Many of these factors are not well understood or quantified.

Projections of wheat supply and demand to the year 2000 suggest that Pakistan needs to reformulate its strategy of increasing yields by adding more inputs and focus instead on increasing the efficiency of use of inputs and arresting the tendency for yields to decline over the long term. This strategy will require well-coordinated, long-term research combined with efforts to improve extension services and farmers' technical knowledge.

Sources of Growth in Wheat in Pakistan's Punjab, 1965-2000:

Is There a Sustainability Issue?

Introduction

Over the past two decades, production of wheat, the staple food crop of Pakistan, has grown rapidly by world standards through the widespread diffusion of high-yielding semidwarf varieties (HYVs) coupled with rapid growth in fertilizer use and increased irrigation water supplies, phenomena associated with what is now known as the Green Revolution.¹ However, as we show in this paper, there are worrying signs that growth in each of these sources of increased yields is slowing. Practically all irrigated area is now sown with HYVs, and the rate of expansion of irrigated area has declined sharply in the 1980s. There are also strong indications that wheat yields are low given the level of inputs applied, especially fertilizer, and even current yields may not be sustainable over the long term. Despite these difficulties, yields must continue to increase rapidly to meet the growing demand for wheat generated by a high population growth rate and rapid economic growth (Government of Pakistan 1988).

This paper explores longer term changes in wheat production in Pakistan, with emphasis on yield changes in the irrigated Punjab. We focus on the irrigated Punjab because it accounts for over 70% of all wheat produced in Pakistan, because generally more data are available for the area, and because interpretation of input-output data is more meaningful for a contiguous and relatively homogeneous region such as the irrigated Punjab. Nonetheless, the general yield trends observed for the Punjab are also apparent for Pakistan as a whole.

We begin with a brief overview of recent trends in wheat yields and production in Pakistan, as well as changes in the use of inputs for wheat production in the Punjab. Using a simple model to disaggregate the effects of different inputs on changes in wheat yields, we project yield changes to the year 2000. We conclude by describing how Pakistan might reorient its strategy for promoting wheat production if the country is to remain self-sufficient in wheat production to the year 2000.

An Overview of Wheat Production Trends

Wheat production in Pakistan can be divided into three distinct periods: 1947-65, prior to the release of semidwarf wheats; 1966-76, the so-called "Green Revolution" period when HYVs were rapidly adopted on about two-thirds of total wheat area; and 1976-88, a post-Green Revolution period, when HYVs continued to spread slowly to cover almost all the irrigated area and were also rapidly adopted over much of the rainfed area.

The relative contribution of area and yield increases to increases in wheat production in Pakistan are given for each of the three periods in Table 1. Between 1948 and 1966, before the release of semidwarf varieties, all the increase in wheat production derived from area increases. That trend was sharply reversed between 1966 and 1976, as wheat yields rose at a very high rate of 4.6% per annum, and these yield increases spurred almost all the growth in wheat production. Since 1976, however, the rate of yield increase has fallen to only 1.9% per annum, well below the population growth rate. Although wheat production in this last period has grown quite rapidly, area increases have accounted for half the growth (Table 1).

1 Wheat is the dominant food crop in Pakistan, occupying 70% of the total *rabi* (winter) cropped area and providing about half of all of food calories.

Table 1. Rates of growth of wheat area, yield, and production for three periods, Pakistan

Period	Area (%)	Yield (%)	Production (%)	Percent production increase from yield increases
Pre-Green Revolution era, 1948-66	1.5***	-0.1	1.5***	0
Green Revolution era, 1967-76	0.5	4.6***	5.0***	92
Post-Green Revolution era, 1977-88	1.5***	1.9***	3.4***	56

Source: Calculated from *Agricultural Statistics of Pakistan* (various issues).

Note: *** denotes significant trend at the 1% level.

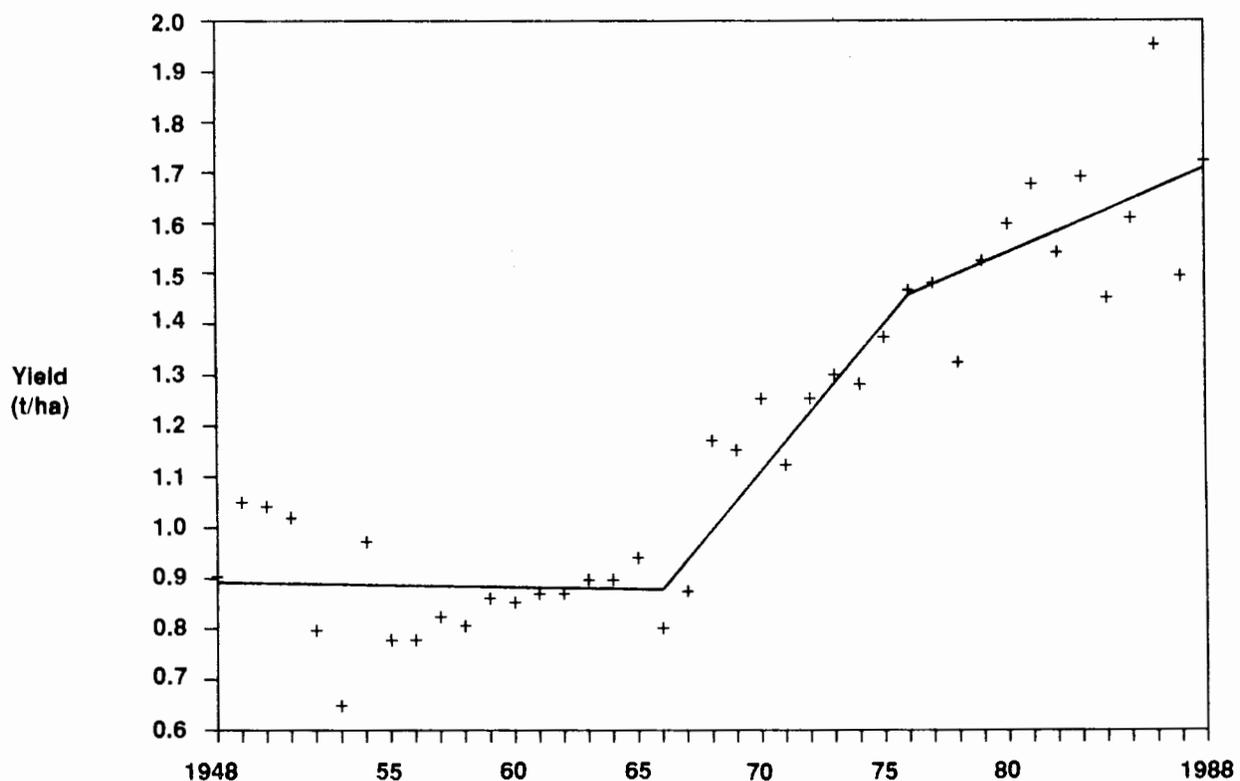


Figure 1. Average wheat yields in the Punjab, Pakistan, 1948-88.

Trends in Punjab Province mirror national wheat production trends (Figure 1). Yield changes can be shown using a spline function to represent the three major periods of wheat production identified above. The form of the spline function is:

$$y_t = b_0 + b_1 w_1 + b_2 w_2 + b_3 w_3,$$

where:

y_t = yield in year t ;

w_1 = t ;

w_2 = 0 if $t < 1966$,
= $t-1966$ if $t > 1966$; and

w_3 = 0 if $t < 1976$,
= $t-1976$ if $t > 1976$.

The coefficients b_2 and b_3 test for significant differences in trends in wheat yields between successive periods. The fitted function for the Punjab is:

$$y = 894 - 0.73w_1 + 58.6w_2 - 36.9w_3,$$

(.18) (5.99)*** (2.99)***

$$R^2 = 0.90, \quad n = 42$$

where t -values are given in parentheses and *** denotes significance at the 1% level (see also Figure 1).

Prior to 1966, yield growth was negligible and non-significant. The highly significant positive coefficient for w_2 indicates that yield growth accelerated to 58.7 kg/ha/yr in the Green Revolution period. Growth in yields during the post-Green Revolution period has slowed markedly relative to the previous period, as indicated by the significant negative coefficient for w_3 . However, yields continued to grow during this period, as estimated by:

$$b_1 + b_2 + b_3 = 20.9 \text{ kg/ha/yr.}$$

The yield increases in the past two decades can be thought of as comprising three major components (shown in Figure 2):

Increased yields resulting from the conversion of rainfed land to irrigated land;

Increased yields resulting from the switch from tall varieties to HYVs; and

Increased yields in the areas sown to HYVs as the result of the release of newer, higher yielding semidwarfs, increased fertilizer use, increased water supply in irrigated areas, and improvements in other cultural practices.

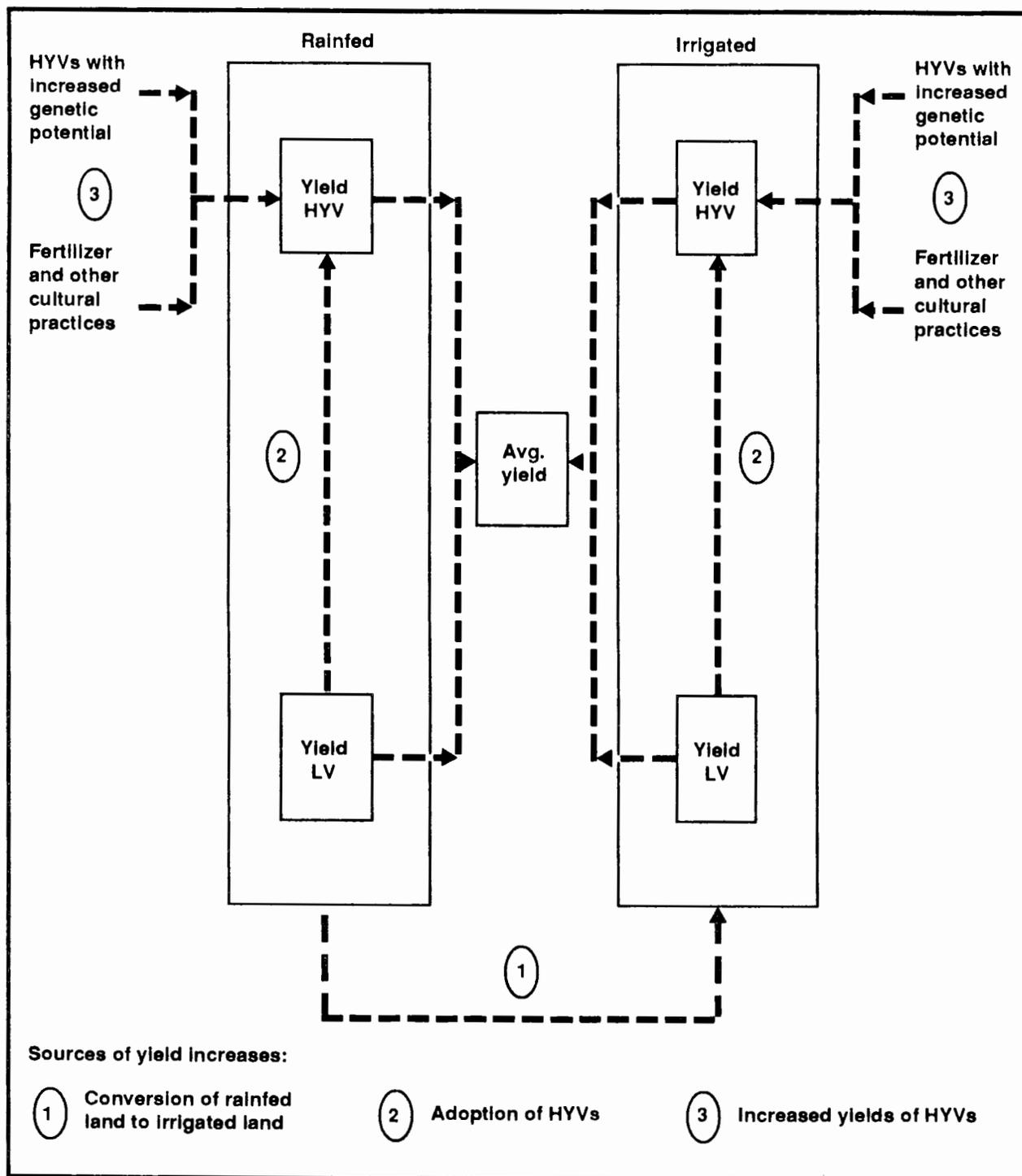


Figure 2. Framework for viewing changes in wheat yields in the Punjab, Pakistan.

Note: HYV = high-yielding variety; LV = local variety.

Table 2. Rates of growth (%/yr) of wheat area, yield, and production by irrigation status and varietal class, Punjab, Pakistan

	Area	Yield	Production
Total Punjab			
1967-76	0.5	3.9***	4.5***
1977-88	1.6***	1.5**	3.0***
Irrigated areas			
1967-76	2.3***	2.8***	5.0***
1977-88	2.2***	1.1	3.3***
Rainfed areas			
1967-76	-4.7***	3.9***	-0.8
1977-88	-1.4**	1.8	0.3
HYVs			
1967-76	27.0***	0.3	27.3***
1977-88	4.1***	0.3	4.4***
Local varieties			
1967-76	-10.6***	-1.9	-12.5***
1977-88	-16.4***	-0.5	-16.9***

Source: Calculated from *Agricultural Statistics of Pakistan* (various issues).

Note: Estimated from loglinear time-trend regression; *, **, and *** denote statistically significant trend at the 10%, 5%, and 1% levels, respectively.

Official statistics from 1966 onward allow some disaggregation of trends in area, yields, and production by these three components. The increase in irrigated wheat area can be attributed to the conversion of rainfed land to irrigated land, increased cropping intensity in irrigated land, and a greater share of wheat in total irrigated cropped area. A comparison of irrigated and rainfed area indicates that a significant part of the expansion in irrigated area occurred because rainfed wheat land was converted to irrigated land (Table 2). Between 1966 and 1988, irrigated area expanded from 68% to 87% of the wheat area. Also, increased cropping intensity (at a rate of about 1% annually) explains much of the growth in irrigated wheat area over the past two decades. In addition, the proportion of total cropped area devoted to wheat has risen from 35.4% to 37.6%.

In the period 1967-76, yields increased rapidly in both irrigated and rainfed areas but slowed sharply in both areas in the period 1977-88. Note that over the whole period yields rose more rapidly in rainfed than in irrigated areas.

When yield increases are disaggregated by varietal type, the most interesting result is the very slow rate at which yields have progressed in areas already sown to HYVs (Figure 3 and Table 2). Over the two periods, farm-level yields of HYVs show no significant trend around an average yield of about 1.7 t/ha. The growth rate in wheat yields in the Punjab over the past two decades is then almost entirely a combination of the conversion of rainfed to irrigated land and the switch from tall varieties to semidwarf varieties (also associated with increased fertilizer use).

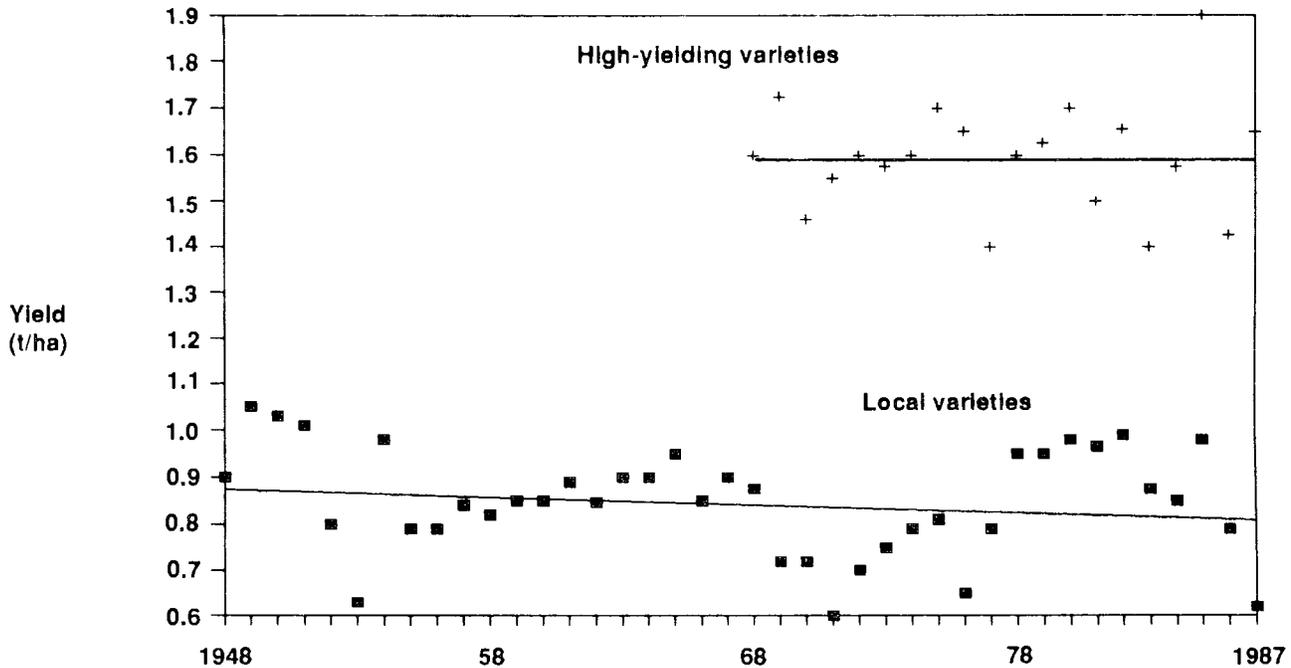


Figure 3. Trends in yields of local and high-yielding varieties, Punjab, Pakistan, 1948-87.

Source: Calculated from *Agricultural Statistics of Pakistan* (various issues).

Trends in Use of Major Inputs

Changes in the use of three inputs--irrigation water, semidwarf wheat varieties, and fertilizer--that generated almost all of the growth in wheat yields in the Punjab during the past two decades are briefly described in the next paragraphs.

Irrigation water

Growth in supplies of irrigation water in the Punjab differed markedly between the decade 1967-76 and the decade that followed (Table 3 and Figure 4). From 1964-76, total *rabi* (winter season) water supply doubled. Canal water supply increased by over 50% in this period after completion of the Mangla and Tabela Dams. As more private tubewells were installed, the groundwater supply increased even more rapidly, tripling from 1967 to 1976. By 1976 groundwater provided nearly half of the water supply during the *rabi* season. The overall annual growth in water supply of 6.7% during this period was used to convert rainfed land to irrigated land (12% of total wheat area) and also to increase the amount of water supplied to wheat from an average of 47 cm/ha to 67 cm/ha (under the reasonable assumption that 80% of *rabi* water is applied to wheat).

In the subsequent decade, 1976-86, growth in supplies of irrigation water slowed substantially to 1.9% annually, slightly below the growth of total irrigated wheat area. Water supply per irrigated hectare remained steady at about 65 cm/ha, and the proportion of irrigated wheat area increased by only 4% of total wheat area. Since total canal water supplies remained unchanged in this period, all increases in water supply were provided by tubewells. By 1986, tubewell water accounted for 59% of total *rabi* water supply, compared to only 36% two decades earlier. Even so, since 1980 investment in tubewells has slowed sharply and the current rate of increase in water supply per hectare is negligible (Hamid et al. 1987).

Table 3. Growth in sources of water supply to wheat, Punjab, Pakistan, 1967-86

	Groundwater	Surface water	Total water
Total supply^a (m³ x 10⁻⁸)			
1967	45	78	123
1986	173	121	294
Supply per ha (cm/ha)			
1967	17	30	47
1986	38	27	65
Water supply by source (%)			
1967	36	64	100
1986	59	41	100
Growth rate of water supply per ha (%/yr)			
1967-76	7.9	1.8	4.4
1977-86	2.2	-3.4	-0.3

a Allocates 80% of total *rabl* water supply to wheat in proportion to irrigated cropped area. Surface water supply at farm gate assumed to be 60% of total supply.

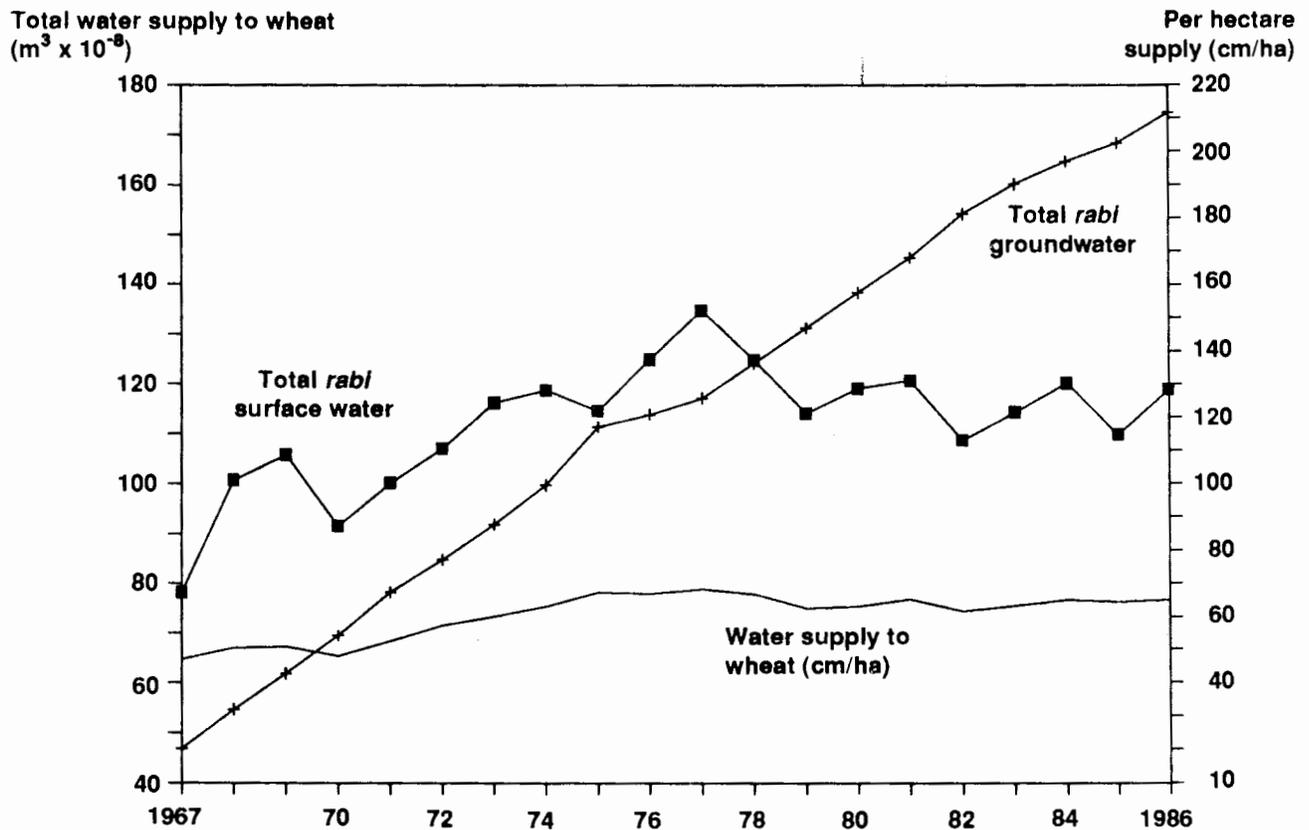


Figure 4. Trends in water supply to wheat, Punjab, Pakistan, 1967-86.

Note: See Table 3 for assumptions used in calculations.

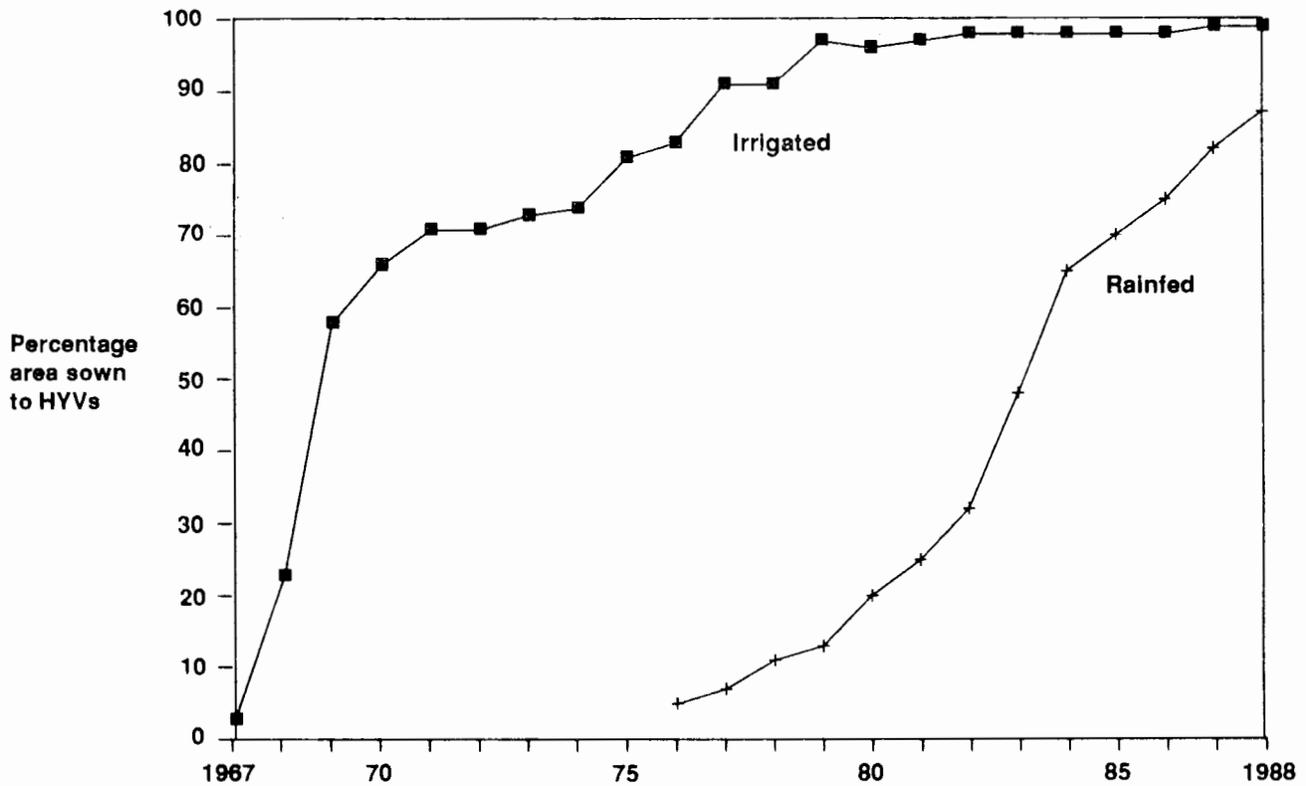


Figure 5. Adoption of high-yielding varieties in the irrigated and rainfed areas of the Punjab, Pakistan, 1967-88.

High-yielding varieties

The patterns of adoption of HYVs in irrigated and rainfed areas are quite distinct (Figure 5). In irrigated areas, the rate of adoption of HYVs was most rapid from 1966 to 1976, when the percentage area sown to new varieties increased from less than 1% to over 80%. Since 1976, the area under HYVs has expanded steadily in irrigated areas to reach 99% by 1988. In rainfed areas, adoption of HYVs was negligible until 1976 but afterward proceeded rapidly to reach over 80% of the area by 1988. In addition, the first semidwarf varieties, such as Mexipak, have been successively replaced throughout the Punjab by newer varieties (Figure 6) which not only possess higher genetic yield potential but also provide new sources of resistance against evolving rust pathogens.

Fertilizer

Estimated use of fertilizer on wheat has risen from less than 10 kg nutrient/ha in 1966 to reach 130 kg nutrient/ha in 1986 in irrigated areas, and 45 kg nutrient/ha in rainfed areas--a growth rate of over 10% annually (Figure 7). Measured by total nutrients applied, the increase in fertilizer use has been somewhat higher in 1977-86 than in the previous decade, 1966-76. Between 1966 and 1976, almost 90% of the fertilizer applied was nitrogenous fertilizer. Since then the use of phosphatic fertilizer has expanded rapidly to account for about 40% of fertilizer applied to wheat in 1986.

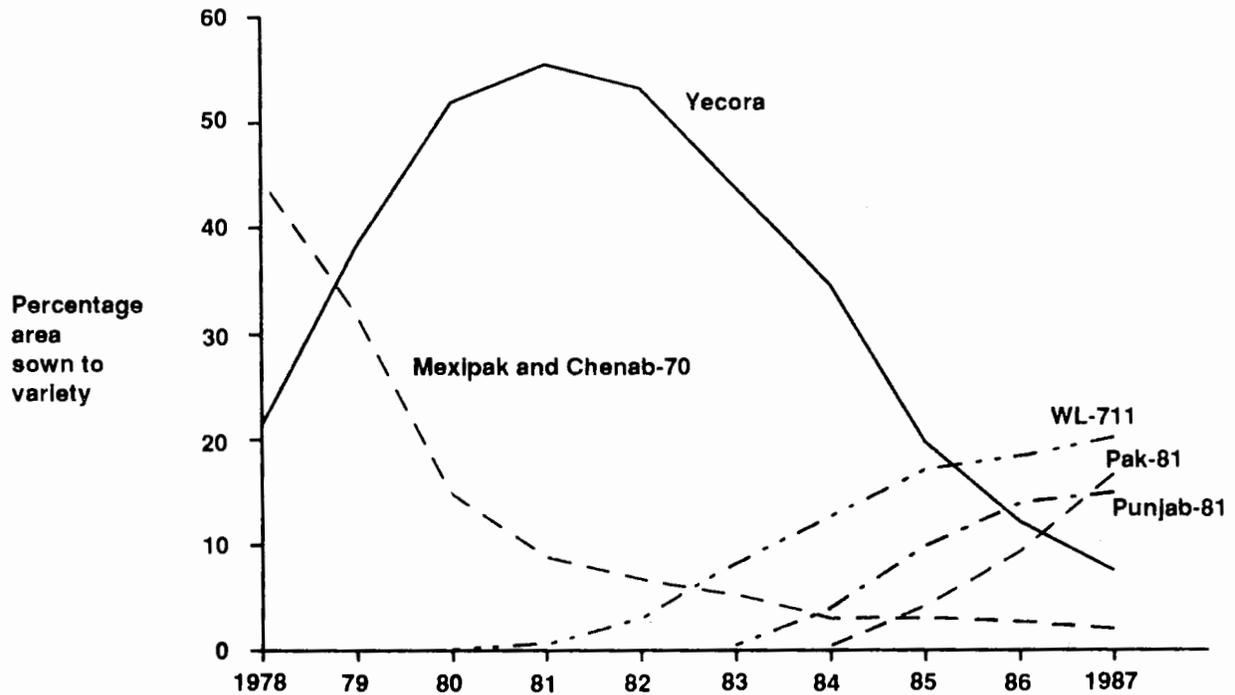


Figure 6. Percentage wheat area sown to major varieties, Punjab, Pakistan, 1978-87. Source: Heisey (1990).

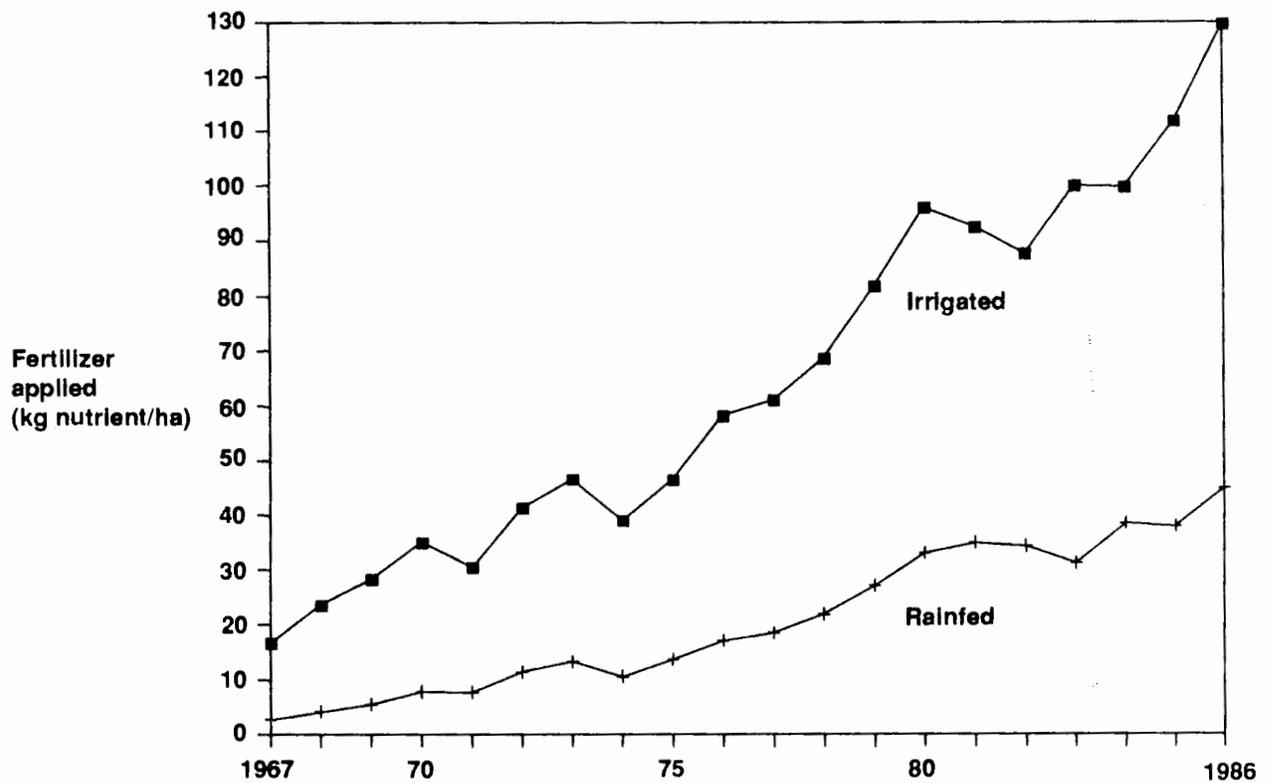


Figure 7. Fertilizer used on wheat, Punjab, Pakistan, 1967-86.

Note: Data disaggregated by rainfed and irrigated according to district; 80% of *rabi* fertilizer off-take allocated to wheat.

Changes in Inputs and Outputs in Wheat Production: The Farm-level Picture

Two farm-level surveys conducted around 1970 provide quite detailed information on production practices for irrigated wheat in the Punjab soon after the introduction of HYVs and fertilizer. Results of these surveys can be compared with survey data on wheat production practices from the mid-1980s (Byerlee et al. 1984; Akhter et al. 1986). In the case of Multan District, comparable data exist for 1970 and 1985. In addition, the Water and Power Development Authority (WAPDA) conducted large sample surveys over the whole province in 1976/77 and 1987/88.

The farm-level survey data on area sown to HYVs and use of fertilizer are generally consistent with the trends observed in secondary data discussed earlier. Trends in other practices are also evident (Tables 4 and 5). For example, since 1970 the use of tractors has spread widely; by the 1980s tractors were the dominant power source for land preparation. An even more significant trend is the shift in planting date for wheat. In the early 1970s almost all wheat was planted on time in both the rice-wheat and cotton-wheat systems. But by the mid-late 1980s, most wheat was planted late (i.e., after 30 November). The various surveys together

Table 4. Comparative data on wheat production practices in the Irrigated Punjab of Pakistan from farm-level surveys, 1969-85

Survey location and year	Sahiwal District, 1969	Multan District, 1970	Gujranwala, Sheikhupura, 1984	Multan, Bahawalpur, 1985
Rotation	Cotton-wheat	Cotton-wheat	Rice-wheat	Cotton-wheat
Author	Eckert (1970)	Lowdermilk (1972)	Byerlee et al. (1984)	Akhter et al. (1985)
Farm size (ha)	9.8	6.8	8.4	8.2
Percent use tractor	na	24	81	57
Seed rate (kg/ha)	81	86	125	110
Percent plant on time ^a	94 ^c	na	40	30
Percent use HYVs	65	72	98	99
Percent apply N	94	89	93	95
Percent apply P ₂ O ₅	na	7	83	83
Average dose (kg/ha):				
N	55	50 ^b	67	95
P ₂ O ₅	5 ^b	5 ^b	44	46
Percent apply FYM	na	85	9	13
Yield HYV (t/ha)	2.1	2.1	1.8	2.3

a Before 1 December.

b HYVs only.

c Estimated from mean and standard deviation.

indicate a steady progression toward late planting in both cropping systems (Figure 8).² Delayed planting results from increased cropping intensity (Table 5), particularly in the cotton-wheat area where wheat is now often planted after cotton, rather than in the traditional fallow-wheat and cotton-fallow rotations.

Seed rates have also increased by about one-third as farmers attempt to improve plant stand and adjust to late planting. A final noteworthy change in input use is that the application of farm yard manure has apparently dropped sharply, probably in response to the increased use of chemical fertilizer, the reduced number of draft animals, and the growing use of manure for cooking fuel.

Survey data on yields are also consistent with official statistics in suggesting that yields have stagnated at a little less than 2 t/ha in areas already sown to HYVs. Because the surveys were undertaken in relatively advanced and productive districts, it is evident that this stagnation is not just the result of HYVs diffusing to more marginal irrigated areas, which would tend to reduce overall average yields. For example, the average yield of HYVs in Multan District was 2.1 t/ha in 1970 compared to 2.3 t/ha in 1985 (Table 4), even though the survey data show that use of chemical fertilizer on HYVs in Multan District almost tripled over this period.

Table 5. Comparative data on wheat production practices in the irrigated Punjab of Pakistan from large-scale WAPDA surveys, 1977 and 1988

	1976/77	1987/88
Number of observations	1,159	293
Farm size (ha)	7.2	8.6
Cropping intensity (%)	127	144
Seed rate (kg/ha)	89	100
Percent plant on time ^a	68	43
Percent use HYVs	94	na
Percent apply N	80	97
Percent apply P ₂ O ₅	39	79
Average dose (kg/ha):		
N	48	93
P ₂ O ₅	<u>19</u>	<u>50</u>
Total	67	143
Percent apply FYM	46	36
Average yield (t/ha)	1.55	1.80

Source: S. Bashiruddin (personal communication).

a Based on time wheat planting is finished.

² These data are not strictly comparable since the WAPDA data record the date a farmer finished planting while the other surveys record planting dates for specific fields.

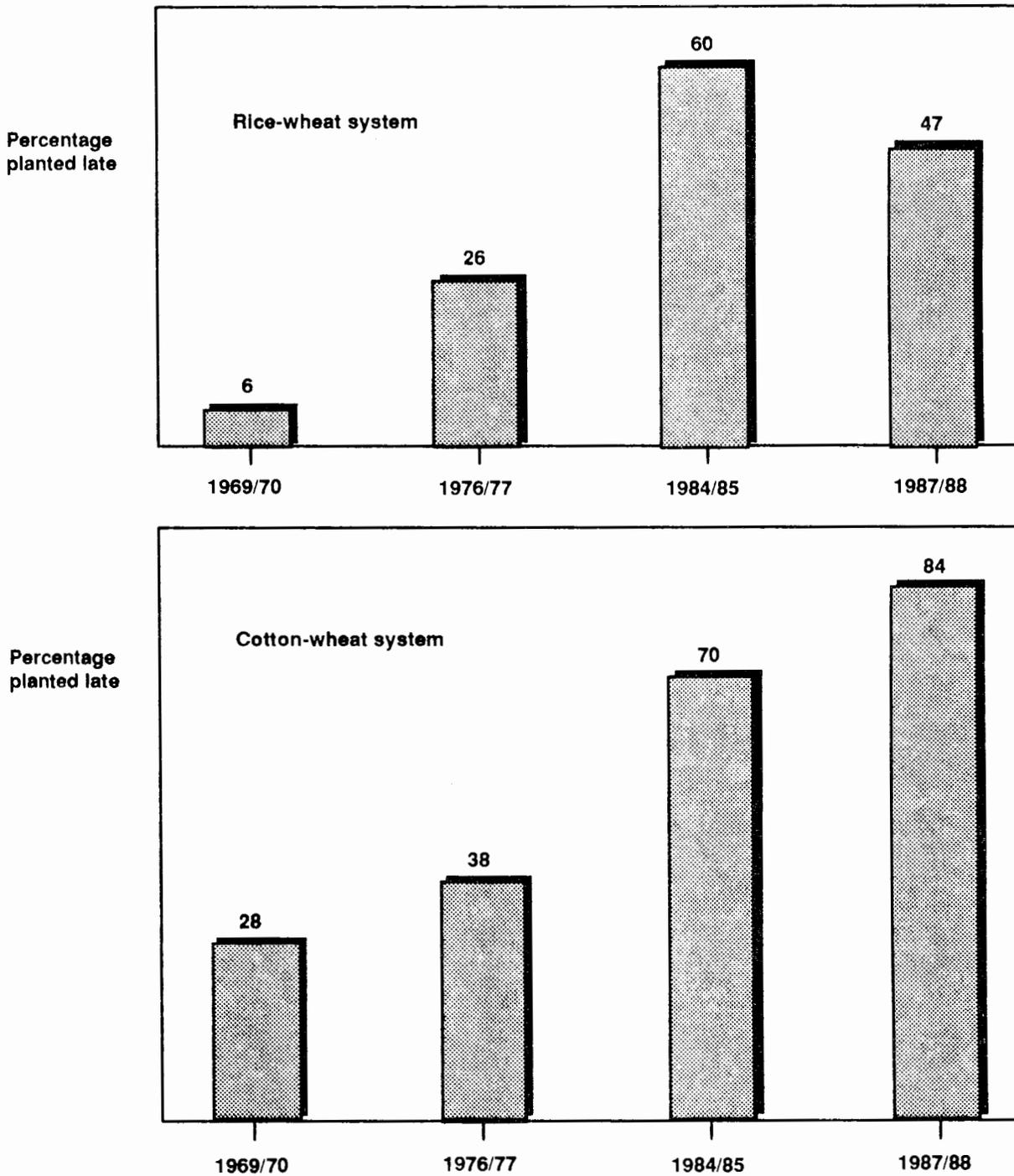


Figure 8. Percentage of wheat planted late (after 1 December) in the Punjab of Pakistan.

Source: S. Bashiruddin (personal communication).

Quantitative Decomposition of Changes in Wheat Yields, 1966-86

Basic framework of analysis

It is instructive to attempt to quantify how various production inputs have contributed to increased yields of irrigated wheat in the Punjab over the past two decades. In this analysis, we depart from the traditional econometric approach, which suffers from severe multicollinearity problems because of the high correlation between inputs over time (for example, between HYVs and fertilizer). Instead we base our analysis on a disaggregated analysis of wheat yields by irrigation regime and variety and on the application of basic agronomic principles and experimental results.

A simple framework for disaggregating changes in yields follows from Figure 2. First, the average wheat yield, y^* , for the Punjab is the weighted average of rainfed and irrigated yields, as follows:

$$y^* = py^I + (1-p)y^N \quad (1)$$

where:

- y^I = average yield in irrigated areas;
- y^N = average yield in rainfed areas; and
- p = proportion of wheat area irrigated.

Using subscripts to denote year, the change in yields from a base period $t = 0$ to year t can be readily disaggregated into three components:

- $p_o(y_t^I - y_o^I)$, representing yield changes in irrigated areas;
- $(1 - p_o)(y_t^N - y_o^N)$, representing yield changes in rainfed areas; and
- $(p_t - p_o)(y_t^I - y_t^N)$, representing the conversion of rainfed to irrigated land.

Likewise, yields in irrigated areas can be expressed as:

$$y^I = qy^{Is} + (1 - q)y^{Iz} \quad (2)$$

where:

- y^{Is}, y^{Iz} = yield of HYVs and local varieties in irrigated areas, respectively, and
- q = proportion of irrigated area sown to HYVs.

Finally, the increase in yields of HYVs in irrigated areas over time can be represented by the following expression:

$$y_t^{is} = y_o^{is} e^{gt} + h(F_t - F_o) + K_t \quad (3)$$

where:

- y_o^{is}, y_t^{is} = yield of HYVs in the base period and in year t;
- F_o, F_t = fertilizer nutrients applied in the base period and in year t;
- g = exponential rate of growth of genetic yield potential;
- h = marginal grain-to-nutrient ratio for fertilizer application; and
- K_t = the combined effects of changes in other cultural practices and in the quality of the resource base.

This equation simplifies the relationship between yields and inputs in three ways. First, the expression assumes no interaction between variety and fertilizer response *within the group of semidwarf varieties* and hence may underestimate the combined effects of these two factors on yields. Second, the coefficient h implies a linear response to fertilizer, although this can easily be adjusted to incorporate non-linear responses. Third, the variable K_t is essentially a residual to measure the effects of changes in other cultural practices and in the quality of the resource base, and may be negative as well as positive. No algebraic expression is developed for the effect of these other factors, but they will be considered individually below.

By substituting Equation 3 into Equation 2 (see Appendix A), the yield increase in irrigated areas can be decomposed into four components:

$(q_t - q_o)(y_o^{is} - y_o^{lz})$ is the component of yield increase that results from changing from tall varieties to HYVs on $100(q_t - q_o)$ percent of the area, with an absolute yield gain of $y_o^{is} - y_o^{lz}$.

$y_o^{is} q_t (e^{gt} - 1)$ is the component resulting from genetic improvements in yields of newer HYVs at a rate of 100g percent per year.

$q_t h (F_t - F_o)$ is the component resulting from increased fertilizer use on HYVs.

$q_t K_t$ is a residual effect of all other factors influencing yields of HYVs.

Because the initial adoption of HYVs strongly interacts with fertilizer use and because these two inputs were in fact adopted almost simultaneously, it is impossible to separate out their individual effects. Hence we assume that adoption of HYVs is accompanied by adoption of a modest dose of fertilizer, empirically estimated at 40 kg/ha in irrigated areas. Thus the yield difference between local varieties and HYVs, $y_o^{is} - y_o^{lz}$, includes the combined effects of adoption of variety and an initial fertilizer dose.

Yield gains due to conversion of rainfed land to irrigated land

The parameters for Equation 3 are readily available from secondary statistics. Over the period from 1964-66 to 1984-86, the proportion of wheat area increased from 68% to 84%, so that $p_t - p_o = 0.16$. The increase in yields in rainfed areas ($y_t^n - y_o^n$) was about 500 kg/ha, while the increase in yields in irrigated areas ($y_t^i - y_o^i$) was about 825 kg/ha. Conversion of rainfed land to irrigated land raised yields by some 900 kg/ha. Substituting these values into Equation 1, we estimate that the overall increase in average yields of 870 kg/ha in the Punjab from 1964 to 1986 can be disaggregated as follows:

	<u>Effect</u>
Increase in yields in irrigated areas	560 kg/ha
Increase in yields in rainfed areas	160 kg/ha
Conversion of rainfed to irrigated land	<u>150 kg/ha</u>
Total	870 kg/ha

By far the largest contribution to average yields has been made by the improvement in yields in irrigated areas. This finding is not surprising since irrigated wheat area is much larger than rainfed wheat area and because HYVs first rapidly spread in irrigated areas. The conversion of rainfed to irrigated area has contributed a little less than 20% of the overall increase in yields in Punjab Province.

Yield gains in irrigated areas

To analyze changes in yields in *irrigated* areas, it is convenient to consider two periods. The years from 1964-66 to 1971-73 were a time of rapid adoption of HYVs. Average wheat yields in irrigated areas are estimated to have increased from 1,050 kg/ha in 1964-66 to 1,450 kg/ha in 1971-73.³ In the second, more recent period between 1971-73 and 1984-86, yields increased more slowly, from 1,450 kg/ha to 1,825 kg/ha. Table 6 summarizes the estimated inputs of HYVs, fertilizer, and water in each period.

The increase in yields of irrigated wheat during the first period can be explained almost entirely by the adoption of semidwarf varieties together with a modest dose of nitrogenous fertilizer. Data from various studies (Eckert 1970; Lowdermilk 1972; Nagy 1984; Narvaez and Borlaug 1966; Mirza et al. 1980) can be used to summarize the increment in yields under farmers' conditions that would be expected from adopting semidwarf varieties and using nitrogenous fertilizer (Figure 9). With a modest dose of fertilizer, HYVs provided an average increment in yields of about 680 kg/ha over unfertilized tall varieties; this figure will be our estimate of $y_o^{is} - y_o^{iz}$ above.

Table 6. Key inputs and yields in irrigated wheat production for three periods, Punjab, Pakistan

	1964-66	1971-73	1984-86
Average wheat yield (kg/ha)	1,050	1,450	1,825
Area under HYVs (%)	< 1	61	93
Fertilizer applied to wheat (kg/ha)	10	40	114
Irrigation water supply (cm/ha)	49	57	65

3 We use averages of three years in these calculations to reduce the effects of random weather phenomena that often dominate yield data from only one year.

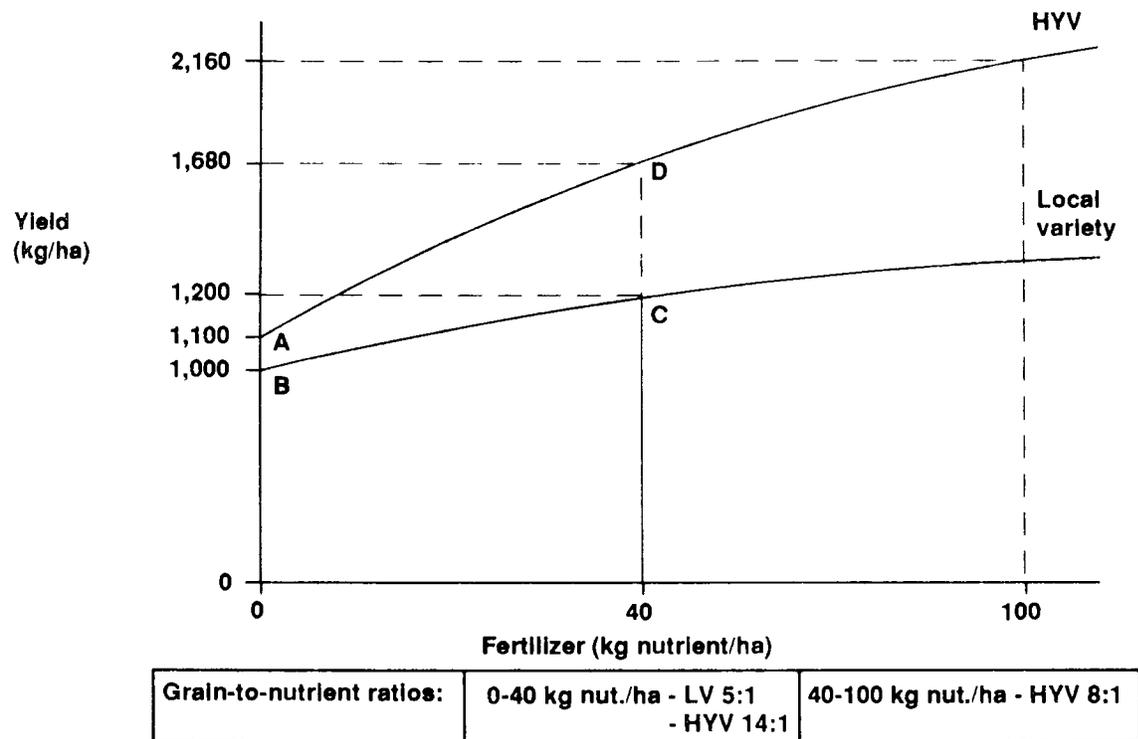


Figure 9. Estimated average fertilizer response at the farm level for local varieties and high-yielding varieties under Irrigation, Punjab, Pakistan.

Source: See text.

When these data are used as estimates of the parameters for the first component of changes in irrigated yields, $(q_t - q_0)(y_0^I - y_0^{IZ})$, the increase in average yields associated with the adoption of HYVs from 1964-66 to 1971-73 on 61% of the irrigated wheat area is estimated to be 415 kg/ha ($.61 \cdot 680$). This number is just slightly higher than the actual increase in irrigated wheat yields of 400 kg/ha during this period.

Since the wheat varieties grown in this period were the original Green Revolution varieties, the parameter g , measuring genetic gains in *newer* varieties, has no effect. Likewise, two-thirds of the increase in fertilizer use during this period can be explained by adoption of HYVs with a fertilizer dose of 40 kg/ha, and this effect is already accounted for by $y_0^{IS} - y_0^{IZ}$ above. Nonetheless, the increase in irrigation water supplies per hectare (Table 6) and the increase in fertilizer use unrelated to first adoption of HYVs are expected to have some positive yield effect and suggest that K_T , the sum of all residual effects, may be negative.

In the more recent period, 1971-73 to 1984-86, the adoption of HYVs increased from 61% to 93% of the area (Table 6). Since HYVs were first adopted by farmers on the best irrigated land, it is reasonable to assume that in this period most of the farmers who grew HYVs for the first time had more marginal, irrigated land suffering from water scarcity, waterlogging, or salinity. Hence, for this period we have assumed that the yield advantage of HYVs over tall varieties is only half of the advantage in the first period, which gives a yield advantage, $y_0^{IS} - y_0^{IZ}$, of 440 kg/ha.

In areas where farmers had adopted semidwarf varieties in the first period, newer HYVs became available, such as Yecora and WL-711 in the late 1970s and Punjab-81 and Pak-81 in the 1980s. These varieties eventually replaced the earlier Green Revolution varieties, Mexipak and Chenab-70. The new varieties' estimated contribution to yield potential under experimental conditions was about 1%/yr over this period (Byerlee 1989). Gains realized in farmers' fields were probably less, perhaps 0.75%/yr, and this figure will be used as the coefficient, g , in Equation 3.

The fertilizer dosage on irrigated wheat in the second period increased by 73 kg nutrient/ha. The switch from tall varieties to HYVs on an additional 32% of the area, associated with the use of 40 kg/ha of fertilizer, accounts for 13 kg nutrient/ha of the overall increase in fertilizer use ($.32 \times 40$). This effect has already been accounted for in $y_t^{18} - y_o^{12}$ above. On-farm fertilizer experiments (Aslam 1989; NFDC 1989) suggest a conservative marginal grain-to-nutrient ratio, h , of 8:1 associated with the increasing use of fertilizer on HYVs from 40 kg/ha to 100 kg/ha (Figure 9).

Substituting these various parameters into the yield decomposition model (presented above and in Appendix A) gives the following estimates of the components of irrigated yield increases between 1971-73 and 1984-86:

	<u>Effect</u>
Further switching from tall varieties to HYVs	141 kg/ha
Genetic gains in yield potential of newer HYVs	138 kg/ha
Increased fertilizer use on HYVs	<u>446 kg/ha</u>
Total	725 kg/ha

The total yield increase during this period was 375 kg/ha (Table 5). Hence K_t can be calculated as the residual of $375 - 725 = -350$ kg/ha. The surprising result is not that K_t is negative but that it is so large—about 20% of irrigated yields in 1984-86.

Expectations versus reality in yield gains

Before discussing the composition of the negative residual K_t , it is instructive to compare our projections with those made in a well-known study by Cownie, Johnston, and Duff (1970), based on information available in the late 1960s after the initial successes of the Green Revolution. Cownie et al. used data from the extensive on-farm trials and demonstrations of the CIMMYT/Government of Pakistan Accelerated Wheat Production Program (Narvaez and Borlaug 1966) to project to 1985 the impact of HYVs, irrigation, and fertilizer adoption on wheat yields. The main assumptions of their base projections were:

HYVs would be fully adopted in irrigated areas by 1979.

Fertilizer use on wheat would reach 125 kg nutrient/ha by 1985.

The average grain-to-nutrient ratio from fertilizer use on HYVs would increase from an observed 12:1 to 16:1 as farmers learned about fertilizer and used it more efficiently and as other cultural practices improved.

Figures 10 and 11 show the effects of these assumptions on projected yields compared with what actually happened. Cownie et al. were surprisingly accurate in their projections of input use. Adoption of HYVs in irrigated areas was 91% in 1979 compared to their projected 100%, and their projected fertilizer use was only slightly above what farmers used.

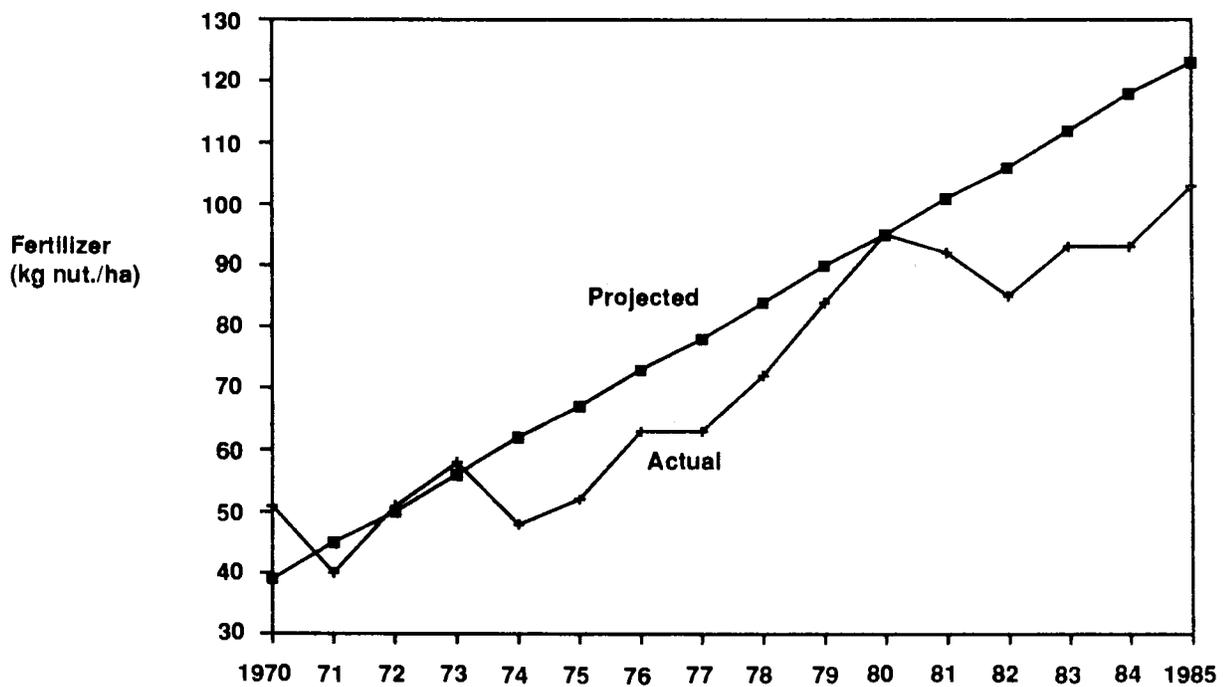
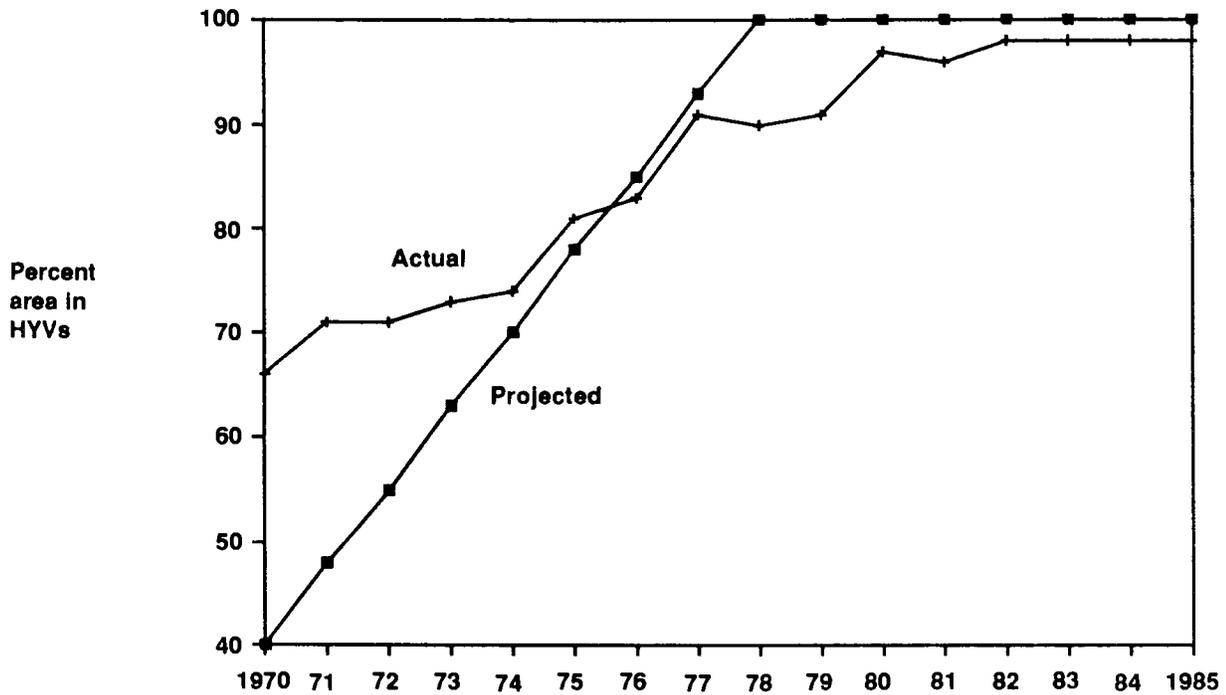


Figure 10. Projected and actual input use in the irrigated Punjab, Pakistan.

Note: Projections based on Cownle et al. (1970).

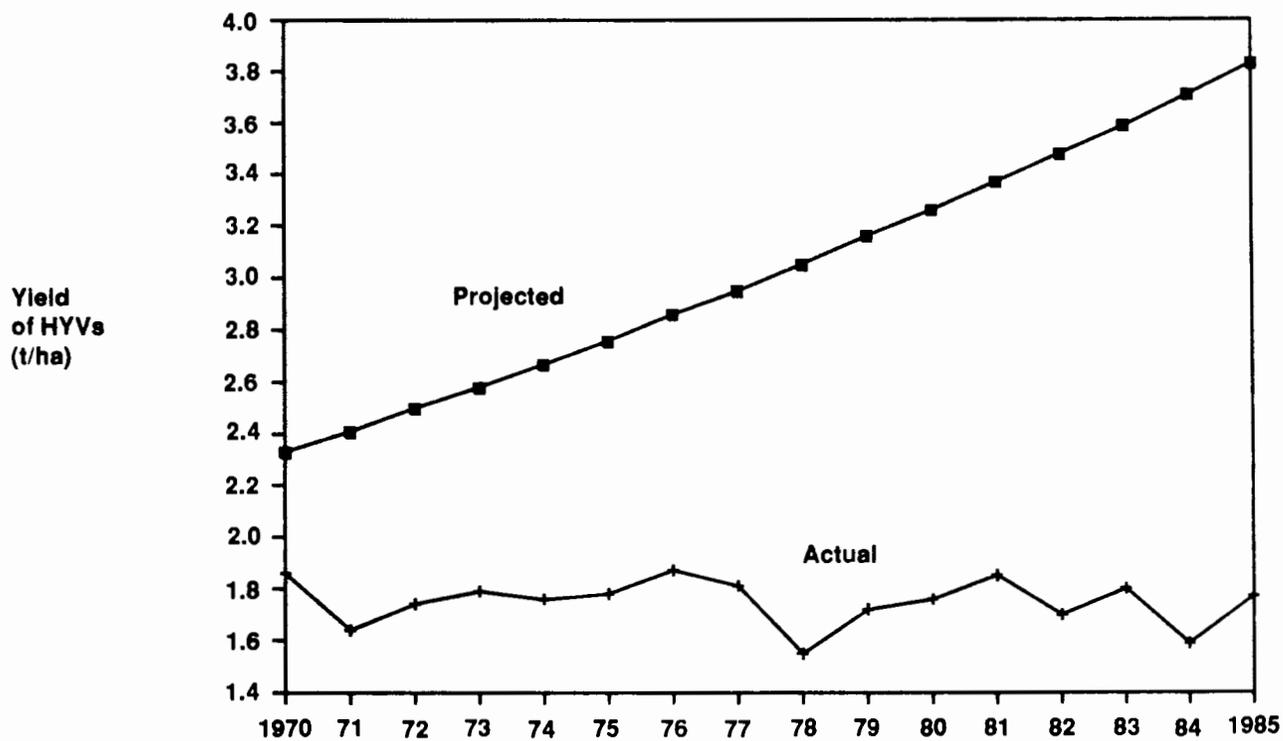
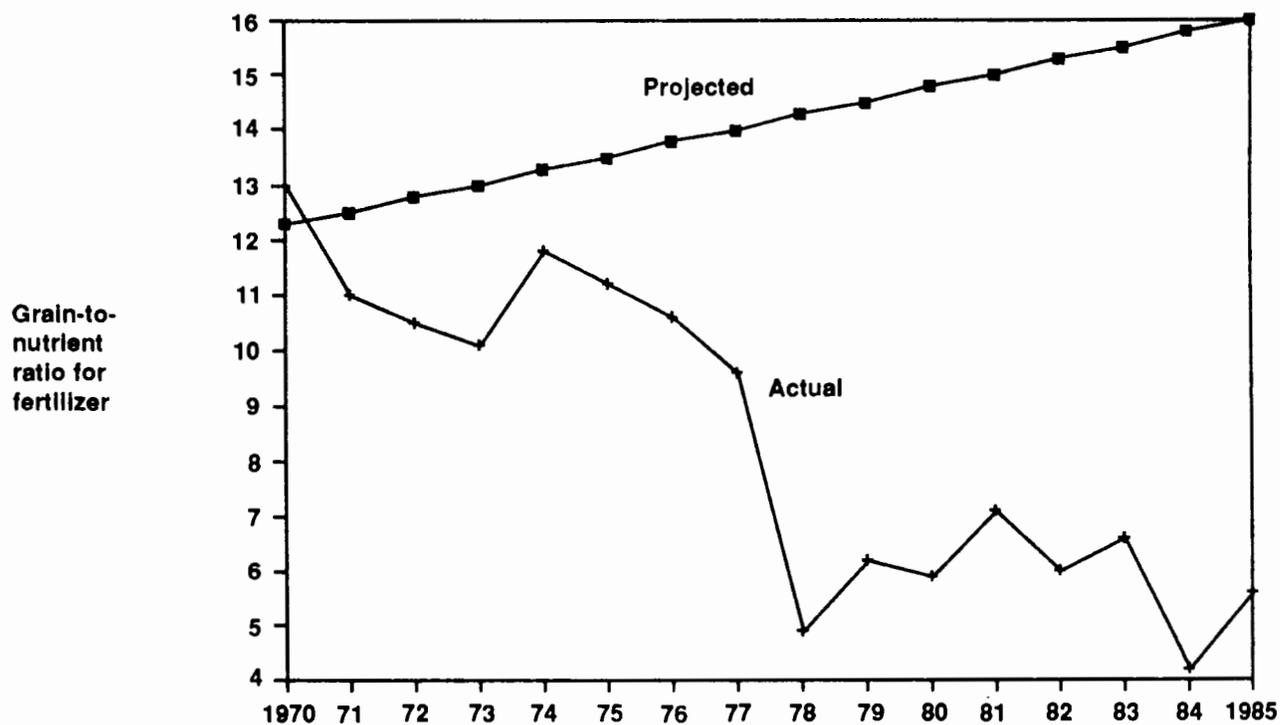


Figure 11. Projected and actual grain-to-nutrient ratios and yields for high-yielding varieties, Punjab, Pakistan, 1970-85.

Note: Projections based on Cownie et al. (1970).

However, Cownie et al. (1970) projected an average irrigated wheat yield in 1985 of 3,900 kg/ha, double the actual yields for 1984-86. This difference is due entirely to the fact that yields of HYVs were expected to increase by 64% because of higher fertilizer doses and improved fertilizer efficiency. In fact, the actual grain-to-nutrient ratio fell sharply (Figure 11). The difference between expectations arising from on-farm experimental data available in 1970 and the reality indicates that unexpected negative trends have influenced yields over this period. These trends are discussed in the section that follows.

Sustainability issues: Negative influences on yields

Sustainability has been defined in many ways, but here we adopt the definition of Lynam and Herdt (1989), who state that a sustainable system is one in which total productivity (value of outputs divided by inputs) does not decrease, while at the same time the quality of the resource base is maintained or even enhanced. Clearly if yields tend to decline for a given level of inputs a system is not sustainable. Given the substantial increases in inputs, especially fertilizer, the stagnating yields of high-yielding wheats in the irrigated Punjab over the past two decades raise serious questions about the sustainability of the system. This disturbing trend should be a major research and policy issue for the 1990s.

It is now apparent that wheat yield increases expected since 1970 from further adoption of HYVs, a tripling of fertilizer dosage, and the release of newer, even higher-yielding varieties have been canceled by several negative influences. These influences may include increased cropping intensity, poor quality groundwater, low fertilizer efficiency, and increased losses to weeds and diseases.

Increased cropping intensity--This factor has been particularly important in delaying wheat planting and probably has had other negative effects on soil structure, soil health, and nutrient availability. For example, survey data from 1970 in Multan District (Lowdermilk 1972) indicate that, at most, 30% of wheat in 1970 was planted late (after the end of November). A survey in 1985 in the same district showed that 70% of the wheat was planted late in that year (Byerlee, Akhter, and Hobbs 1987). In the rice-wheat and cotton-wheat systems, two of the dominant cropping systems of the Punjab, an average of 50% of the wheat may be sown late. Conservatively, the average date of planting of HYVs in the Punjab is estimated to be at least seven days later now than in 1970. Given an approximate yield decline per day of 1% or 30 kg/ha under farmers' conditions (Hobbs 1985), an average delay in planting of seven days would decrease wheat yields by about 200 kg/ha over the period.⁴

Poor quality groundwater--The data presented above show that groundwater from tubewells has increased as a share of all irrigation water, from 36% in 1966 to 60% in 1986. In some major wheat growing areas, tubewell water provides 75% of the irrigation water applied to the wheat crop (Tetlay, Byerlee, and Ahmed 1990).⁵

However, after widespread testing of water from over 1,000 tubewells in the 1980s, the Punjab Soil Fertility Institute classified only 25% of tubewells as providing useable water, 21% as marginally useable, and 54% as "hazardous." A decade ago, Choudhri et al. (1978) similarly concluded that sodicity caused by unsuitable tubewell water was a major problem affecting half of the cultivated area in the Punjab. Sodicity, which is a cumulative process, causes topsoil to harden, reduces plant stand by impeding emergence and seedling survival (especially in wheat), and reduces water infiltration.

4 This decrease in wheat yields may be associated with an overall increase in system productivity as a result of increased cropping intensity. Decreased wheat yields might also be expected to be associated with reduced efficiency of fertilizer response as a result of late planting, but in fact, Aslam et al. (1989) in an extensive series of on-farm experiments found no interaction between nitrogen response and late planting.

5 Over the whole of the irrigated Punjab, 47% of the wheat area is supplied with water by a combination of canals and tubewells, 19% by tubewells only, and 34% by canals only.

Data from the Soil Fertility Institute from thousands of on-farm fertilizer experiments on wheat from 1975 to 1983 suggest that wheat yields are declining by 1.5% per year at the recommended fertilizer level in areas that depend primarily on tubewell water (although much more work is needed to sort out the causes of variation in these data).

Sodicity from poor quality tubewell water can be arrested at least partially by applying gypsum (Choudhri et al. 1978), although at the moment the use of gypsum in the Punjab is negligible.⁶ The effects of secondary salinity on seedling emergence may also be reduced by a higher seed rate. Data presented in Table 4 indicate that farmers have in fact increased seed rates by about one-third over the past decade, but wheat plant stands still remain low (Aslam et al. 1989; WAPDA 1979). Yet another means of slowing the effects of sodicity is to use organic manure. However, the evidence presented above suggests that use of organic manure has declined sharply and probably aggravated the problem of sodicity.⁷

Low fertilizer efficiency--Several factors suggest that fertilizer efficiency on irrigated wheat in the Punjab is low. The balance of nutrients applied may be inappropriate. About one-third of the increase in fertilizer nutrients applied from 1971 to 1986 was provided by phosphorus (P_2O_5). Although in Pakistan the conventional recommendation is that the N: P_2O_5 ratio should be 2:1, the current N: P_2O_5 ratio for fertilizer applied to wheat is about 3:1.

On the other hand, in 42 fertilizer experiments sown in the rice-wheat zone of the Punjab from 1984 to 1988, no overall phosphorus response was observed (Aslam et al. 1989). The farmers in this area, who apply an average of about 50 kg P_2O_5 /ha, appear to be applying more than the optimum dosage. Clearly phosphorus use must be tailored to the specific agroclimatic, edaphic, and economic conditions of each location. In some locations, deficiencies of potassium and micronutrients may be limiting the overall efficiency of applied nitrogen.

There is also evidence that efficiency of applied nitrogen is low. Given average yields of 2 t/ha with the average application of 90 kg N/ha, the estimated efficiency of nitrogen recovery is at most 28%.⁸ Even in on-farm fertilizer trials in the Punjab, nitrogen-use efficiency for an application of 150 kg N/ha is estimated at a low 33% (M. Bell, CIMMYT, personal communication). Reasons for low nitrogen efficiency may include inappropriate application methods (uneven fertilizer distribution in the field and volatilization) as well as the reduced use of organic manure and greater problems of sodicity and weeds and other pests.

Increased weed and disease losses--The weed *Phalaris minor* has spread very rapidly in the rice-wheat and the central areas of the Punjab over the past two decades. This weed causes average losses of about 500 kg/ha in about 30% of fields classified as seriously infested (Byerlee et al. 1984). Likewise, Malik (1986) observed a yield loss to weeds of 230 kg/ha in 65 on-farm "constraints" experiments in the rice-wheat zone. Over the whole Punjab these yield losses may be equivalent to at least 50 kg/ha.

Diseases are also a serious problem. During the past decade much of the wheat area has been sown to rust-susceptible varieties. Although an epidemic occurred in only one year, 1978, annual losses to rust may be as high as 5-10% in many years (PARC 1987).

6 However, gypsum is widely used in the Indian Punjab.

7 Lowdermilk (1972) reported that 70% of farmers in Multan applied farm yard manure to wheat in 1969. Akhter et al. (1986) reported that, in the same area in 1985, fewer than 20% of farmers applied farm yard manure.

8 Based on a harvest index of 35%, a base yield without nitrogen of 1,000 kg/ha, and grain and straw nitrogen content of 1.8% and 0.4%, respectively (M. Bell, CIMMYT, personal communication).

Other factors--Other factors may also contribute to declining yields, such as increasing waterlogging in some areas, soil health problems caused by continuous planting of wheat, and soil compaction resulting from the widespread use of tractors for land preparation. At present only fragmentary data are available to quantify the magnitude and extent of these problems. For example, in the rice-wheat area, rotation appears to be a key determinant of yields; yields from fields planted continuously to wheat for three or more years have shown a significant negative tendency (Byerl e et al. 1984).

Combined effects of negative factors

Overall, the negative effects listed above may account for much of the difference observed between actual yields and yields predicted by Equation 3 on the basis of increased use of HYVs and fertilizer. Average losses (weighted by the area affected) of 200 kg/ha to late planting and 100 kg/ha to increased weed and disease losses, as well as losses caused by increased secondary salinity/sodicity from use of poor quality groundwater, easily account for the difference between actual and projected yields.

Finally, we should note that the negative trends in yields are not specific to wheat. Yields of rice, maize, and sugarcane in the Punjab have all stagnated over the past 10-15 years, despite substantial increases in fertilizer use. Only in cotton has there been a yield breakthrough since the recent release of new varieties and a dramatic increase in pesticide use in the 1980s.

Outlook to the Year 2000

Based on reasonable assumptions, wheat consumption in Pakistan is projected to grow at 3.3% annually to the year 2000.⁹ Over the period 1966-88, wheat production has grown at 4.5%/yr and in the period 1977-88 at 3%/yr. It is unlikely that these growth rates in production can be sustained to the year 2000. The potential to increase area and yields to the year 2000 is discussed in the following section.

Increasing wheat area

Growth in wheat area occurs by bringing new land under cultivation, especially through increased irrigation water supplies; by increasing cropping intensity; and by increasing the percentage of total cropped area sown to wheat. Over the next decade or more, there is little reason to expect any significant increase in total cultivated area. Increases in canal water supplies will be marginal since no new dams are under construction, and, as discussed earlier, increases in tubewell water supplies have slowed significantly. However, there is substantial scope to increase water use efficiency and to use savings in water to expand cropped area.

Cropping intensity in the irrigated Punjab of Pakistan is still low, especially compared to the Punjab of India. Whether or not cropping intensity increases depends largely on whether available water is used more efficiently. Double cropping is facilitated by newer, earlier maturing varieties, and plant breeders have also given greater emphasis to developing varieties specifically to fit more intensive cropping patterns (Tetlay, Byerlee, and Ahmed 1990). Earlier maturing cotton and Basmati rice varieties have been released in the last few years. Their rapid adoption has not only made it easier for farmers to increase cropping intensity but has

⁹ Assumes annual population growth and income growth of 2.7% and 5.6%, respectively, and an income elasticity of demand for wheat of 0.2. Our projections are somewhat higher than those of Harmlid et al. (1987), who assume a slower rate of population growth.

tended to reduce the problem of planting wheat late (Byerlee et al. 1987; Sharif et al. 1988). Hence cropping intensity can be expected to increase at about the same rate as in the past (about 1% annually). However, it is unlikely that wheat will expand as a proportion of total cropped area,¹⁰ so total wheat area will also expand by about 1% annually, plus a small margin for new land being brought under cultivation--say 0.2% annually.

Increasing wheat yields

Given the somewhat optimistic projection that wheat area will increase at 1.2% yearly, an increase in yields of about 2%/yr will be needed to match the growth in wheat demand to the year 2000.¹¹ To achieve an annual growth in yields of 2%, the average wheat yield in irrigated areas needs to increase from 1.8 t/ha in 1984-86 to 2.5 t/ha in the year 2000.

Attaining the required rate of yield gain will demand a very different strategy than was used to raise yields in the past. The process of switching from tall to semidwarf varieties is now complete in irrigated areas. Newer varieties with steadily increasing yield potential are continually released. Release and adoption of these newer varieties, especially varieties that yield better if planted late, have the potential to contribute about 0.75% per year to increased yields.

Given fertilizer responses estimated by the National Fertilizer Development Centre (1989) and Aslam et al. (1989), and a price ratio of nitrogen to wheat of about 3:1, the optimum nitrogen dosage that farmers in the Punjab should apply would appear to be no more than 130 kg/ha. The documented response to P_2O_5 is more variable (Aslam et al. 1989 and NFDC 1989), but an average optimum of 40 kg P_2O_5 /ha may be appropriate. Since farmers currently apply levels of phosphorus that are close to this optimum, future fertilizer growth should emphasize nitrogen. This recommendation has implications for the fertilizer subsidy which is now applied solely to phosphorus in the belief that it is the limiting nutrient.

To reach these optima, fertilizer use on wheat would need to increase by only 2.9% per annum to the year 2000 (from 120 kg nutrient/ha to 170 kg nutrient/ha) compared to the overall average increase in fertilizer use of 5% annually projected by the National Commission on Agriculture. The *marginal* grain-to-nutrient ratio observed from on-farm experiments (Malik 1986; Aslam et al. 1989; NFDC 1989) for increasing fertilizer use from the current 120 kg nutrient/ha to 170 kg nutrient/ha (mostly through increasing nitrogen) is about 6:1. Hence fertilizer use may add only about 1% growth annually (that is, a total of 300 kg/ha) to average yields over the next decade.

In the past, government policies, such as fertilizer subsidies and extension campaigns, have promoted higher doses of fertilizer--that is, movement along the response curve. Given the apparent low efficiency of fertilizer use, future policies should emphasize moving the response curve upward through improved management practices (e.g., weed control, improved plant stand, correction of secondary salinity/sodicity) that raise the efficiency of and the marginal returns to using current levels of fertilizer.

A number of other technological components can increase productivity and help improve the *efficiency* of water and fertilizer use. Herbicides are now rapidly being adopted, even by small farmers (Ahmed et al. 1989). Reduced and zero tillage promise not only to lower costs, but to increase yields by allowing more timely planting; adoption of these practices could be rapid in the next few years.

10 In fact there will be pressure to reduce wheat as a percent of cropped area in order to satisfy the increasing demand for other crops, especially oilseeds.

11 This is a much more modest target than the 3% yield growth specified by the Government of Pakistan's National Commission on Agriculture (1988).

The combination of gains from improved genetic yield potential, increased fertilizer use, and better management practices should allow an increase in yields of 2% annually, *without considering for the moment the negative influences on yields discussed above*. However, a number of obstacles may impede even these modest yield gains:

Realizing the genetic gains from newer varieties requires that they spread much more rapidly to farmers' fields (Heisey 1989). At present, a new variety requires 10 years from the time it is released until it reaches maximum adoption (assuming that the variety is accepted by farmers). Given this lag, there is a high chance that the rust resistance of "new varieties" has broken down at the time of peak adoption, and hence genetic gains are negated by vulnerability to rust. Major changes in seed distribution and extension are needed to ensure that new varieties are adopted more rapidly in the future.

The projected rate of fertilizer growth, although modest, seems unlikely to be achieved unless price incentives change. Wheat prices in Pakistan have fallen well below world prices since the last half of the 1980s, and, together with a reduction in fertilizer subsidies, have reduced the incentive for applying more fertilizer. At current prices, farmers' average fertilizer doses approach the economic optimum indicated by responses in on-farm experiments.

Improvements in other cultural practices, such as better weed control, balanced fertilizer doses, and better irrigation scheduling will require a well-developed adaptive research and extension system. Such a system will be essential for formulating location-specific recommendations and providing farmers with the improved technical information they will need to manage increasingly complex agricultural enterprises (Byerlee 1987).¹²

Clearly, substantial institutional and policy reforms will be needed to meet the technological requirements for increasing the productivity of resources devoted to wheat production to the year 2000.

A critical element in achieving an adequate growth rate in wheat yields will be to find ways to reduce the apparent tendency for yields to decline. The negative influences discussed earlier in this paper could cancel out most of the expected yield gain from improved genetic potential, increasing fertilizer dosages, and improvements in other cultural practices. The pressure brought by increased cropping intensity has been one cause of declining wheat yields; as noted above, greater emphasis on developing varieties to fit intensive cropping systems should partly alleviate this problem. Recent progress in breeding early rice and cotton varieties may also have positive effects on future wheat yields. Likewise, improving input supplies of seed of new varieties and herbicides will reduce the problem of increasing disease and weed losses. Further gains are also possible by applying gypsum to ameliorate effects of sodic tubewell water, and by applying microelements where specific micronutrient deficiencies have been identified.

However, the most urgent need at present is a concentrated research program to quantify the magnitude of the yield decline (for given input levels) and to identify its causes more precisely. This work will require a truly interdisciplinary long-term approach that relies on the expertise of soil scientists, agronomists, pathologists, irrigation specialists, and social scientists. Selecting one major cropping system, such as the rice-wheat system, would help focus this work. The interdisciplinary group should organize a diagnostic team to synthesize secondary data and conduct detailed informal and formal surveys and observations. This work should

¹² However, this optimum is considerably below the recommendation.

emphasize the integration of information across disciplines and commodity research programmes for a specific cropping system in order to understand critical soil/water/pest/rotation interactions. The diagnostic team should review available data from long-term experiments and surveys and design new experiments and surveys to monitor long-term trends in productivity and key management practices (e.g., rotation, use of unsuitable tubewell water, use of organic manures, and phosphorus levels). Because this research may not yield results for several years, it should be initiated as soon as possible.

Conclusions

A disaggregation of changes in wheat production in the Punjab over the past two decades indicates that the three major sources of production increases have been:

- 1) Area increases, especially from 1976 to 1986, through increased cropping intensity;
- 2) Yield increases from the conversion of rainfed to irrigated land; and
- 3) Yield increases resulting from the switch from tall varieties to HYVs and the adoption of fertilizer.

However, one major source of yield increases has not materialized: the increase in yields of HYVs that was expected under farmers' conditions given rapid growth in fertilizer use, the release of newer, higher yielding varieties, and the adoption of better cultural practices. This source of yield gain has apparently been negated by a number of factors. These factors are not well understood, and vigorous long-term research should begin immediately to quantify and eliminate the gap between current yields and potential yields that could be achieved with *current* levels of inputs.

We believe that the evidence presented in this paper is cause for serious concern about Pakistan's ability to sustain even modest growth in wheat yields to the year 2000. In the future the major sources of production increases will play a much smaller role than they have assumed in the past two decades; only increased area because of higher cropping intensity will be significant. Fertilizer doses will be higher but the marginal pay-off is now relatively low under current production practices. The emphasis in Pakistan on raising yields through higher levels of inputs must change to an emphasis on raising yields through more efficient use of inputs at current levels.

Clearly the major source of growth over the next decade will have to be in irrigated areas where farmers have already adopted HYVs and use moderate doses of fertilizer (over 100 kg/ha). The average wheat yield in these areas is still about 2 t/ha; hence there is substantial potential to further expand production through yield increases. However, this projection assumes that negative effects on yields will be less acute in the future. Although new, early maturing cotton and rice varieties, as well as improved weed control, will alleviate some negative influences, the effects of other factors, such as the use of saline tubewell water, may become more severe unless immediate steps are taken.

This paper has raised disturbing questions about longer term yield trends to emphasize the urgency of conducting further research in this important area. Only coordinated, in-depth research can provide a basis for the major changes that must take place in Pakistan's wheat production strategy to the year 2000 and beyond. Such research must involve specialists from major disciplines, working together to develop an integrated perspective on longer term changes in wheat yields and to seek appropriate courses of action.

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Appendix A

Decomposition of Yield Changes

This appendix provides the algebraic expressions for decomposing changes in yields into components that reflect the contribution of various inputs to changing yields.

Let yields in irrigated areas at time t , $y_t^{I^*}$, be represented by the following two equations:

$$y_t^{I^*} = qy_t^{Is} + (1 - q)y_t^{Iz}, \quad (1)$$

$$y_t^{Is} = y_0^{Is} e^{gt} + h(F_t - F_0) + K_t. \quad (2)$$

Equation 1 simply states that irrigated yields are the average of yields of semidwarf varieties, y_t^{Is} , and tall varieties, y_t^{Iz} , weighted by the proportion of area sown to semidwarfs, q . Equation 2 represents the yield of semidwarfs as the sum of three effects:

- 1) The effect of genetic gains at an annual rate of 100g percent per year.
- 2) The effect of increasing fertilizer from F_0 in the base period to F_t with a grain nutrient ratio of h .
- 3) K_t is the effect of all other factors such as weed control, changing residual fertility, and so on, and K_0 is arbitrarily assigned a value of zero.

Yield changes from the base period ($t = 0$) to time t can then be represented by:

$$y_t^{I^*} - y_0^{I^*} = q_t y_t^{Is} - q_0 y_0^{Is} + (1 - q_t) y_t^{Iz} - (1 - q_0) y_0^{Iz}, \quad (3)$$

and assuming $y_t^{Iz} = y_0^{Iz}$ and substituting Equation 2 into Equation 3, we get:

$$y_t^{I^*} - y_0^{I^*} = q_t y_0^{Is} e^{gt} + q_t h(F_t - F_0) + q_t K_t - y_0^{Iz}(q_t - q_0).$$

Rearranging, we get:

$$y_t^{I^*} - y_0^{I^*} = (y_0^{Is} - y_0^{Iz})(q_t - q_0) + y_0^{Is} q_t (e^{gt} - 1) + q_t h(F_t - F_0) + q_t K_t$$

where:

$(y_0^{Is} - y_0^{Iz})(q_t - q_0)$ is the effect due to the switch from tall to short varieties;

$q_t (e^{gt} - 1)$ is the effect due to genetic gains in yields;

$q_t h(F_t - F_0)$ is the effect due to increasing fertilizer doses; and

$q_t K_t$ is a residual of all other effects, given $y_t^{I^*} - y_0^{I^*}$.