A Joint-Product Analysis of the Adoption of Modern Cereal Varieties in Developing Countries

Greg Traxler and Derek Byerlee

Semi-dwarf wheat varieties have been slow to diffuse in some regions despite their superior grain yield. We analyze varietal differences in yields of the joint products of grain and straw, the decision to adopt new varieties, and nitrogen demand. The low straw yield of semi-dwarf varieties under low input conditions is shown to be a plausible explanation for their slow adoption in some regions. First generation modern varieties induced a large increase in the derived demand for nitrogen, but subsequent varietal development appears to have had little impact on nitrogen demand.

Key words: derived demand, joint products, modern varieties, technical change, wheat.

Adoption of improved high yielding or modern cereal varieties (MVs) has been a major stimulus to agricultural transformation in many poor countries, especially in those areas where the green revolution has led to rapid adoption of improved rice and wheat varieties beginning in the late 1960s. Several models have been used to explain small farmers' decisions to adopt (or not adopt) improved varieties (Feder, Just, and Zilberman). Feder, Heibert and others, model farmers as risk averse so that the decision to adopt is a function not only of the mean net return from MVs but also of the variability of returns. It has also been shown that adoption of MVs depends on availability of credit or other institutional factors (e.g., Jansen, Walker, and Barker). Each of these explanations has added to our understanding of the adoption of MVs.

In this paper, we propose a model of joint-product profit maximizing behavior that complements previous models in explaining the decision to adopt or reject MVs. The model we present assumes that (*a*) the profitability of varietal technologies is very location specific (Griliches 1957) and (*b*) when evaluated within a joint-product framework, the ranking of varieties in terms of profitability may depart markedly from the ranking when only grain yield is considered.

Cereal production has not previously been viewed within a joint-product framework for two reasons.[1] First, the joint-product problem is trivial if outputs other than grain are assigned a zero value, as is usually done by plant breeders responsible for varietal improvement. Yet straw is a valuable source of animal fodder for small farmers in regions characterized by intensive crop-livestock systems, low or highly seasonal biomass production, and local fodder markets that are isolated by high transportation costs. Second, the joint-product model is interesting only if producers are able to allocate inputs between the joint products. At first glance, the partitioning of inputs between grain and straw production might appear to be a purely biological process beyond the producer's control. However, one of the principal manifestations of technical change in crop production over the past 25 years has been the appearance of varieties with a range of harvest indices—that is, the ratio of grain to total biomass production (where biomass is the sum of grain and straw production). Because of this, farmers are now able to select varieties to produce grain and straw in the

The authors are, respectively, assistant professor in the Department of Agricultural Economics and Rural Sociology, Auburn University, and economist with the International Maize and Wheat Improvement Center (CIMMYT), Mexico.

We are grateful to Pat Wall for providing the original data used in the analysis. We also appreciate helpful comments on earlier drafts by Mitch Renkow, C. Robert Taylor, and two AJAE referees. The views expressed in this paper are those of the authors and are not to be attributed to CIMMYT. Journal Paper No. 1–933407 of the Alabama Agricultural Experiment Station, Project No. S 232 Ala 790.

Review coordinated by Richard Adams.

[1] McIntire et al. and Kelly et al. examine the importance of grain and fodder production for evaluating sorghum varieties.

Amer. J. Agr. Econ. 75 (November 1993): 981–989

proportions which maximize profit at the relative output prices that they face. The model we develop has important implications in providing a simple indicator of joint-product profitability that can be used to guide plant breeders in making varietal selections.

We examine the grain and straw production functions from three eras of varietal development—the pre-green revolution (prior to 1965), the green revolution (roughly 1965–75), and the post-green revolution (after 1975). The adoption of MVs of wheat has been more rapid and widespread than for other crops and now accounts for nearly 75% of the wheat area in developing countries. Yet traditional varieties (TVs) are still grown on 25% of the wheat area. This is something of a puzzle, because there is substantial evidence that yields of MVs are at least as high as those of traditional varieties across a wide range of input levels and production environments (Wall, McMahon, and Ranson; Parikh; Lipton, with Longhurst; Singh, Sharma, and Mishra). We believe a missing element in the analysis of adoption in many of these areas is the failure to consider the joint-product nature of wheat production. The paper shows the effect of the evolution of joint-product characteristics on the profitability of varietal adoption and on optimal nitrogen levels. Some preliminary evidence on varietal diffusion that is consistent with the model is also presented.

Varietal Technology in a Joint Product Framework

The standard treatment of the joint-product model with two outputs and one allocable factor of production, uses a product transformation function, $X = W(S,G)$, to express the joint-product technology (Beattie and Taylor, pp. 179–93). This transformation function is the locus of combinations of products S and G attainable at a given input level (X°). The optimal output combination for each input level is derived by maximizing revenue subject to a fixed level of input X°, and subject to the technical constraints embedded in the product transformation function. For product prices P_S and P_G, the Lagrangean function is

$$(1)\quad \max_{S,G} \quad \Phi = P_S S + P_G G + \Theta[X^{\circ} - W(S,G)].$$

Defining the rate of product transformation (RPT) as $RPT_{GS} = -dS/dG = W_G/W_S$, the marginal condition, or output expansion path is

$$(2)\quad -dS/dG = MPP_{XS}/MPP_{XG} = P_G/P_S.$$

Supply of each output, and therefore the optimal proportion of each product, is conditional on relative output prices, the quantity of the variable input being used, and technology parameters, $G^*(P_G/P_S,X)$ and $S^*(P_G/P_S,X)$.

A given crop variety presents a very restricted set of joint-production possibilities for grain (G) and straw (S) in which the production possibilities curves ($PPCs$) are single points. The expansion path is therefore independent of relative prices but will bend toward the axis of the more input-responsive output unless G and S have identical input response functions.

The technical change induced by varietal development may take either of two forms (figure 1). The first type of technical change occurs when a new variety (with straw-grain yield combinations represented by the B points) yields a similar quantity of total dry matter as existing variety A, but has a different harvest index. This adds another point to each PPC, transforming the single value $PPC's$ into a curve such as $S_A ABG_B$ in figure 1. The $PPC's$ are not smooth, but with the appearance of the new variety, the producer gains some choice in output proportions at each input level. For example, variety B is more profitable than A at "high" grain/straw price ratios.

The second form of varietal technical change occurs when a new variety C yields more of both outputs than existing variety A. Such a variety (points C in figure 1) effectively shifts the production possibilities frontier out to $S_C CG_C$ such

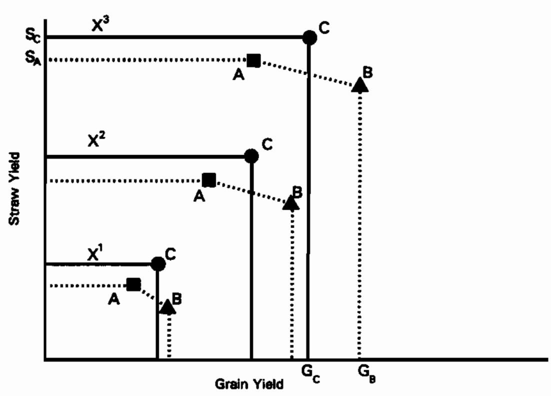

Figure 1. Two forms of varietal technical change

that variety A becomes obsolete, because it is less profitable at all output price combinations.[2]

Optimal Input Choices

Decision rules derived from the joint-product model differ from those arising from a model which assigns a zero value to crop byproducts. We first develop a model of varietal choice that focusses on the short-run adjustment to the disequilibrium caused by the appearance of a new production technology (Schultz). This is followed by analysis of the equilibrium level of nonvarietal inputs, X.

Varietal Choice

Assume that in the short run, the producer holds other inputs fixed at $X°$ while deciding whether to experiment with a new variety.[3] Under this assumption, the producer's objective function reduces to choosing the variety that maximizes total revenue at the existing input level. Let concave production functions for grain and straw production for each variety be denoted as $G_{TV}(X)$, $S_{TV}(X)$, $G_{MV}(X)$, and $S_{MV}(X)$, so that total revenue at $X°$ is

$$(3) \quad TR_{TV} = P_G G_{TV}(X°) + P_S S_{TV}(X°) \quad \text{if variety} = TV \text{ and}$$

$$TR_{MV} = P_G G_{MV}(X°) + P_S S_{MV}(X°) \quad \text{if variety} = MV.$$

The MV will be adopted only if $P_G G_{MV}(X°) + P_S S_{MV}(X°) > P_G G_{TV}(X°) + P_S S_{TV}(X°)$. This condition can be solved to give an expression defining the minimum output price ratio (P_G/P_S) required for adoption to occur. That is,

$$(4) \quad P_G/P_S > -\Delta S/\Delta G$$

where $\Delta S/\Delta G = [S_{MV}(X°) - S_{TV}(X°)]/[G_{MV}(X°) - G_{TV}(X°)]$. Equation (4) is the discrete analog to the marginal condition presented in (2) above. If TV and MV respond differently to input X, i.e. $G_{TV}(X) \neq G_{MV}(X)$ or $S_{TV}(X) \neq S_{MV}(X)$, the RPT will vary with the input level. The two important points are that the rate of product transformation is a more reliable indicator of the financial incentive to switch varieties than is the difference in grain yields alone; and that a low relative price of grain to straw may discourage MV adoption.[4]

A number of factors influence relative output prices. Straw prices will be high in livestock-intensive farming systems where seasonal fodder shortages occur due to long winters, dry seasons, etc. The grain-straw price ratio is also influenced by the costs of transportation, especially in isolated areas.[5] Furthermore, price ratios are sometimes distorted by food policies which hold grain prices down, but allow fodder prices to move freely (Morris, Belaid, and Byerlee).

Optimal Levels of Nonvarietal Inputs

Assume now that the varietal decision has been made, and joint-product criteria are being used to select the optimal input level. With a single nonallocable input, joint-product profit maximization occurs where

$$(5) \quad P_G G_X + P_S S_X - P_X = 0$$

where G_X and S_X denote first derivatives of the functions G and S.

Equation (5) can be solved to yield the profit maximizing level of X, $X^*(P_G, P_S, P_X)$. Contrary to the single product case, input demand need not be monotonically increasing in output prices, because $\delta X^*/\delta P_S = -S_X/(P_G G_{xx} + P_S S_{xx})$ will have the same sign as S_X. In the joint product case S_X can be either positive or negative within the input use range that is economically relevant, because the grain and straw production

[2] Variety A might still be preferred by risk-averse producers if the new variety is considered to be riskier.

[3] The view that farmers make input decisions sequentially has gained considerable recent support in the literature (Feder, Just, and Zilberman; Leathers and Smale; Byerlee and Hesse de Polanco). It is difficult to generalize about the time required to bring all inputs to their equilibrium levels, but adjustment has been observed to take as long as 15–25 years even in areas endowed with good infrastructure and extension services (Ali and Byerlee; Huffman, p. 71).

[4] This is a partial analysis of the costs of varietal change. The effect of costs of extra labor for harvesting, can be included by using field prices net of harvesting and transport costs for P_g, P_s, and P_x. In the longer run there may be other adjustment costs that are not considered here such as investment in irrigation which becomes profitable with MV adoption. Likewise, there may be longer run benefits that are not considered such as increased cropping intensity made possible by earlier maturing MVs.

[5] In equilibrium, prices in two regions will differ by T, the cost of transportation and handling. Assuming that $P_g > P_s$, the price ratio in a remote food deficit region is a decreasing function of T; $P_g/P_s > (P_g + T)/(P_s + T)$. For example, if transportation costs are equal to 20% of P_g ($P_g + T = 1.2P_g$), a price ratio of 6.0 in the exporting region would fall to 3.2 in the remote region. The decrease in the price ratio will be even sharper if the greater bulk of straw causes its handling cost to exceed that of grain.

functions may have different shapes. It will be profitable to apply additional input even if straw output is reduced, if grain response is strong enough. In other words, in the area around X^*, it is possible that the marginal value product of nitrogen in grain production might be great enough to offset the negative straw marginal value product. Input demand will always be less elastic ($\eta = P_X/(P_G G_{xx} + P_S S_{xx})X$) when straw has a non-zero price.

Response Function Estimation and Hypothesis Tests

The improved input responsiveness of the MV's measured in terms of grain yield has been recognized in the literature which discusses the development and diffusion of modern varieties (Lipton with Longhurst). The central proposition of this paper is that this discussion needs to be broadened to include straw response. We test two hypotheses; (1) that output (grain or straw) without nitrogen is the same for the MV's as for the TV and (2) that nitrogen response is equal for the TV and the MV's for both grain and straw yield.

Data for the analysis are taken from variety by nitrogen experiments on irrigated wheat conducted by the International Maize and Wheat Improvement Center (CIMMYT) in 1979, 1980, and 1981 in northwest Mexico (Wall, McMahon, and Ransom). Varieties from three technological eras are used in the analysis. Yaqui 50 (referred to hereafter as TV) is a pre-green revolution tall variety released in 1950. Siete Cerros 66 (MV_1) is the major green revolution variety that, along with sister varieties, was planted on some 13 million ha worldwide in the early 1970s. The third line, Veery (MV_2), is a group of post-green revolution varieties based on a single cross which are now grown on more than 4 million ha in the developing world. Both MV_1 and MV_2 are semi-dwarf varieties. TV and MV_1 were grown in all trial years, while MV_2 was grown only in 1980 and 1981. The trials used five nitrogen levels in 1979 and 1980; 0, 75, 150, 225, and 300 kg/ha; and four levels in the 1981; 0, 80, 160, and 240 kg/ha. Other nutrients were applied in nonlimiting amounts.

Several recent studies have compared the performance of linear response and plateau (LRP) models and traditional differentiable functional forms (Ackello-Ogutu, Paris, and Williams). Neither approach has established a clear dominance over the other on theoretical or empirical grounds (Swanson; Tronstad and Taylor). We use a three-halves function to model input response since it allows nested tests of hypotheses concerning the evolution of varietal technologies, while the LRP would require nonnested tests with the associated inference problems (Judge et al., p. 889).

The polynomial specification in equation (6) was estimated for grain and straw yield by OLS.[6]

$$(6)\quad Y_j = \xi + \beta_{j1}X + \beta_{j2}X^{1.5} + \beta_{j3}D_1 + \beta_{j4}D_1X + \beta_{j5}D_1X^{1.5} + \beta_{j6}D_2 + \beta_{j7}D_2X + \beta_{j8}D_2X^{1.5} + \beta_{j9}D_3 + \beta_{j10}D_4 + \epsilon$$

Y_j = yield in kg/ha (j = 1 for grain, 2 for straw)
X = nitrogen in kg/ha
D_1 = 1 if MV_1, = 0 otherwise
D_2 = 1 if MV_2, = 0 otherwise
D_3 = 1 if trial conducted in 1980, = 0 otherwise
D_4 = 1 if trial conducted in 1981, = 0 otherwise

The plot of the predicted response functions for grain (figure 2a) shows that the yield of TV, MV_1, and MV_2 are similar at $X = 0$. Neither of the dummy intercept coefficients in the response function for grain is significantly different from zero (table 1). On the other hand, both MV_1 and MV_2 yield significantly less straw than TV at $X = 0$ (figure 2b, table 1). The hypotheses of equal grain response to nitrogen between TV and MV_1 and between TV and MV_2 are both rejected (table 2). Equal straw response to nitrogen for TV and MV_1 is not rejected, but equality between TV and MV_2 in straw response is rejected.

It is clear that wheat varietal technology has continued to evolve since the green revolution, but both the magnitude and the nature of the realized improvement have changed. The first modern varieties provided a grain yield advantage of 35% over the TVs at 75 kg/ha of nitrogen. By contrast, the difference between MV_1 and MV_2 was only 10%, which nonetheless represents a 500 kg/ha increase in grain yield potential. Our analysis supports previous studies which have found that the grain yield of the MVs is no worse than the TV at any nitrogen level and considerably better at most levels because of their strong nitrogen response. The TV produces more straw than MV_1 at all input levels,

[6] Contemporaneous correlation between errors of the grain and straw yield equations was tested and rejected at the 10% level using a Lagrange multiplier (LM) test (Judge et al., p. 476). Also Bartlett's test (Judge et al., p. 448) failed to reject the null hypothesis of homogeneity of variances at the 10% level for either the grain or the straw response model.

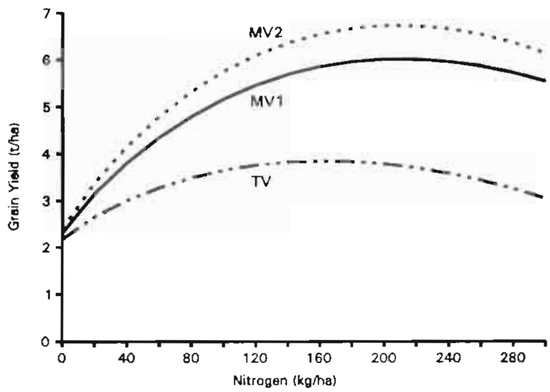

Figure 2a. Predicted grain response to nitrogen

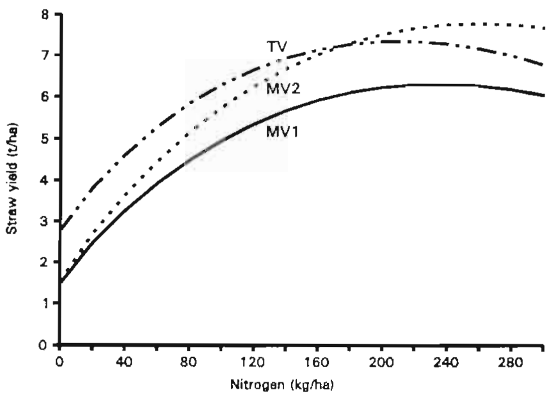

Figure 2b. Predicted straw response to nitrogen

Table 1. Estimates of Parameters of Response Function for Grain and Straw Yields of Wheat, Northwest Mexico

	Grain yield (kg/ha)	Straw yield (kg/ha)
X	30.8	65.1
	(5.15)***	(6.41)***
$X^{1.5}$	−1.61	−2.99
	(−4.69)***	(−5.12)***
D_1	139.4	−1304.7
	(0.44)	(−2.40)**
D_1X	21.98	−3.23
	(2.60)**	(−0.23)
$D_1X^{1.5}$	−0.82	0.30
	(−1.68)	(0.36)
D_2	216.4	−1258.3
	(0.66)	(−2.27)**
D_2X	31.7	7.1
	(3.62)***	(0.48)
$D_2X^{1.5}$	−1.28	0.01
	(−2.50)**	(0.01)
D_{80}[a]	−675.1	1233.7
	(−3.88)***	(4.18)***
D_{81}[b]	461.97	1601.4
	(2.53)**	(5.18)***
Intercept	2175.3	2774.4
	(8.71)***	(6.55)***
R-Squared	0.96	0.93
Observations	41	41

Note: Figures in parenthesis below coefficients are t-statistics.
*, **, and *** indicate significance at 10%, 5% and 1% level, respectively (two-tail test).
[a] Dummy variable for trials conducted in 1980
[b] Dummy variable for trials conducted in 1981

but has a much smaller straw yield advantage over MV_2, and actually produces less straw than MV_2 at high (above 175 kg/ha) nitrogen levels.

In summary, the green revolution was realized through a breakthrough in partitioning of biomass—increases in the amount of grain produced at nearly all nitrogen levels—but only by sacrificing straw production. Increased yield potential in the post-green revolution era, on the other hand, has evolved largely through a breakthrough in conversion efficiency—more total biomass is produced for a given nitrogen input.

Production Possibilities

An empirical measure of the rate of product transformation that can be achieved by switching varieties was derived by using the response functions to compare grain and straw yield of TV to the yields of each MV at several nitrogen levels (figures 3a and 3b). Figure 3a represents the PPC's at the beginning of the green revolution period, when producers were deciding whether to plant a tall variety or a first-generation modern variety. Figure 3b shows the joint-product possibilities in the post-green revolution period, representing the choice facing producers who rejected the first modern varieties (MV_1), but who gained access to a Veery variety (MV_2) in the 1980s.

At $X = 0$, MV_1 is more profitable than TV only at a grain-straw price ratio above 9.4. MV_2 is more profitable than TV when grain sells for more than 5.8 times the price of straw. The price ratio required for each MV to dominate TV falls as the nitrogen level increases, reflecting the fact that MV grain response to nitrogen is greater than that of TV. MV_2 was found to produce more total revenue than MV_1 at all price ratios (i.e. produces more of both products at all nitrogen levels). This suggests that MV_2 will replace MV_1

Table 2. Results of Hypothesis Testing

Null Hypothesis	Parameter restriction	Test statistic
TV and MV_1:		
Equal grain yield at $N = 0$	$\beta_{13} = 0$	$t = 0.44$[b]
Equal grain yield response to N	$\beta_{14} = \beta_{15} = 0$	$F = 15.56$[a]
Equal straw yield at $N = 0$	$\beta_{23} = 0$	$t = -2.40$[a]
Equal straw yield response to N	$\beta_{24} = \beta_{25} = 0$	$F = 0.33$[b]
TV and MV_2:		
Equal grain yield at $N = 0$	$\beta_{16} = 0$	$t = 0.67$[b]
Equal grain yield response to N	$\beta_{17} = \beta_{18} = 0$	$F = 23.90$[a]
Equal straw yield at $N = 0$	$\beta_{26} = 0$	$t = -2.27$[a]
Equal straw yield response to N	$\beta_{27} = \beta_{28} = 0$	$F = 3.60$[a]

[a] Reject H_0 at 5% significance level
[b] Fail to reject H_0 at 5% significance level

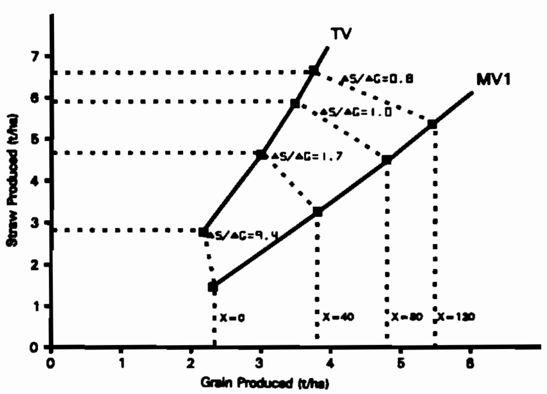

Figure 3a. Production possibilities curves facing producers during the Green Revolution period

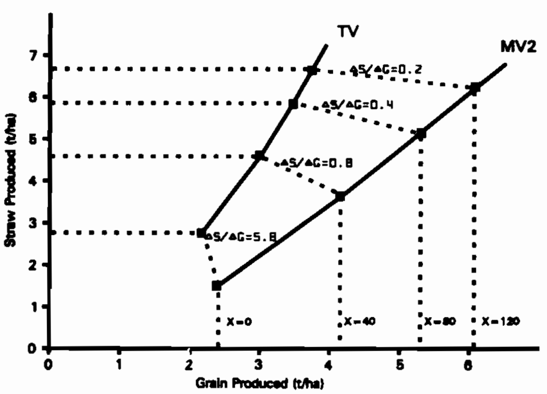

Figure 3b. Production possibilities curves facing producers during the post-Green Revolution period

regardless of nitrogen level or relative output prices, in all areas. Conceivably, however, TV may remain superior to MV_2 in a few areas where straw is very highly valued and input use is low.

Two other important characteristics associated with the modern varieties are high grain test weight and stiff straw that resists lodging. Market discounts of 10%–20% are common for the coarser MV grain (Lipton with Longhurst, p. 49), while the less digestible straw has been reported to sell at a discount of as much as 50% (Whiteman, p. 55). These price differences have a large effect on varietal choice.

Figure 4 shows the combinations of grain-straw price ratios and nitrogen application levels at which the revenue from each MV would exceed that of the TV when the prices of both MV products are discounted by 15%. When either nitrogen application is low, or the relative grain price is low, the TV will dominate the MVs (unshaded area of figure 4). From the diagram it is clear that notably higher relative grain prices are required for the MV's to be superior to the tall variety in total revenue when price discounts on MV products prevail. In fact, for a grain-to-straw price ratio below 3.5, the green revolution variety would produce more revenue only at nitrogen application rates exceeding 80 kg/ha—an application rate above that used by most farmers in the developing world.

Optimal Nitrogen Levels

The comparative static results suggested that, depending on the parameters of the straw response function, the optimal nitrogen level might

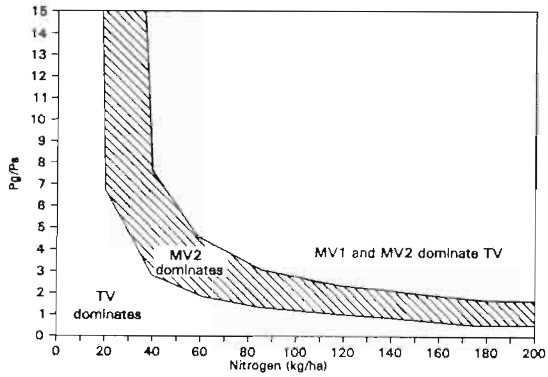

Figure 4. Combinations of relative output prices and nitrogen levels at which MV_1 and MV_2 produce more revenue than TV (price discounts on MV products assumed)

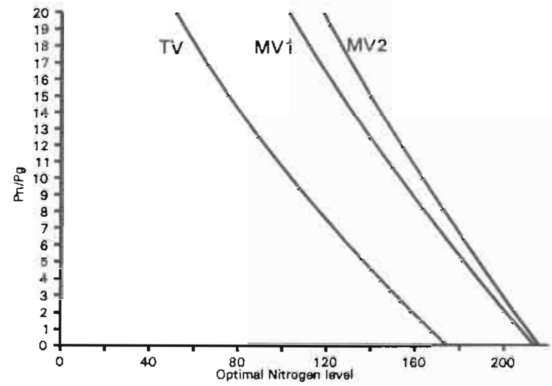

Figure 5. Derived demand for nitrogen with Pg/Ps = 5

be either overestimated or underestimated if straw values are ignored. For each variety i, the straw and grain response functions estimated above can be written as, $S_i(X) = \alpha + \gamma_1 X + \gamma_2 X^{1.5}$, and $G_i(X) = a + b_1 X + b_2 X^{1.5}$. For relative prices $P_G/P_S = \Theta$, and $P_G/P_X = \rho$, the derived demand function for nitrogen is

$$(7) \quad X_i^*(P_G/P_S, P_X) = [(\Theta - b_1 - \gamma_1/\rho)/1.5(b_2 + \gamma_2/\rho)]^2.$$

The derived demand curves[7] for each variety are traced in figure 5 for a grain-straw price ratio of five. Assigning a zero price to straw reduces demand for nitrogen by approximately 20% for TV and by 10% for MV_1 and MV_2.

Since the adoption of green revolution variety MV_1, the amount of nitrogen applied to wheat by third world farmers has increased almost linearly over time (CIMMYT 1989). This increase is most likely explained by improved infrastructure for fertilizer distribution, stronger price incentives and improvements in allocative efficiency over time as farmers adjust to the new equilibrium, rather than to adoption of newer varieties with increased responsiveness to nitrogen. The introduction of MV_1 caused the optimal nitrogen rate to increase by some 30–40 percent from the TV optimum. Since the introduction of MV_1 however, the economic optimum has only increased by approximately 5 percent.[8] This differs from the finding of Hayami and Ruttan (1985, p.294) who attribute increased nitrogen use on rice in Asia to the release of increasingly responsive varieties.

Adoption of MVs in Mountainous Areas of South Asia

Straw prices are determined in local markets due to the high transportation and handling costs associated with the bulky product and therefore vary substantially in space and time. Thus data on straw prices are usually not available from official sources and a rigorous econometric test of the adoption implications of the model is not possible. However some evidence is available from surveys conducted in South Asia which document an interregional variation in the rate and time of adoption of MVs of wheat that is consistent with the model.

First generation MVs diffused rapidly in the irrigated plains of India and Pakistan where the grain price averaged between 10 and 20 times the straw price (Byerlee and Iqbal; Sidhu and Byerlee). Adoption occurred despite warnings by some concerning the implications for straw yields. Farmers in these regions also generally adopted MVs concurrently with a modest dose of fertilizer, averaging about 40 kg/ha of nitrogen (e.g., Lowdermilk). This combination of prices and nitrogen levels was sufficient to ensure that the first generation of MVs were more

[7] The curves represent upper bounds on per hectare nitrogen demand since they are estimated with data from controlled experiments and do not consider discounts for risk aversion or interaction with other management practices.

[8] The yield-maximizing nitrogen level is the same for MV_1 and MV_2.

profitable than the TVs, even in the presence of price discounts for grain and straw quality.[9]

The irrigated mountain valleys of northern Pakistan demonstrated a very different pattern of MV acceptance. Diffusion of first generation MVs stagnated at a low ceiling[10] even after two decades of extension efforts to encourage adoption and in spite of experimental evidence showing that increases in grain yields on the order of 40% could be attained with the MVs (Whiteman). The grain yield advantage of the MVs was very similar to that experienced in the irrigated plains, but the grain/straw price ratio was much lower in the mountain valleys because of long winters and high transport costs due to physical isolation. Pakistan's policy of maintaining uniform national grain prices through food subsidies also worked to suppress the relative price of grain. Three surveys in Northern Pakistan from the mid 1980s all report grain-straw price ratios in the range from 2 to 3.75 (Whiteman, p. 55; Hussain, p. 60; Ahmad et al. 1990, p.32). Both Hussain and Whiteman report the low quantity and quality of MV straw as one reason frequently mentioned by farmers for rejecting MVs.

In 1985, the variety Pak 81, which is based on the post-green revolution cross, Veery, was tested in an irrigated mountain valley of northern Pakistan. By 1989, three years after seed was first made available, Ahmad et al. reported that 24% of farmers had adopted the variety. Ahmad et al. also report that crop cuts taken in farmers' fields showed that Pak 81 gave higher grain and straw yields than the TV that it was replacing. Because the new variety yielded more of both products, the low grain-straw price ratio has not served as barrier to adoption.

The experience in South Asia supports the implications of the joint-product model. The first generation varieties which diffused rapidly in areas with high grain-straw price ratios were rejected in areas with lower price ratios even though agronomic performance was similar in both areas. On the other hand, once the next generation of post-green revolution varieties became available they diffused quickly. With newer generations of improved varieties and increasing levels of fertilizer use by farmers, the conditions are now more favorable for adoption of MVs in those areas where adoption has lagged until recently.

Conclusions

In this paper, we have analyzed crop production decisions using a model of joint-products with nonallocable inputs. The model shows that with input levels fixed in the short run, varietal adoption depends on relative prices of grain and straw and on input use. The minimum relative grain price at which two wheat varieties, representing different eras of technological change, would be adopted was estimated. The evolution of the nitrogen response function was also analyzed.

Although data on straw prices in other developing countries is spotty, model results are consistent with MV adoption patterns observed in South Asia. We suspect that joint-product characteristics may explain lagging MV adoption in a wide variety of settings since grain-straw price ratios on the order of two or less are not uncommon (Morris, Belaid and Byerlee, 1989). In some cases, such as in Egypt in the 1970s, this results from policies which distort the relative prices of grain and livestock products, suggesting that the grain-to-straw price ratio can be low even in areas with good infrastructure (Cuddity).

Acceptance of MVs has been slowest in low rainfall areas, where the grain yield advantage of MVs is modest and where fodder prices often exceed grain prices in dry years (Kelley, Rao, and Walker). Thus the evaluation of varietal releases for low rainfall areas in terms of both grain and straw production is likely to be especially important. The grain-straw RPT is an easily calculated indicator that can be used by breeders and extension personnel when screening varieties for these areas.

Griliches (1980), and Jansen, Walker, and Barker suggest that ceiling diffusion levels encountered by "first generation" varieties can be increased as plant breeders release a wider range of varieties to fit production zones where the initial releases were not accepted. Evidence presented here suggests that the number of production zones in which TVs remain more profitable than MVs should continue to fall, as the new MVs replace both TVs and earlier generation MVs in more marginal environments. Diffusion of these post-green revolution varieties will, however, have a much more modest impact on

[9] RPTs estimated with data reported in Sharma et al. (pp 99–100) for India suggest that first generation MVs would be more profitable than TVs at grain-straw price ratios greater than six. This agrees closely with the calculations which we have presented using data from Mexico. In addition, the earlier maturity of the MV's facilitated double cropping in India.

[10] Adoption occurred mostly in areas where the earlier maturity of MV_1 facilitated double cropping. In areas where double cropping was already the norm, adoption of MV_1 was minimal (Hussain).

aggregate grain production and on fertilizer demand than did the diffusion of the green revolution varieties two decades ago.

[Received April 1992; final revision received January 1993.]

References

Ackello-Ogutu, C., Q. Paris, and W. A. Williams. "Testing a von Liebig Crop Response Function Against Polynomial Specifications." *Amer. J. Agr. Econ.* 67(November 1985):873–80.

Ali, M., and D. Byerlee. "Economic Efficiency of Small Farmers in a Changing World: A Survey of Recent Evidence." *J. Int. Develop.* 3:1(January 1991)1–27.

Ahmad, Z., K. A. Tetlay, C. Asghar, and J. Longmire. *Wheat Technologies and the Impact of AKRSP Wheat Development in the Double Cropping Zone of Gilgit, 1988–89.* PARC/CIMMYT Paper 90–6, Islamabad, 1990.

Beattie, B. R., and C. R. Taylor. *The Economics of Production.* New York: John Wiley & Sons, 1985.

Byerlee, D., and M. Iqbal. "Recent Trends and Variability in Prices of Selected Crop and Livestock Products in Pakistan." *Pak. J. Agr. Social Sci.* 1(April 1987):158–68.

Byerlee, D., and E. Hesse de Polanco. "Farmers' Stepwise Adoption of Technological Packages: Evidence From the Mexican Altiplano." *Amer. J. Agr. Econ.* 68(August 1986):519–27.

CIMMYT. *1987–88 CIMMYT World Wheat Facts and Trends. The Wheat Revolution Revisited: Recent Trends and Future Challenges.* Mexico, D.F.: CIMMYT, 1989.

Cuddihy, W. *Agricultural Price Management in Egypt.* World Bank Staff Paper No. 388, Washington, D.C.: The World Bank, 1980.

Feder, G. "Farm Size, Risk Aversion and the Adoption of New Technology Under Uncertainty." *Oxford Econ. Papers*, 32(July 1980):263–83.

Feder G., R. E. Just, and D. Zilberman. "Adoption of Agricultural Innovations in Developing Countries: A Survey." *Econ. Develop. and Cultur. Change* 33(January 1985):255–98

Griliches, Z. "Hybrid Corn: An Exploration in the Economics of Technological Change." *Econometrica* 25(October 1957):501–22.

——. "Hybrid Corn Revisited: A Reply." *Econometrica*, 48(September 1980):1463–65.

Hayami, Y., and Ruttan, V. W. *Agricultural Development: An International Perspective.* Baltimore: Johns Hopkins University Press, 1985.

Heibert, L. D. "Risk, Learning, and the Adoption of Fertilizer Responsive Seed Varieties." *Amer. J. Agr. Econ.* 56(November 1974):764–68.

Huffman, W. E. "Allocative Efficiency: The Role of Human Capital." *Quart. J. Econ.* 91(February 1977):59–79.

Hussain, T. *Wheat in the High Mountain Valleys of Gilgit.* Rural Sciences Research Programme Report No. 2. Gilgit, Pakistan: Agha Khan Rural Support Programme, 1986.

Jansen, H. G. P., T. S. Walker, and R. Barker. "Adoption Ceilings and Modern Coarse Cereal Cultivars in India." *Amer. J. Agr. Econ.* 72(August 1990):653–63.

Judge, G. G., W. E. Griffiths, R. C. Hill, H. Lütkepohl, and T. Lee. *The Theory and Practice of Econometrics.* New York: John Wiley and Sons, 1985.

Kelly, T. G., P. Parthasarathy Rao, and T. S. Walker. *The Relative Value of Cereal Straw Fodder in the Semi-Arid Tropics of India.* Econ. Progress Report No. 105. Patancheru, India: ICRISAT, 1991.

Leathers, H. D., and M. Smale. "A Bayesian Approach to Explaining Sequential Adoption of Components of a Technological Package." *Amer. J. Agr. Econ.* 73:3(August 1990):734–42.

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

Lowdermilk, M. K. "Diffusion of Dwarf Wheat Technology in Pakistan's Punjab." Ph.D. thesis, Cornell University, 1972.

McIntire, J., J. D. Reed, A. Tedla, S. Jutzi, and U. Kebede. "Evaluating Sorghum Cultivars for Grain and Straw Yield." *Plant Breeding and the Nutritive Value of Crop Residues.* J. D. Reed, B. S. Cappes, and P. J. H. Neater, (eds) pp. 282–302. Addis Ababa: ILCA, 1988.

Morris, M. L., A. Belaid, and D. Byerlee. *1990–91 CIMMYT World Wheat Facts and Trends: Wheat and Barley Production in Rainfed Marginal Environments of the Developing World.* Mexico, D.F.: CIMMYT, 1991.

Schultz, T. W. "The Value of the Ability to Deal with Disequilibria." *J. Econ. Lit.* 13(September 1975):827–46.

Sharma, K. C., R. D. Misra, B. C. Wright, and B. A. Krantz. "Response of Some Dwarf and Tall Wheats to Nitrogen." *Indian J. Agron.* 15(June 1970):97–105.

Sidhu, D. S., and D. Byerlee. *Technical Change and Productivity in Wheat in the Indian Punjab in the Post-Green Revolution Period.* CIMMYT Economics Working Paper, Mexico DF, 1992.

Singh, I. J., K. C. Sharma, and J. P. Mishra. "Production Functions for the New Dwarf Wheats." *Indian J. Agr. Econ.* 25(1976):74–81.

Swanson, R. E. "The Static Theory of the Firm and Three Laws of Plant Growth." *Soil Sci.* 88(May 1963):338–43.

Tronstad, R., and C. R. Taylor. "An Economic and Statistical Evaluation of Functional Forms and Estimation Procedures of Crop Yield Response to Primary Plant Nutrients." Dep. Agr. Econ., University of Illinois, 1989.

Wall, P. C., M. A. McMahon, and J. K. Ransom. "Do Semi-Dwarf Wheats Require More Nitrogen Than Traditional Tall Varieties?" Paper presented to American Society of Agronomy, 26–30 November, 1984, Las Vegas, Nevada.

Whiteman, P. T. S. *Mountain Oases. A Technical Report of Agricultural Studies in the Hunza, Ishkoman and Yasin Valleys of Gilgit District.* FAO/UNDP, PAK 80/009. Gilgit: Dept. of Agr./Integrated Rural Development Project, 1984.