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George E. Battese, Hina Nazli and Melinda Smale[1]

ABSTRACT

HarvestPlus seeks to select one or more wheat varieties in Pakistan to biofortify with zinc to improve the health of the Pakistani population, especially women and children. The choice of varieties to enrich, and their diffusion patterns, will influence the productivity and efficiency of wheat production. This analysis seeks to (1) compare the relative productivity and efficiency of farmers currently growing the most widely diffused wheat varieties, and (2) update our understanding of factors that influence productivity and efficiency of wheat production. We estimate a stochastic production function model with data from a survey of wheat farmers conducted in Punjab, Pakistan, in 2011. We find no differences in technical inefficiency effects associated with farmers growing the top four varieties, either alone or in combination with other varieties. With respect to human capital, older farmers tend to be more technically inefficient than younger farmers, but education has no statistical significance. Wheat farmers with access to extension advice are more efficient. Smaller-scale farmers and those in the mixed production zone tend to be more technically inefficient. Later adopters were not less efficient than earlier adopters, but time to varietal change is negatively related to the efficiency of wheat production. Farmers growing wheat in the rice-wheat and cotton-wheat zones tend to be less productive (but more efficient) than farmers from the mixed zone. Finally, farmers whose land suffered from severe salinity or severe toxicity are less productive and efficient than other farmers.

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CONTENTS

I. INTRODUCTION

Farmers in the Indus River basin of the Punjab have supplied the bread of the Asian subcontinent since ancient times. During the 1960s, public investments in restoring irrigation canals and market infrastructure, combined with the rapid diffusion of semi-dwarf varieties of wheat, spurred the social and economic transformation that became known as the Green Revolution. In the irrigated areas of Punjab, the synergies of fertilizer-responsive varieties, good soils, and adequate moisture led to "a quantum leap in wheat yields" (Pal and Byerlee, 2006). Through expanding the demand for farm labor and lowering the price of wheat, technical change generated welfare benefits for poor people beyond the adopting farmers in the Punjab (see Hazell, 2010; and Otsuka and Larson, 2013).

Despite the productivity gains documented in a body of research spanning decades, large numbers of Pakistanis continue to live in poverty. Today, malnutrition and its components, such as micronutrient deficiencies, are better understood. In Pakistan, zinc deficiency is prevalent and is particularly severe among women and children. Zinc is crucial for resistance to disease, control of diabetes, healing of wounds, digestion, reproduction, and physical growth. One way to reduce this zinc deficiency in the Pakistani population is to introduce higher zinc content into wheat, the dominant food staple. To reach poorer people in remote rural areas who do not have access to zinc-enriched food or zinc supplements, the Government of Pakistan in association with HarvestPlus aims to introduce one or more high-zinc biofortified wheat varieties by 2016.

The analysis presented here is intended to support decision making by wheat scientists working to introduce high-zinc wheat varieties. We hypothesize that the varieties selected for biofortification, and the speed of varietal adoption and replacement, will affect the productivity and efficiency of wheat production. To test these hypotheses, we apply stochastic frontier analysis (SFA) to data collected from a survey of wheat farmers in Punjab, Pakistan, in 2011. In our multivariate modeling framework, given the historical context of the Green Revolution and its aftermath, we also examine the significance of production zone, farm size, soil characteristics, and wheat growers' access to extension services and human capital (age and education). Our statistical aim is to (1) compare the productivity and technical efficiency of wheat production among farmers growing the most popular wheat varieties at the time of the survey; and, (2) identify and compare the factors influencing productivity and efficiency.

Maintaining wheat productivity (output relative to inputs) and the efficiency of wheat production (actual output relative to potential output) in Pakistan's Punjab has been a policy priority and a focus of applied research over the decades. A longstanding concern about the inequitable distribution of land, reinforced by the perception that the Green Revolution generated greater benefits for larger-scale farmers, prompted analysts to test the effects of landholding size on the efficiency of wheat production. Applying the profit function approach developed by Lau and Yotopoulos (1972), Khan and Maki (1979) found that larger farms were more efficient than smaller farms in both Punjab and Sindh provinces, in contrast to findings reported for India's Punjab (Yotopoulos and Lau, 1973). We test this recurring hypothesis once again.

Despite a dynamic wheat breeding program, the slow rate of varietal replacement by farmers has posed a major challenge in promoting new wheat varieties in Pakistan (e.g., Heisey, 1990; Farooq and Iqbal, 2000; Khan, Morgan and Sofranko, 1989). During the post-Green Revolution period in the Indian Punjab, slow varietal change appears to have offset the positive productivity effects of diversifying the genetic base in wheat breeding (Smale et al., 2008). As a consequence of these findings, we investigate the possible effects of both the number of years from variety release to adoption and the number of years growing a variety on wheat production efficiency.

By the early 1990s, evidence was also accumulating that farmers in the irrigated areas of Punjab were beset with stagnating yields (Byerlee and Siddiq, 1994). In their analysis of total factor productivity, conducted with district-wide data from 1971 to 1994, Ali and Byerlee (2002) concluded that degraded soils and declining water quality had reduced annual productivity growth significantly, especially in the rice-wheat zone. Murgai, Ali and Byerlee (2001) found evidence of resource degradation in both Punjab provinces in India and Pakistan. Motivated by these findings and recent papers that recommend inclusion of soil characteristics to reduce potential bias in estimated parameters (Sherlund et al. 2002; Chavas 2011; Mancino 2012), we test the effects of severe salinity and toxicity on wheat production.

In the next section, we define terms and summarize previous studies that served as the foundation for our approach. The data source is described in Section III. Section IV presents contextual information and descriptive statistics that motivated the structure of the econometric analysis. Section V summarizes the essential features of the stochastic frontier production model, together with the specification of the econometric models and definitions of the variables involved. The empirical estimates and test results are reported and interpreted in Section VI. The final section of the paper draws conclusions and implications for agricultural policy and the biofortification interventions in Pakistan.

2. STUDY CONTEXT

In stochastic frontier analysis, productivity refers to production per unit of area grown of the crop, or yield, for given levels of inputs. Technical efficiency measures the closeness of realized production to potential production, given the technology and the levels of inputs used. Inefficiency effects in an SFA model are random variables associated with the differences between potential and actual levels of production, given the technology and the levels of inputs.

Landmark studies in the early 1990s applied SFA models to analyze how key policy-related factors, such as landholding size and tenure, provision of extension services, and farmer education, influenced the technical inefficiency of farm production in Pakistan. An analysis by Parikh, Ali and Shah (1995) showed that smaller farms and farms managed by more educated farmers were more cost-efficient in the wheat-based, mixed farming of Peshawar District of the Northwest Frontier Province (NWFP) (called the "Khyber Pakhtunkhwa" province since April 2010). Battese, Malik and Broca (1993) demonstrated the heterogeneity among rates of technical change and relative inefficiencies in wheat farming among four districts of Punjab, Sindh, and NWFP, based on panel data collected by the International Food Policy Research Institute (IFPRI).

Of particular relevance to our study is that the data analyzed by Battese, Malik and Broca (1993) indicated a retraction in the production frontier over time in Faisalabad District of irrigated Punjab. The authors rejected the "no technical inefficiency" hypothesis, explaining that farmers in irrigated Punjab had adopted the variety Mexipak and other leading semi-dwarf wheat varieties of the Green Revolution earlier than in other areas, but tended to re-use seed and change varieties slowly.

Wheat production in Pakistan has served as a "laboratory" for the advancement of applied statistical methods and estimation techniques. Employing the IFPRI panel data, Battese, Malik and Gill (1996) illustrated the advantages of the general, single-stage model (Battese and Coelli, 1993, 1995) compared with the two-stage, "residual" approach previously used by researchers. Battese and Broca (1997) compared translog and Cobb-Douglas specifications of production functions and three models for explaining technical inefficiencies, using data on wheat farming in Pakistan.

As they embark on a program to develop high-zinc wheat, scientists in Pakistan must choose suitable genetic backgrounds for those varieties. A simple algorithm for success is to choose the most popular wheat variety: the more popular the high-zinc varieties they develop, the more likely it is that their adoption will generate larger-scale, measurable health benefits. However, predicting popularity is not easy. As noted above, slow varietal change is a prominent feature of wheat-farming systems in Pakistan. Furthermore, negative externalities are potentially associated with the popularity of wheat varieties. Concentrating the wheat area with a few popular varieties can depress yield potential and aggravate the crop's vulnerability to plant disease, including endemic strains of wheat rust (Heisey et al., 1997).

In this study, we estimate SFA models involving four of the most popular wheat varieties for which we have sufficient sample data. Seher-06, which is currently the most popular variety, was released in 2006 and was rapidly adopted. Inqilab-91 was sown across a more extensive area than any other modern wheat variety in Pakistan, and is still widely grown. The other leading varieties are Bhakkar-02 and Faisalabad-08.

We include in our empirical models the effect of the length of the adoption lag (years from variety release until adoption by individual farmers) on the technical inefficiency of wheat farmers. Touching on the topic of wheat area concentration per farm, we also consider whether each popular variety is grown alone or in combination with other varieties. Consistent with earlier studies conducted during the Green Revolution, we estimate the effects of farm size, land tenure, education and access to extension services on the technical inefficiency of the wheat farmers. Reflecting more recent concerns about soil quality and consequences for SFA estimation, we include variables for the salinity and toxicity of soils. We test whether a production function model without inefficiency effects adequately reflects the data, and also whether the Cobb-Douglas functional form is an appropriate representation of the production technology.

3. DATA

The data are drawn from a survey of wheat farmers conducted by HarvestPlus and Innovative Development Strategies (IDS) during the months of October and November 2011 in Punjab, the largest province of Pakistan. Over three-quarters (76 percent) of Pakistan's wheat area is located in Punjab Province (Government of Pakistan, 2011). The sample of wheat farmers was selected from 93 villages, located in 23 districts of three agro-climatic zones (cotton-wheat, rice-wheat, and mixed).

A stratified two-stage (unequal size) cluster design was used to select the sample farmers. The three wheat production zones represented the strata or first-stage sampling unit. The second-stage sampling unit was the *mouza*, known as a "revenue village". The *mouzas* were allocated proportionately across the agro-climatic zones based on the share of the zone in the total area sown with wheat. A systematic probability-proportionate-to-estimated-size approach was used to select *mouzas* within each agro-climatic zone using secondary data on each *mouza*'s population size (total number of households).

After the *mouzas* were selected in the first stage and wheat-growing households listed, sample households were selected at random within each village. From previous surveys and research conducted in Pakistan, the non-response rate was estimated at 33 percent for interviews conducted at the second-stage selection. Our study took this rate into account and prescribed that six spare households be selected within each *mouza*. A total of 18 households were selected in each *mouza*, of which 12 were interviewed. Figure 1 shows the locations of the selected *mouzas*. A total of 1,116 wheat farmers were interviewed in the sample survey. In the overall sample, about 32 percent of the farmers were located in the rice-wheat zone, compared with about 41 percent in the cotton-wheat zone and 27 percent in the mixed zone.

The suffix of a wheat variety's name indicates the year of release. However, for the remainder of the paper, we drop the suffixes after the first mention in order to simplify presentation.

Figure 1: Map showing the locations of the selected *mouzas* [a]

[a]Red spots indicate the locations of the selected *mouzas*. Source: HarvestPlus

4. POPULAR WHEAT VARIETIES IN PAKISTAN

Wheat research records in the Asian subcontinent date back to 1905. The Punjab Department of Agriculture and the Punjab Agricultural College and Research Institute at Lyallpur (now Faisalabad) were established in 1905 and 1906, respectively (Akhtar et al., 2010). For the years 1911–2008, Akhtar et al. (2010) list over 70 important varieties that were released by the program (before partition, there was one program for the region that is now India and Pakistan). All of the wheat varieties bred before the early 1960s were tall in stature, and only minor yield gains were achieved by plant breeding programs. Mexipak, the semi-dwarf variety that "launched the Green Revolution in Pakistan," was released in 1965 (Akhtar et al., 2010: 130) and, by 1968, covered 60 percent of the irrigated wheat area in the country, only to succumb shortly thereafter to rust disease (Khan, 2010).

In general, the rust diseases of wheat limit the field life of varieties in Pakistan, but farmers often continue to grow popular varieties even when they become susceptible and are no longer recommended for cultivation. Wheat data obtained from national research institutes showed that Mexipak was still grown as late as 1990, despite its susceptibility to rust (Smale et al., 2002). Advances in breeding genetic resistance to wheat rusts have also extended the longevity of varieties in farmers' fields. These include methods for stacking multiple sources of genetic resistance in one cultivar. For example, Inqilab was grown on over 70 percent of the wheat area for 13 years, and on nearly half of Punjab in 2007/08. Seher replaced Inqilab as the most popular variety within a few years of its release. By 2011, Seher was grown across 43 percent of the wheat area in Punjab (Government of Punjab, 2011).

The 2011 HarvestPlus-IDS survey confirmed Seher as the most popular variety in the irrigated Punjab, planted by 67 percent of the sample farmers in over 55 percent of the wheat area involved. Inqilab was also still popular, covering 16 percent of the wheat area. Other common varieties were Watan-93, Bhakhar, and Faisalabad, occupying 8 percent, 7 percent, and 3 percent, respectively, of the wheat area (Figure 2). In fact, Watan was never officially released by the national wheat program.

Over two-thirds (71.3 percent) of the farmers grew only one variety, and so slightly under one-third (28.7 percent) of the farmers surveyed grew more than one variety, although a mere 6 percent grew more than two varieties. When grouped according to whether they grew one or multiple varieties of wheat, Seher and Inqilab remained the most popular varieties. The proportion of farmers growing multiple varieties was higher for non-popular varieties such as Faisalabad, AS-2002, Shafaq-06, and Lasani-08.

The data shown in Figure 2 and Table 1 demonstrate clearly that Seher and Inqilab were the most popular varieties grown by the sample farmers. The percentages of wheat farmers who grew a single variety appear to decline with the popularity of varieties, and are smallest for Lasani and the category that combines other less popular varieties.

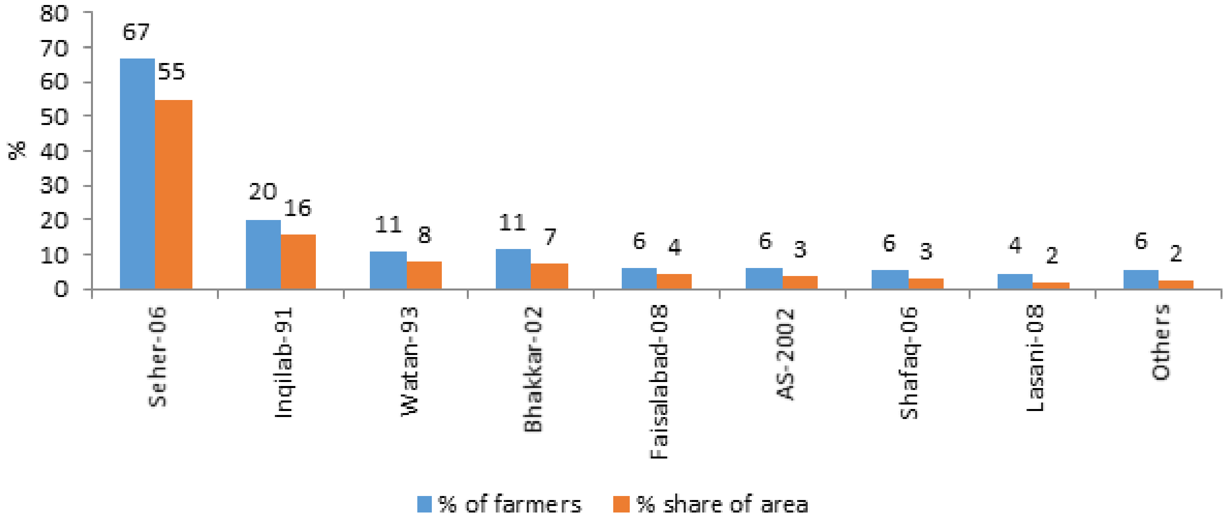

Figure 2: Percentage distributions of wheat area and wheat farmers by variety[a]

[a]The percentages for farmers growing the different wheat varieties do not add up to 100 because some farmers grew more than one variety.
Source: Authors

Table 2 reports the distributions of single- and multiple-variety farmers by agro-climatic zones and farm sizes. Following the standard classification used in Pakistan, we group farmers into four categories based on the area of their cultivated land: *marginal* (acres ≤ 5); *small* (5 < acres ≤ 12.5); *medium* (12.5 < acres ≤ 25); and *large* (acres > 25).

More than two-thirds of the wheat farmers (70.8 percent) belong to the marginal- and small-farm categories (35.1 percent and 35.7 percent, respectively). About 18 percent of the farmers are medium-scale and 12 percent are large-scale.

Overall, about 71 percent of all sample farmers grew only one variety of wheat, whereas the percentages of marginal, small, medium and large farmers who grew one variety were about 90, 71, 55 and 39, respectively. The percentages of marginal and small farmers who grew a single variety are quite consistent across the different zones. However, the distributions of medium and large farmers who grew one variety differ somewhat across the three zones. The number of medium farmers growing a single variety was smallest in the cotton-wheat zone, being about 42 percent, whereas the percentages of medium farmers for the rice-wheat and mixed zones were about 65 and 63, respectively. Among the large farmers who grew a single variety of wheat, the percentages were different across zones (about 54, 39 and 30 percent for the mixed, rice-wheat and cotton-wheat zones, respectively).

Table 1: Percentage distributions of wheat farmers by variety and growing conditions[a]

	All farmers (number)	Farmers growing variety (%)	Single-variety growers (%)	Multiple-variety growers (%)
Seher-06	745	66.8	63.4	36.6
Inqilab-91	225	20.2	61.8	38.2
Watan-93	121	10.8	50.4	49.6
Bhakkar-02	127	11.4	40.2	59.8
Faisalabad-08	69	6.2	33.3	66.7
AS-2002	65	5.8	32.3	67.7
Shafaq-06	62	5.6	22.6	77.4
Lasani-08	50	4.5	10.0	90.0
Other varieties	63	5.6	15.9	84.1

[a] In column 3, the percentages are of the farmers growing the given varieties relative to the total number of sample farmers. The percentages in columns 4 and 5 are of farmers who grew the different varieties alone and of those who grew them in combination with one or more other varieties, respectively. The row sums of the percentages in the last two columns are 100.0.
Source: Authors

Table 2: Percentage distributions of single- and multiple-variety farmers by zone and farm size

Zone	Farm size	Percentage distribution of farmers by: Single-variety growers	Multiple-variety growers	Total number of farmers
Rice-wheat zone		**73.9**	**26.1**	**360**
	Marginal farmer	91.4	8.6	128
	Small farmer	71.0	29.0	131
	Medium farmer	64.6	35.4	65
	Large farmer	38.9	61.1	36
Cotton-wheat zone		**65.8**	**34.2**	**456**
	Marginal farmer	87.4	12.6	151
	Small farmer	69.8	30.2	169
	Medium farmer	41.8	58.2	79
	Large farmer	29.8	70.2	57
Mixed zone		**76.7**	**23.3**	**300**
	Marginal farmer	92.0	8.0	113
	Small farmer	74.5	25.5	98
	Medium farmer	63.0	37.0	54
	Large farmer	54.3	45.7	35
All areas		**71.3**	**28.7**	**1,116**
	Marginal farmer	90.1	9.9	392
	Small farmer	71.4	28.6	398
	Medium farmer	55.1	44.9	198
	Large farmer	39.1	60.9	128

Source: Authors

Given the results presented in Table 2 and discussed above, the prevalence of multiple varieties among farmers increased from marginal to large farmers. Only about 10 percent of marginal farmers grew more than one variety whereas 29, 45 and 61 percent of small, medium and large farmers, respectively, grew more than one variety. At first glance, this finding appears to contradict the stereotype that larger-scale farmers specialize in activities with higher returns because they can afford to take risks, while most land-poor farmers seek to diversify as a means of offsetting risks. Instead, the observed pattern may reflect a form of "subsistence first" mindset among farmers who have smaller wheat areas. In other words, these farmers choose to grow only their preferred variety in an attempt to produce enough food and also generate some cash. On the other hand, larger-scale farmers have the opportunity to produce wheat varieties that satisfy more than one objective, such as those related to the quality of *chapatti*, yield potential and yield stability.

Based on the information presented above, this paper analyzes the wheat data for the farmers who grew the four most popular varieties of wheat solely or in combination with one or more of these varieties. The two varieties, Seher and Inqilab, were grown by large numbers of farmers. They represent extremes in terms of varietal age and years until adoption. We also consider Bhakkar and Faisalabad as intermediate examples in terms of varietal age and popularity (released in 2002 and 2008, respectively). The number of observations involved in our empirical analyses is 1,166, which is greater than the number of sample farmers (1,116) because there were farmers who grew more than one variety and we consider the data for the different varieties grown by each sample farmer.

5. STOCHASTIC FRONTIER MODEL

5.1 Overview of Approach

We estimate a general SFA production function model that includes the specification of a model for the technical inefficiency effects as proposed by Battese and Coelli (1993, 1995). The model accounts for possible differences in productivity and efficiency associated with characteristics of the four varieties involved, together with the effects of the number of years farmers took to adopt their varieties and the number of years they grew the particular varieties. As described in the study context (Section II), we anticipate that later adopters may be less productive and less efficient than earlier adopters, although they may also benefit from observing the practices of other farmers. We consider that the slower the replacement of varieties, or the longer a variety is grown, the lower the productivity and efficiency relative to more recently released varieties and newly purchased seed. In addition to a set of observed inputs used by the wheat farmers, we consider the effects of the severity of salinity and toxicity of the soils involved in the production of the wheat.

5.2 Model Specification

The SFA production function model that is used to analyze the data from the farmers who grew one or more of the four wheat varieties, Seher, Inqilab, Bhakkar and Faisalabad, is of translog functional form and is defined by:

$$\ln Y_i = \beta_0 + \sum_{j=1}^{7}\beta_j \ln X_{ji} + 0.5\sum_{j=1}^{7}\sum_{k=1}^{7}\beta_{jk}\ln X_{ji}\ln X_{ki} + \sum_{j=1}^{6}\beta_{0j}D_{ji} + \sum_{j=1}^{2}\beta_{Wj}W_{ji} + \sum_{j=1}^{7}\beta_{Vj}D_{Vji} + V_i - U_i \qquad (1)$$

where:

- The subscript i indicates the i^{th} observation in the data set (i = 1, 2, ..., 1,166);
- Y is the *output* of a given wheat variety harvested (in kgs) for the sample farmer;
- X_1 is the total area of *land* (in acres) on which the given variety was grown;
- X_2 is the total *labor* (in man days) used in the production of the wheat variety;
- X_3 is the quantity of *seed* (in kgs) used in sowing the wheat variety on the land;
- X_4 is the amount of *nitrogen* (in kgs) applied on the land involved;
- X_5 is the amount of *phosphorus* (in kgs) applied on the land involved;
- X_6 is the quantity of *weedicide* (in mls) applied on the land involved;
- X_7 is the number of *irrigations* applied to the variety in the growing season;
- D_1 is the dummy variable for observations from the *rice-wheat zone*;
- D_2 is the dummy variable for observations from the *cotton-wheat zone*;
- D_3 is the dummy variable for the reported incidence of *rust* in the wheat crop;
- D_4 is the dummy variable for the reported incidence of *lodging* in the wheat crop;
- D_5 is the dummy variable for the incidence of *phosphorus*=0;
- D_6 is the dummy variable for the incidence of *weedicide*=0;
- W_1 and W_2 are the dummy variables that indicate the incidence of severe or very severe *salinity* and *toxicity* in the soil, respectively; and

- D_{Vj}, j=1,2,..., 7, are seven dummy variables associated with the four different varieties and whether they are grown alone or not, as defined in Table 3.

The dummy variables for handling zero values of phosphorus and weedicide (i.e., none applied) are based on Battese (1997). This approach is extended to the translog model (see the Appendix). In some cases, there were also zero values for nitrogen and the number of irrigations. However, in cases where there were only a few zeros for these inputs, the corresponding dummy variables to account for possible different intercepts were excluded to increase the estimation efficiency of the SFA model's parameters.

The statistical properties of the random variables in the SFA production function model of equation (1) are defined as follows:

- The V_is are random errors that are assumed to be independently and identically distributed as $N(0, \sigma_V^2)$-random variables; and

- The U_is are the non-negative technical inefficiency effects that are assumed to be independently distributed among themselves and between the V_is, such that U_i is defined by the truncation (at zero) of the $N(\mu_i, \sigma^2)$ distribution, where μ_i is defined by:

$$\mu_i = \delta_0 + \sum_{j=1}^{11}\delta_j Z_{ji} + \sum_{j=1}^{2}\delta_{Wj} W_{ji} + \sum_{j=1}^{7}\delta_{Vj} D_{Vji} \qquad (2)$$

where:

- Z_1 is the *age* of the household head (in years);

- Z_2 is the years of formal *education* of the household head;

- Z_3 is the number of years the farmer has been growing the variety (*years growing*);

- Z_4 is the number of years from varietal release to the first year the farmer grew the variety (*years to adopt*);

- Z_5 is the dummy variable indicating the farmer had access to *extension* advice;

- Z_6 is the dummy variable indicating the farmer *owns the land* the variety is grown on;

- Z_7 is the dummy variable for the *rice-wheat zone* (i.e., $Z_7 \equiv D_1$);

- Z_8 is the dummy variable for the *cotton-wheat* zone (i.e., $Z_8 \equiv D_2$); and

- Z_9, Z_{10} and Z_{11} are dummy variables that indicate the incidence of *marginal*, *small* and *medium farmers*, respectively.

The above model of equations (1)-(2) is a traditional SFA model of the Battese-Coelli (1995) type in which the explanatory variables for the production function and the inefficiency model are considered to be independent variables as per traditional regression models. There is no consideration of the possible problem of endogeneity of explanatory variables, which was raised by a reviewer of an earlier version of this paper. The reviewer suggested that an omitted variable such as intelligence or innate ability of farmers might be driving differences in productivity and efficiency. We use the level of education as an explanatory variable for the inefficiency effects but have not specified that education might influence productivity of the farmers. An alternative parameterization that might account for the effects of education on parameters of the SFA model is that the coefficients (of the production function and/or the inefficiency model) are an appropriate function (linear or quadratic, say) of the level of formal education. This would reduce to a more complicated model that might not be estimable unless there are large numbers of observations for varieties involved. We do not pursue this or the more general question of endogeneity in this paper.

5.3 Explanatory Variables

Definitions and descriptive statistics for the explanatory variables used in the estimation of the production function and the inefficiency model (1)-(2) are reported in Table 3. Statistics are shown for wheat outputs for the four varieties grown by the sample farmers who grew any of the four major varieties (Seher, Inqilab, Bhakkar, and Faisalabad) alone or in combination with another of these four.

Variables are grouped according to whether they are in the production function, the inefficiency model, or in both models. Economic theory guides the choice of generic factors to include in the production function, such as land, labor, seed, fertilizer, irrigation, and other inputs. Factors such as weedicides and dummy variables to measure the incidence of biotic and abiotic stress (rust and lodging) are specific to the empirical context of irrigated Punjab. Factors included in the inefficiency model are those shown to be important in earlier work in Pakistan, as well as those related to the major hypothesis of slow varietal change (see the Introduction for these references).

With respect to the variables that measure input use, the minimum and maximum values show considerable variation, much of which can be attributed to the scale of

Table 3: Descriptive statistics of the variables used in the empirical analyses

Variable Name	Variable Definition	Mean	Std. Dev	Minimum	Maximum
Production function variables					
Quantity	Wheat quantity harvested[a] (kg)	9,612	14,041	280	149,800
Land	Wheat area (acres)	6.5	10.5	0.3	210.0
Labor	Labor (man-days)	62.7	54.4	4.6	596.7
Seed	Quantity of seed sown (kg)	329	527	5.0	10,500
Nitrogen	Quantity of nitrogen applied (kg)	328	503	0	6,720
Phosphorus	Quantity of phosphorus (kg)	160	264	0	4,830
Weedicide	Quantity of weedicides (ml)	4,578	7,535	0	105,000
Irrigation	Number of water irrigations	4.2	1.0	0	6
D(Rust)	Incidence of rust (yes=1)	0.148	0.356	0	1
D(Lodged)	Incidence of lodging (yes=1)	0.368	0.482	0	1
D(P=0)	Incidence of "no P" (yes=1)	0.025	.0.156	0	1
D(Weedicide=0)	Incidence of "no weedicide"	0.100	0.299	0	1
Inefficiency model variables					
Age	Age of farmer (years)	49.9	12.9	17	86
Education	Education of farmer (years)	5.6	4.7	0	18
Years Growing	Number of years growing	3.2	2.3	1	20
Years to Adopt	Years to adopt after the release	5.0	5.2	0	19
Extension	Access to extension (yes=1)	0.137	0.344	0	1
Own Area	Wheat area owned (yes=1)	0.929	0.257	0	1
D(Marginal)	Marginal farmer (yes=1)	0.309	0.462	0	1
D(Small)	Small farmer (yes=1)	0.354	0.478	0	1
D(Medium)	Medium farmer (yes=1)	0.193	0.395	0	1
Variables used in both production function and inefficiency model					
D(R-W)	In rice-wheat zone (yes=1)	0.320	0.467	0	1
D(C-W)	In cotton-wheat zone (yes=1)	0.419	0.494	0	1
W_1	Severe salinity[b] (yes=1)	0.449	0.498	0	1
W_2	Severe toxicity[b] (yes=1)	0.099	0.298	0	1
D(Inqilab)	Grew Inqilab (yes=1)	0.193	0.395	0	1
D(Bhakkar)	Grew Bhakkar (yes=1)	0.109	0.312	0	1
D(Faisalabad)	Grew Faisalabad (yes=1)	0.059	0.236	0	1
D(1Variety)	Grew only one variety (yes=1)	0.587	0.492	0	1
D(Inqilab1)	Grew Inqilab alone (yes=1)	0.119	0.324	0	1
D(Bhakkar1)	Grew Bhakkar alone (yes=1)	0.044	0.205	0	1
D(Faisalabad1)	Grew Faisalabad alone (yes=1)	0.020	0.139	0	1

[a]The quantities of wheat harvested are for the individual varieties grown by the sample farmers. For farmers who grew more than one variety, there are two or more observations for the different varieties grown.

[b]The survey data did not include information on soil and environmental characteristics. To construct these variables, we utilized geo-referenced data imported from the FAO data base (details in Fischer et al., 2008) by Jose Funes at HarvestPlus.

the wheat operation, which ranged from a mere 0.3 acre to 210 acres for particular varieties. The average size of the cultivated area under any given wheat variety was 6.5 acres, illustrating considerable skew in the distribution of cultivated area under wheat varieties.

The average harvested quantity of any given wheat variety was about 1,480 kg/acre. The use of labor among the wheat farmers showed wide variation, the average labor input being about 63 man-days per farmer per variety. The data indicate that farmers used, on average, the recommended amount of seed (50 kg/acre).

The average quantities of applied nitrogen and phosphorus from the different fertilizers applied were 328 kg/acre and 160 kg/acre, respectively, but 2.5 percent of farmers did not apply phosphorus. On average, 4.6 liters of weedicides were applied per variety of wheat grown, but 10 percent of the farmers did not apply them. About 15 percent and 37 percent of farmers indicated the incidence of rust and lodging, respectively. The statistic on rust needs to be interpreted with some caution. Wheat rust diseases cause annual yield losses, but often at low percentages. The data suggest that these varieties are "rust resistant" in a broad sense.

Turning to the hypothesized determinants of technical inefficiency, the average age of farmers in the selected sample was 50 years. On average, the surveyed wheat farmers nearly completed primary school education. Among these sample farmers, the mean time growing a variety was 3.2 years. This figure attests to the popularity of Seher and its recent adoption by numerous farmers. Similarly, on average, farmers adopted a variety five years after its release. The number of years growing a variety ranged from 1 to 20, while the number of years to adoption ranged from zero (adopters in the year of release of the variety) to 19 (late adopters). Even in the irrigated areas of Punjab, in 2011 only about 14 percent of the sample farmers had access to formal extension services. In terms of land tenure, nearly 93 percent of the plots of wheat were on land that the farmers owned.

Among the variables that are used in both the production function and the inefficiency model, the dummy variables for the incidence of severe salinity and severe toxicity in the soils show that about 45 percent was designated as having the former and 10 percent as having the latter. These factors are expected to significantly affect the productivity and efficiency of the wheat farmers. Further, the means of the three variety dummy variables for the incidence of Inqilab, Bhakkar and Faisalabad, indicate that about 19, 11 and 6 percent of the observations were for those varieties, respectively; hence, 64 percent of the observations were for Seher. These observations include single- and multiple-variety farmers. The mean for the dummy variable, D (1Variety), shows that 58.7 percent of the observations in the dataset were from farmers who grew one variety only.

The translog functional form of equation (1) with the seven inputs has 28 second-order variables, in addition to the seven first-order variables, plus 15 dummy variables associated with the agro-climatic zones, the incidence of rust and lodging, the incidence of zero observations for phosphorus and weedicide, the severity of salinity and toxicity of the soils, and the dummy variables associated with the four different varieties and whether or not the varieties were grown alone. We use mean-corrected values of the inputs involved so that the first-order coefficients of the inputs in the translog production function are estimates of the elasticities of the inputs at the mean levels. This involves subtracting the average of the logarithms of the values of an input from the individual logarithms of the input's values.

6. EMPIRICAL RESULTS

The translog SFA production function model of equations (1)-(2) is estimated with a total of 1,166 observations, obtained from 745 farmers who grew Seher (472 grew it alone), 225 farmers who grew Inqilab (139 grew it alone), 127 farmers who grew Bhakkar (51 farmers grew it alone) and 69 farmers who grew Faisalabad (23 grew it alone). We first present some tests of null hypotheses related to the technical inefficiency effects and the parameters of the SFA model involved. These tests of hypotheses are presented in Table 4. The preliminary tests of hypotheses involving the parameters of the stochastic frontier model are conducted at the 10 percent level of significance.

The first null hypothesis is that the inefficiency effects in the SFA model of equation (1) are, in fact, not present, and so the traditional production function applies. This is strongly rejected by the data on the four varieties, as shown by the very large generalized likelihood statistic in Table 4. (This is also indicated by the estimates for the γ-parameter being about 0.93, as shown in Table 5b below.) Thus, the traditional regression model is not an adequate representation of the data, given the assumptions of the translog stochastic frontier model of equations (1)-(2).

The second null hypothesis in Table 4 is that the second-order coefficients of the translog production function are all zero, which means that the Cobb-Douglas production function applies. This is also strongly rejected by the data on the four wheat varieties. The implication is that using the Cobb-Douglas production function to investigate the productivity and efficiency of wheat farmers who grew these four varieties either alone or in combination with other varieties may lead to inappropriate inferences and give biased estimates of some parameters of interest.

The third null hypothesis tested in Table 4 is that the coefficients of the dummy variables associated with the severity of salinity and toxicity of the soil are simultaneously zero in the production function and the inefficiency model. This is rejected using the 10 percent level of significance, implying that the salinity and toxicity data (not collected in the survey) are important for the productivity and efficiency of the wheat varieties.

The fourth null hypothesis of interest in Table 4 is that there are no differences in the technical inefficiencies of farmers who grew one or more of the four different varieties either alone or in combination with other varieties. This is supported by the data, which is perhaps not surprising because farmers growing these different varieties of wheat may not have different management practices leading to different levels of inefficiencies in their farming.

The estimated parameters of the different stochastic frontier models are presented in Tables 5a and 5b. The parameter estimates and their standard errors are generated by the FRONTIER 4.1 program (Coelli, 1996), which involves an iterative technique that requires initial values for the maximization of the loglikelihood function for the SFA model. The estimates for the parameters of the translog production functions are presented in Table 5a, but only the first-order coefficients of the seven input variables are presented, which are elasticity estimates for the inputs at their mean values. The three sets of estimates presented in Tables 5a and 5b are for the original SFA model defined by equations (1)-(2), the corresponding Cobb-Douglas model and the preferred SFA model that is involved when the fourth null hypothesis of Table 4 is imposed in equation (2).

The estimates for the corresponding parameters of the different SFA models presented in Table 5a are very similar, even for the elasticity estimates from the Cobb-Douglas model, which is not an adequate representation of the data, as shown in Table 4. However, the elasticities for the inputs would deviate much more from those of the Cobb-Douglas production function model at input values quite different from their mean values. From the estimates for the preferred model, presented in the last column of Table 5a, the mean elasticities range from the maximum value for land (0.730), followed by irrigation (0.080), phosphorus (0.080), nitrogen (0.074), seed (0.049), labor (0.022) and weedicide (0.021). All these elasticity estimates are statistically significant at the 5 percent level, except for seed.

The dummy variables for the rice-wheat and cotton-wheat zones were highly significantly negative, indicating that the productivities of wheat farmers in those two regions were less than those in the mixed zone. Further, farmers who grew wheat on land that was severely affected by salinity or toxicity were less productive than farmers who did not grow their wheat on such soils.

The coefficients of the dummy variables for the different

Table 4: Tests of hypotheses for the translog SFA production function models for farmers who grew one or more of the four wheat varieties: Seher, Inqilab, Bhakkar and Faisalabad

Null Hypothesis	*Loglikelihood*	*Test Statistic, λ*	*df, CV**	*Decision***
Given TL model (1)-(2)	192.287			
H_0: No inefficiencies	54.416	275.74	22, 30.24	Reject H_0
H_0: $\beta_{jk} = 0$, for all j and k	149.751	85.07	28, 37.92	Reject H_0
H_0: $\beta_{wj} = \delta_{wj} = 0$, j=1,2	164.464	55.65	4, 7.78	Reject H_0
H_0: $\delta_{vj} = 0$, j=1,...,7	188.780	7.01	7, 12.02	DNR H_0

*The *CV*-values are *critical values* (upper 10% values) for the appropriate X^2_{df}-distribution with the degrees of freedom (*df*) indicated, except for the first value, which is taken from Table 1 of Kodde and Palm (1986). The tests of the null hypotheses are at the 10% level.
** DNR stands for “do not reject” rather than stating “accept” the appropriate null hypothesis, H_0.
Source: Authors

Table 5a: Maximum-likelihood estimates for parameters[a] of translog and Cobb-Douglas SFA production function models for farmers who grew one or more of four wheat varieties[b]

Variable	Parameter	Translog	Cobb-Douglas	Preferred TL[c]
Constant	β_0	8.876 (0.033)	8.877 (0.031)	8.875 (0.028)
D(R-W)	β_{01}	-0.076 (0.025)	-0.073 (0.028)	-0.083*** (0.025)
D(C-W)	β_{02}	-0.097 (0.025)	-0.092 (0.027)	-0.099*** (0.025)
D(Rust)	β_{03}	0.011 (0.017)	0.021 (0.017)	0.012 (0.017)
D(Lodged)	β_{04}	0.004 (0.013)	0.005 (0.013)	0.003 (0.013)
D(P=0)	β_{05}	0.02 (0.22)	0.140 (0.093)	0.04 (0.22)
D(Weedicide=0)	β_{06}	0.01 (0.30)	0.098 (0.082)	0.03 (0.30)
W_1 = D(Salinity)	β_{W1}	0.111 (0.019)	0.112 (0.018)	-0.108*** (0.018)
W_2 = D(Toxicity)	β_{W2}	0.157 (0.036)	0.153 (0.035)	-0.150*** (0.035)
D(Inqilab)	β_I	-0.146 (0.032)	-0.140 (0.033)	-0.109*** (0.028)
D(Bhakkar)	β_B	-0.065 (0.039)	-0.062 (0.038)	-0.073*** (0.026)
D(Faisalabad)	β_F	-0.026 (0.040)	-0.039 (0.041)	-0.005 (0.031)
D(1Variety)	β_{1V}	-0.041 (0.021)	-0.037 (0.020)	-0.030* (0.016)
D(Inqilab1)	β_{I1}	0.043 (0.044)	0.038 (0.045)	-0.012 (0.032)
D(Bhakkar1)	β_{B1}	-0.033 (0.059)	-0.041 (0.058)	-0.004 (0.041)
D(Faisalabad1)	β_{F1}	0.142 (0.071)	0.132 (0.069)	0.140*** (0.054)
Land	β_1	0.728 (0.058)	0.770 (0.059)	0.730*** (0.058)
Labor	β_2	0.022 (0.012)	0.018 (0.011)	0.022** (0.012)
Seed	β_3	0.051 (0.052)	0.064 (0.052)	0.049 (0.052)
Nitrogen	β_4	0.075 (0.018)	0.060 (0.015)	0.074*** (0.018)
Phosphorus	β_5	0.078 (0.022)	0.055 (0.020)	0.080*** (0.022)
Weedicide	β_6	0.021 (0.012)	0.019 (0.010)	0.021** (0.012)
Irrigation	β_7	0.078 (0.032)	0.160 (0.026)	0.080*** (0.032)

[a] The standard errors are presented to two-significant digits and the parameter estimates are given to the same number of digits behind the decimal points as the corresponding standard errors; [b] These results involve the four varieties grown alone or in combination with one or more other varieties. The cases of growing a variety alone are indicated by the digit 1 behind the name of the variety involved; [c] Large sample Z-tests are conducted and coefficients that are significant at the 10%, 5% and 1% levels are indicated by the asterisks, *, ** and ***, respectively. These asterisks are only included in the preferred model. Source: Authors

Table 5b: Maximum-likelihood estimates for parameters of the inefficiency models for translog and Cobb-Douglas SFA models for farmers who grew one or more of four wheat varieties

Variable	Parameter	Translog	Cobb-Douglas	Preferred TL model
Constant	δ_0	-2.61 (0.78)	-2.98 (0.90)	-3.34 (0.99)
Age	δ_1	0.0131 (0.0034)	0.0102 (0.0032)	0.0117*** (0.0033)
Education	δ_2	0.0069 (0.0053)	0.0061 (0.0058)	0.0053 (0.0051)
Years Growing	δ_3	-0.042 (0.064)	-0.032 (0.064)	0.071*** (0.020)
Years to Adopt	δ_4	-0.099 (0.066)	-0.087 (0.066)	0.0049 (0.0071)
Extension	δ_5	-0.76 (0.21)	-0.81 (0.22)	-0.75*** (0.24)
Own Area	δ_6	0.057 (0.094)	0.228 (0.094)	0.104 (0.095)
D(R-W)	δ_7	-0.87 (0.16)	-0.82 (0.16)	-0.92*** (0.19)
D(C-W)	δ_8	-1.31 (0.23)	-1.30 (0.23)	-1.32*** (0.26)
D(Marginal)	δ_9	1.12 (0.25)	1.32 (0.31)	1.11*** (0.27)
D(Small)	δ_{10}	0.87 (0.21)	1.07 (0.26)	0.86*** (0.22)
D(Medium)	δ_{11}	0.41 (0.13)	0.61 (0.17)	0.36*** (0.12)
W_1 = D(Salinity)	δ_{W1}	1.14 (0.24)	1.33 (0.29)	1.10*** (0.24)
W_2 = D(Toxicity)	δ_{W2}	1.18 (0.23)	1.26 (0.26	1.13*** (0.24)
D(Inqilab)	δ_I	0.63 (0.93)	0.72 (0.94)	-
D(Bhakkar)	δ_B	0.52 (0.30)	0.50 (0.30)	-
D(Faisalabad)	δ_F	-0.69 (0.28)	-0.96 (0.33)	-
D(1Variety)	δ_{S1}	-0.28 (0.11)	-0.26 (0.11)	-
D(Inqilab1)	δ_{I1}	1.24 (0.38)	1.01 (0.35)	-
D(Bhakkar1)	δ_{B1}	-0.41 (0.24)	-0.52 (0.23)	-
D(Faisalabad1)	δ_{F1}	-0.19 (0.42)	-0.53 (0.50)	-
	$\sigma_S^2 \equiv \sigma_V^2 + \sigma_U^2$	0.316 (0.061)	0.377 (0.080)	0.333 (0.075)
	$\gamma \equiv \sigma_U^2 / \sigma_S^2$	0.928 (0.014)	0.939 (0.016)	0.933***[a] (0.016)
	Loglikelihood	192.287	149.751	188.798
	Mean Tech Eff	0.865	0.855	0.862

[a]A large sample Z-test of H_0:γ=1 is rejected at the 1% level, which indicates that there were significant random errors in the wheat data, in addition to the technical inefficiency effects in the wheat production. Thus, the SFA model is significantly different from the deterministic frontier model with no random errors. Source: Authors

varieties and growing situations in Table 5a were jointly statistically significant and indicate that there were different mean yields for the four varieties and under the two different growing situations. The estimated coefficients indicate that farmers growing Inqilab and Bhakkar had significantly less productivity than Seher, but Faisalabad was as equally productive as Seher. Further, our results indicate that, in general, the productivities of the farmers who grew one wheat variety alone were less than for farmers who grew more than one variety, except in the case of farmers who grew Faisalabad. The finding that farmers who grew Faisalabad alone had higher productivity than those who grew it in combination with other varieties is worth further investigation.

The estimates for the parameters in the inefficiency models associated with the SFA models involved are presented in Table 5b. The estimates for the inefficiency effects indicate that older farmers tended to be more inefficient than younger farmers. However, farmers with more education were not found to be more efficient than the farmers who had less years of formal education. This indicates that lack of formal education has not been a restriction on the production efficiency of the surveyed wheat farmers. Farmers who had access to extension advice tended to be less inefficient in their wheat farming operations, as indicated by the significant negative coefficient of the *Extension* dummy variable.

The variable representing the time-to-varietal change (*Years Growing*) had a positive and significant coefficient, indicating that the wheat farmers' production inefficiency tended to increase with the years growing the same variety. This finding is consistent with earlier research and principles of wheat breeding—higher rates of varietal change support greater yield potential. On the other hand, time to adoption had no statistically significant effect. That is, later adopters are no less efficient than early adopters, other factors held constant.

Farmers in the rice-wheat and cotton-wheat zones tended to be less inefficient than those in the mixed zone, as indicated by the negative and significant estimates of the coefficients of the dummy variables for those two zones. This is likely to be associated with the complexity of the farming systems in the mixed zone relative to the more specialized farming systems in the other two zones.

The marginal, small and medium farmers tended to be more inefficient than the large farmers but the size of the inefficiency effects tended to decrease as the size of the areas operated increased, as indicated by the significantly positive coefficients of the dummy variables for the marginal, small and medium farmers.

The coefficients of the dummy variables indicating severe salinity and severe toxicity show that the farmers whose land suffered from severe or very severe salinity or toxicity tended to have significantly higher technical inefficiencies than others.

The mean technical efficiency of the full sample of the wheat farmers who grew one or more of the four varieties was estimated to be 0.862 using the preferred translog production function model. There was a large variation

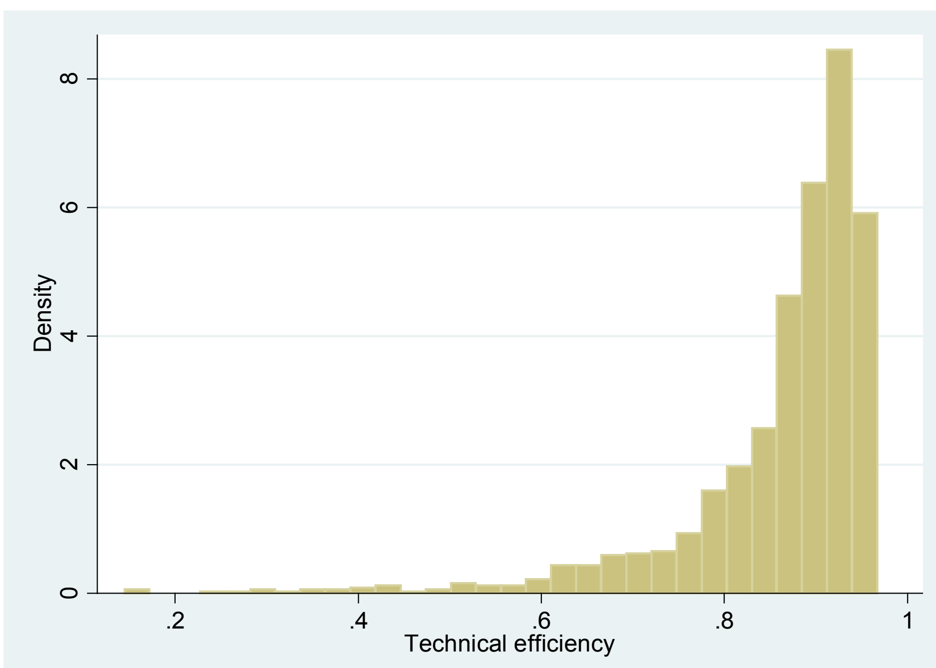

Figure 3: Distribution of technical efficiencies of farmers growing four wheat varieties
Source: Authors

in the predicted technical efficiencies of the individual farmers, the minimum being 0.145 and the maximum 0.967, with a widely spread and skewed distribution, as shown in Figure 3. This distribution of the technical efficiencies of the farmers who grew one or more of the four popular varieties of wheat clearly has a very long tail to the left but there were many very highly efficient wheat producers whose technical efficiencies were between about 0.85 and 0.95, as seen from Figure 3.

7. CONCLUSIONS AND POLICY IMPLICATIONS

Using the stochastic frontier model applied to survey data collected in 2011, this paper examined the productivity and technical efficiency of wheat farmers who grew one or more of the four most popular varieties in the irrigated areas of Pakistan's Punjab. Building on past research, the authors tested specific hypotheses related to persistent concerns about the effects of farm size, access to extension, human capital, and, in the post-Green Revolution period, soil salinity and the speed of varietal diffusion.

The HarvestPlus-IDS survey identified four varieties that represented the largest percentage of wheat area in 2011. Seher, the most popular variety, was released in 2006 and was rapidly adopted. Released in 1991, Inqilab was sown across a more extensive area than any other modern wheat variety in Pakistan, and it ranks among the top four. The other leading varieties are Bhakkar, released in 2002, and Faisalabad, released in 2008.

We began by testing several general hypotheses related to functional form. The results indicated that the Cobb-Douglas production function model was not an adequate representation of the data on wheat farmers who grew one or more of the four most popular wheat varieties, given the assumptions of the translog stochastic frontier production function model.

Next, we found that soil salinity and toxicity, which are represented by dummy variables in our model, were important determinants of wheat productivity and efficiency. Our analysis also indicated that there were no significant differences in the technical inefficiency effects of farmers who grew different varieties of wheat, or grew their varieties alone or in combination with other varieties. Hence, we based our findings concerning individual regression parameters on the preferred translog production function without the dummy variables that control for variety and growing single versus multiple varieties in our inefficiency model.

Our analysis indicated that the growers of Inqilab and Bhakkar were significantly less productive than growers of Seher and Faisalabad. We also found that, in general, farmers who grew their variety of choice alone had lower productivity than those growing it in combination with other varieties. However, farmers who grew Faisalabad alone were more productive than those who grew it in combination with other varieties.

We found that the inefficiency of production increased as the years growing a variety increased. This is contrary to our expectation that learning-by-doing would increase efficiency of production, but is consistent with previous evidence concerning the depressing effects on yield of slow varietal change and re-use of seed. However, the length of the time lag from varietal release to adoption by farmers had no statistically significant effects on the technical inefficiency of wheat production. Thus, ceteris paribus, later adopters were no less efficient than early adopters. These farmers may benefit from learning-by-observation. This finding may also reflect the fact that the average time to adoption was only five years—which is relatively rapid. Of the four most popular varieties, the average time to adoption was under five years for all but Inqilab, the old dominant wheat variety. This is encouraging for diffusion of zinc-biofortified varieties given that their traits are similar to Seher, Faisalabad and Bhakkar.

Our findings suggest that smaller farm size and growing wheat in the mixed production zone in Punjab are associated with greater technical inefficiency. Although formal education had no effect on inefficiency of wheat production, access to extension services resulted in significant decreases in technical inefficiency. Thus, despite the known significance of farmer-to-farmer exchange of wheat varieties and related information, extension services are important for diffusion strategies. There is a need to supplement the role of formal extension services with other approaches, such as field demonstrations, farmers' cooperatives, and use of print and electronic media.

Given the heightened vulnerability to biotic pressures that can result from spatial concentration of wheat area with a single variety, and a history of this problem in Pakistan, we recommend biofortification of multiple varieties, possibly including those with contrasting characteristics. Our findings support the notion that, on average, in any given year, there are few trade-offs among the most popular varieties in terms of productivity or inefficiency of production in the Punjab of Pakistan. Our empirical results also confirm the importance of breeding for tolerance to salinity and toxicity.

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APPENDIX: Estimating the Translog Model with Zero Input Values

The extension of the Cobb-Douglas model, outlined in Section 2 of Battese (1997), is as follows (for the two-variable case only):

Suppose that the production relationships, involving one output and two inputs, are defined by

$$\ln Y_i = \beta_0 + \beta_1 \ln X_{1i} + \beta_2 \ln X_{2i} + \beta_{11} 0.5 \times (\ln X_{1i})^2 + \beta_{22} 0.5 \times (\ln X_{2i})^2 + \beta_{12} (\ln X_{1i})(\ln X_{2i}) + V_i, \; i = 1,2,\ldots,n_1$$

$$\ln Y_i = \alpha_0 + \beta_1 \ln X_{1i} + \beta_{11} 0.5 \times (\ln X_{1i})^2 + V_i, \; i = n_1 + 1, n_1 + 2, \ldots, n_1 + n_2 = n,$$

where n_1 is the number of observations for which $X_{2i} > 0$; and

n_2 is the number of observations for which $X_{2i} = 0$; etc., as in Battese (1997).

The model can be combined into one regression model by introducing the dummy variable, D_{2i}, which is defined by

$D_{2i} = 1$, if $X_{2i} = 0$; and $=0$, otherwise.

The combined model for estimation of the parameters is

$$\ln Y_i = \beta_0 + (\alpha_0 - \beta_0) D_{2i} + \beta_1 \ln X_{1i} + \beta_2 \ln X^*_{2i} + \beta_{11} 0.5 \times (\ln X_{1i})^2 + \beta_{22} 0.5 \times (\ln X^*_{2i})^2 + \beta_{12} (\ln X_{1i})(\ln X^*_{2i}) + V_i, \; i = 1,2,\ldots,n;$$

where $X_{2i} = Max(X_{2i}, D_{2i})$.

This is the appropriate model to estimate, given that the errors in the two situations have the same distributions. However, if there are few observations with zero values of a given input variable, it may be best to delete the associated dummy variable because it may result in a poorly conditioned design matrix for the estimation to be effectively obtained.