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The extent of resource use inefficiencies in cotton production in Pakistan's Punjab: an application of Data Envelopment Analysis

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Abstract

This paper attempts to identify sources of resource use inefficiency for cotton production in Pakistan's Punjab. The use of a non-parametric method, Data Envelopment Analysis (DEA), is developed to study the relative technical and allocative efficiencies of individual farms which use similar inputs, produce the same product and operate under comparable circumstances. In the 'cotton–wheat' system of Pakistan, there are a considerable number of farms that are both technically and allocatively inefficient. The use of DEA shows that the technique provides a clear identification of both the extent and the sources of technical and allocative inefficiencies in cotton production. However, both the interpretation of the farm level results generated and the projection of these results to a higher level require care, given the technical nature of the agricultural production processes.

Keywords: Data Envelopment Analysis; Technical efficiency; Allocative efficiency; Cotton

1. Introduction

Several recent studies on the technical and economic efficiencies of crop production in Pakistan, particularly for wheat and rice, have pointed out the existence of a 'yield gap'. This 'gap' refers to the difference in productivity on 'best practice' and on other farms operating with comparable resource endowments under similar circumstances (Akhtar et al., 1986; Ali and Flinn, 1987; Hussain et al., 1991; Khan et al., 1994). Surprisingly, these studies have ignored cotton, despite it being the major export from Pakistan.

The existing studies on technical and economic efficiencies have used the traditional parametric methods to estimate 'average' efficiencies only (Khan and Maki, 1979; Ali and Flinn, 1987; Ali and Chaudhry, 1990; Ali et al., 1993; Battese et al., 1993; Parikh and Shah, 1994; Parikh et al., 1995). The estimation of such 'average' efficiencies appears to ignore the argument that the study of the individual farm is more important to measure the resource use efficiency, and that the parametric methodology provides insufficient information for policy analysis (Kalirajan, 1984; Kalirajan and Shand, 1986). The research reported here supports the importance of studying the individual farm efficiency, and it is the first study of its kind to have used the non-parametric method of Data Envelopment Analysis (DEA) for analysing the efficiency of individual farms in Pakistan.

The paper begins with a brief introduction of efficiency measurement and of the development of DEA. The description of data sources precedes the explanation of the DEA model in general and the specification

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of this model for cotton production. Next, the use of a Cobb–Douglas type of production function for identifying the important inputs in the production process is discussed before presenting the results of the technical and allocative efficiency analyses. Finally, the usefulness of the DEA model for examining the resource use inefficiency of cotton production in Pakistan is assessed.

2. Measurement of efficiency

The efficiency of production units is measured either by parametric or by non-parametric methods. The first approach estimates the parameters of the production or cost functions statistically. The second one, in contrast, builds a linear piece-wise function from empirical observations of inputs and outputs, without assuming any a priori functional relationship between the inputs and the outputs. The non-parametric or 'frontier' method of measuring efficiency was first introduced by Farrell (1957) and since then several improvements and extensions have taken place (see Battese (1992) and Coelli (1995)).

Building on Farrell's work, Charnes et al. (1978) have developed the fractional linear programming method of DEA, which compares inefficient firms with the 'best practice' ones within the same group. It has been used widely for efficiency studies for both public and private organizations (see Seiford and Thrall (1990)). In the agricultural economics literature, however, only a few examples of the application of DEA could be found (Haag et al., 1992; Shimizu, 1992; Cloutier and Rowely, 1993).

2.1. DEA

The DEA technique has come to be named after its originators and is referred to as the CCR model. It involves optimizing a scoring function defined as the ratio of weighted sum of outputs of a particular production unit and the weighted sum of its inputs, that is efficiency. This function is optimized subject to the condition that with any of the production units included in the analysis, the value of the objective function achieved cannot be more than 1, implying that the efficient units will have a score of 1.

The DEA method is regarded as one of the most successful techniques of analysis proposed by researchers in Management Science and Operations Research, as is evident by the profligacy of its applications (see Coelli (1995)). However, the original version of the CCR model is not very convenient for a linear programme as it has more restraints than variables, making it difficult to solve. Hence, the 'dual' version of the CCR model is more popular as the DEA model. The technical details can be found in Charnes et al. (1978), Norman and Stoker (1991), Charnes et al. (1995), and Coelli et al. (1998).

3. The sample of cotton producers

The data were collected from a randomly drawn sample consisting of 120 farms from the cotton–wheat area of the southern part of Pakistan's Punjab. The sample farms can be treated as a homogenous group for several reasons. First, all of the farms are in an area where technical and agronomic practice recommendation domains are the same. Second, they are in reasonable proximity to each other. Third, all of them face uniform natural and market conditions and the same infrastructure. Finally, all the farms have broadly similar types of soils.

3.1. Characteristics of farmers and farms

Information such as the farm operator's age, his educational attainment, the size of the farm family and the number of family members involved in farming is given in Table 1. Most of the farmers are over 25 years old, with the age ranging from 20 to 60 years. The family size is large and three-fourths of the farms had more than nine members per household, and on nearly half of the farms, at least two of the family members were working as full time farm workers on farm.

Most of the farmers till their own land, but quite a few rent additional area to increase the operational size of their holdings. The holdings are divided into three categories: farms which are less than 5 ha, 5–10 ha and greater than 10 ha. All the sample farms have similar types of soils that are ideal for growing cotton. Cotton occupies 77–85% of the area on different farms and this proportion is even higher on large farms. Small farmers in the area keep milch animals requiring land

Table 1
Characteristics of farms and farmers included in the sample

Characteristics of farmers	Frequency	
Age of the farm operator		
<25 years	9	8
25–35 years	45	39
35–45 years	32	27
Above 45 years	31	26
Family size		
1–4	8	7
5–8	28	24
9–12	49	42
>12	32	27
Family members involved in full time farming		
1	31	26
2	56	48
3	14	12
4 or more	16	14
Education attainment (years of schooling)		
No schooling	32	27
up to 5 years	16	14
5–10 years	53	45
10–12 years	10	9
Over 12 years	6	5
Characteristics of farms	Frequency	Mean area (ha)
Farm size		
<5 ha	33	3.46
5–10 ha	39	6.52
>10 ha	45	16.02
Type of tenure on farm		
Owned	71	61
Rented	18	15
Owned plus rented	28	24
Area under cotton crop on different farm size categories		
<5 ha	33	2.67
5–10 ha	39	5.49
>10 ha	45	13.63
Share of cotton crop on different farm size categories		
<5 ha	33	77
5–10 ha	29	84
>10 ha	45	85

for fodder production, thus the area available to them for cotton production is reduced.

4. The DEA model for cotton production

The model developed to study the efficiency of cotton production is the input minimization version (dual) of the CCR model as specified below.

$$\text{Min } Z_o \tag{1}$$

s.t.

$$\sum Y_{mj}\lambda_j \geq Y_o \tag{2}$$

$$\sum_{i=1}^{s} X_{ij}\lambda_j - X_o Z_o \leq 0 \tag{3}$$

$$X_i, Y_j \geq 0 \tag{4}$$

where $j=1, \ldots, 117$ is the number of farms or Decision Making Units (DMUs) in the sample, $m=1$ represents cotton in the cotton–wheat system, $i=1, \ldots, 6$ is the number of inputs included in the analysis, Z_o is the relative efficiency score of the DMU, 'o', under study, λ_j are lambda values that are the weights to be used as multipliers for the input levels of a referent farm to indicate the input levels that an inefficient farm should aim at to achieve efficiency, X_{ij} is the level of use for the ith input on the jth farm, Y_{mj} is the level of the mth output on the jth farm, Y_o is the level of the output on unit 'o', and X_o is the vector of the levels of inputs being used by the DMU 'o'.

The minimum value of Z_o (≤ 1) for the unit 'o' is found by 'combining' the performance of all units being analyzed. This is done in such a way that, for each input, the combination of inputs does not exceed the inputs of unit 'o' and for each output and the combination of outputs is at least as great as that of unit 'o'. On solving the model separately for each DMU in the sample, the efficiency scores (<1 for the inefficient units and 1 for the efficient ones) are established. A score less than 1 means that a linear combination of other units from the sample could produce the same vector of outputs using lower levels of inputs. The problem of returns to scale can be dealt with by using the Banker et al. (1984) extension to the CCR model as: (a) for constant returns to scale (CRS), the condition $\sum \lambda_i \geq 1$ is added; and (b) for variable returns to scale (VRS), the restraint $\sum \lambda_i = 1$ is imposed.

To obtain the efficiency scores, a linear programming matrix was constructed which included input and output data for each of the farms in the sample. It was then used to evaluate the efficiency of an individual farm by substituting its inputs and outputs into the vectors Y_o and X_o in Eqs. (2) and (3) above.

This 'iteration' or substitution was repeated 117 times (three outlier farms were dropped from further analysis) to obtain efficiency scores for all the sample farms. For a firm to be efficient, two conditions must hold: (a) that the calculated value of Z_o that is Z^* must equal 1; and (b) all the slack variables in the LP solution must be 0 (Charnes et al., 1978).

5. Role of various inputs in crop productivity

It is quite usual to integrate some form of functional analysis with the DEA model, mostly regression models, to identify those inputs that play a prominent role in determining productivity. Subsequently, the relative efficiency of a production unit can be measured (Charnes et al., 1978; Bowlin et al., 1985; Dyson et al., 1990; Roll and Cook, 1993; Thanassoulis, 1993). Thus, a Cobb–Douglas type of production function was fitted to the data collected from the survey and the results are discussed below.

5.1. Explanation of the variables

The major inputs that are assumed to determine the cotton crop output (kg/ha) include irrigation water (number per hectare), nitrogen (kg nutrients/ha), phosphate (kg nutrients/ha), labour (h/ha), pesticide costs (Rs. per hectare) and tractor hours required per hectare for levelling, ploughing, planking and planting. The basic statistics related to these variables are presented in Table 2. It is clear that there is a wide variation in both the input use and the cotton output. The output obtained by some of the farmers in the sample was three times as high as that achieved by others; and there were wide variations in the levels at which inputs were being used. There were large differences in the use of nitrogenous fertilizer as some farmers were using six times more fertilizer as compared to others and some farmers did not use any phosphatic fertilizer. In preparing their fields for cotton planting, some farmers use as few ploughings as two, whilst some plough the fields 13 times before planting. Such a variation in the levels of inputs being used suggests that possibly these levels represent a mismanagement of resource use.

6. Results of the statistically estimated function

In Table 3, a very low value of the adjusted R^2 (0.044) shows that the production function does not explain a great deal of the relationship between the dependent and the independent variables as most of the variables had a non-significant effect on the increase in cotton output. Variables like phosphatic fertilizer use, labour and tractor hours used show negative returns, implying an excessive use of these inputs. Thus, the levels at which these inputs are being used could be lowered without reduction in output levels. These results in effect confirm the need for undertaking the analysis of the efficiency of production using a non-parametric method like DEA, as identifying inefficient farms would imply discovering the extent by which their input use could be improved. Furthermore, when there is as much variation in inputs used

Table 2
Basic statistics of cotton output and major inputs used[a]

Input/output variables	Minimum	Maximum	Mean	S.D.
Cotton yield (kg/ha)	1144.32	3644.66	2267.3	499.59
Inputs				
Irrigation (number per hectare)	5	20	6.83	1.83
Nitrogen fertilizer use (kg nutrient/ha)	56.833	340.99	165.62	44.515
Phosphatic fertilizer use (kg nutrient/ha)	0.00	158.144	43.96	32.4135
Labour use (h/ha)	70.81	317.05	170.479	57.2914
Pesticide costs (Rs. per hectare)	1260.21	6449.31	3146.18	897.86
Tractor hours (h/ha)	3.34	25.52	15.58	3.96

[a] Note: large variation in labour hours used per hectare is because some farmers undertake manual hoeing and thinning of cotton twice.

Table 3
Production coefficients estimated from the Cobb–Douglas cotton production function

Variables	Coefficient	Standard error	Significance
Constant	5.5845	1.118	0.000
Nitrogen fertilizer use (kg nutrient/ha)	0.0008	0.0812	0.992
Phosphatic fertilizer use (kg nutrient/ha)	−0.0003	0.0027	0.905
Irrigation (number per hectare)	0.1507	0.1004	0.136
Labour use (h/ha)	−0.123	0.0588	0.039
Pesticide costs (Rs. per hectare)	0.0174	0.0799	0.828
Tractor hours (h/ha)	−0.0518	0.072	0.474
R square		0.101	
Adjusted R^2		0.044	
F-Statistics		1.772	0.10
Durbin–Watson statistics		1.513	

and the output produced as shown in Table 2, the efficiency analysis of individual farms assumes much greater relevance.

7. Technical efficiency analysis

The use of the basic DEA model started with the single input–single output situation. More inputs were introduced into the analysis, one at a time, to evaluate the relative efficiency of individual farms. This procedure also shows how the increase in the number of inputs affects the efficiency rating of individual farms. As the basis for comparison among them is broadened, the ranking of individual producers improves. In the initial run, the single input is nitrogen. The second run involved two inputs, nitrogen and pesticide expenditure; and for the third run, multiple inputs as defined for the cotton production function were used. In all the runs, seed cotton is the output. The efficiency scores of the individual farms were calculated separately for both CRS and VRS assumptions.

The basic DEA model for the 'DMU-1' assuming CRS is stated below:

Min Z_1

s.t.
Cotton yield

$$1445.54\lambda_1 + 1455\lambda_2 + \cdots + 1581\lambda_{120} \geq 1445.54$$

Phosphorus

$$28.42\lambda_1 + 0\lambda_2 + \cdots + 28.42\lambda_{120} - 28.42Z_1 \leq 0$$

Nitrogen

$$198.92\lambda_1 + 56.83\lambda_2 + \cdots + 198.9\lambda_{120} - 198.95Z_1 \leq 0$$

Irrigation

$$8\lambda_1 + 8\lambda_2 + \cdots + 6\lambda_{120} - 8Z_1 \leq 0$$

Labour

$$224.42\lambda_1 + 151.9\lambda_2 + \cdots + 258.8\lambda_{120} - 224.42Z_1 \leq 0$$

Pesticide

$$2816.94\lambda_1 + 3553\lambda_2 + \cdots + 5752\lambda_{120} - 2816.94Z_1 \leq 0$$

Tractor

$$10.28\lambda_1 + 18.53\lambda_2 + \cdots + 12.65\lambda_{120} - 1028Z_1 \leq 0$$

$$\lambda_1 + \lambda_2 + \cdots + \lambda_{120} \geq 1$$

In the above equations, the subscript '120' refers to the identity of the last farm.

The nature of a DEA model is illustrated in Fig. 1 for a single input–single output situation. Each point represents a farm included in the efficiency analysis. The line OA is the efficient frontier assuming CRS, as for each farm on that frontier, there is no other farm with a better input/output conversion ratio and there is only one farm (54) on the efficient frontier. All other farms are inefficient, as they use greater amounts

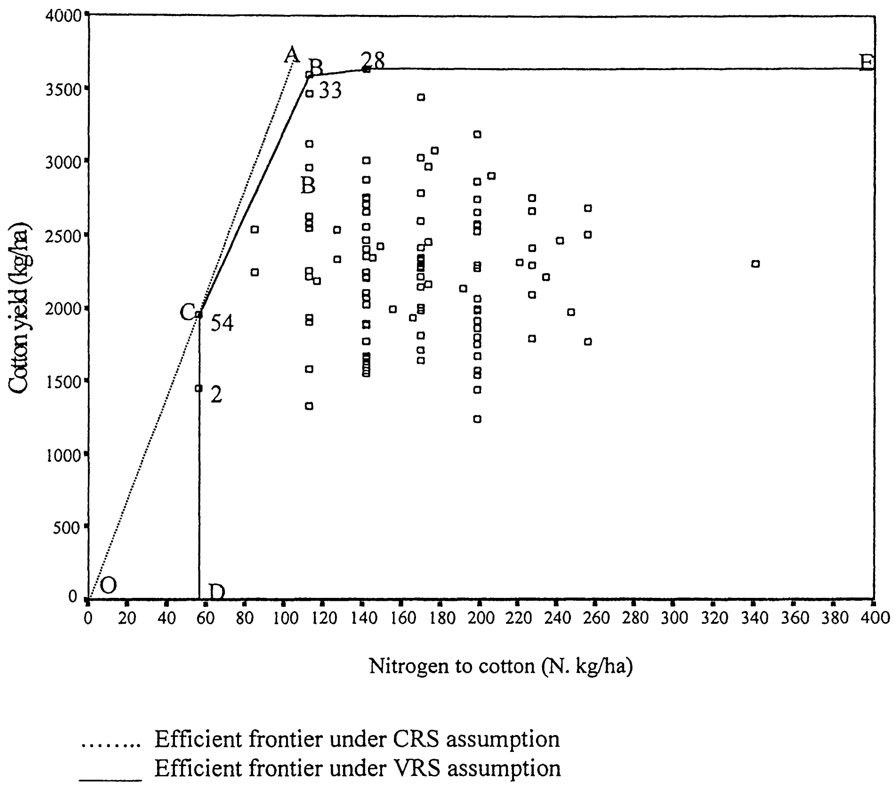

Fig. 1. Graphical presentation of the single input–single output DEA model.

of fertilizer to achieve their current levels of output when compared to farm 54. Given a high variation in nitrogen use, the pertinent question is, do higher levels of nitrogen application contribute to an increase in the crop yield? The results show that this is not the case, suggesting that an excessive use of nitrogen on these farms takes them below the efficient frontier.

The points depicted in Fig. 1 are scattered, and therefore, the CRS assumption would seem not to apply. Assuming that VRS do exist and as this assumption is not so demanding, more farms are likely to be located on the efficient frontier. There are four farms (DMUs 2, 54, 28 and 33) with efficiency scores of 1 lying on the frontier, and they form the envelope *DCBE* representing the frontier to be used as referent for other farms. The use of nitrogen on the efficient farms shows that the output increases with increase in the level of input use.

The inefficient farms in the sample were using inputs at levels greater than required relative to the output levels being obtained by other farms in the sample. A summary of the efficiency scores for all farms is presented in Table 4. It is interesting to note that, when VRS are assumed, only one farm has an efficiency score of less than 60%. Whereas, when CRS

Table 4
Results of the DEA models — technical efficiency scores

Ranges	Number of DMUs falling in ranges	
	The CRS case	The VRS case
	All inputs	All inputs
Equal to 100%	10	30
>90<100%	9	18
80–<90%	9	38
70–<80%	21	20
60–<70%	23	10
50–<60%	25	1
40–<50%	16	–
Less than 40%	4	–

are assumed, 38% of the farms have efficiency scores of less than 60%.

7.1. *Use of DEA results to study inefficiency on an individual farm*

By using the results of the DEA model, it is possible to work out what is required by inefficient farms to become efficient. Take the farm DMU-70, with efficiency scores of 57.97 and 58.78 under the CRS and VRS assumptions, respectively. For this farm, the farms 40 (0.287), 54 (0.309) and 86 (0.382) are its referent units when CRS are assumed, while the DMUs 6 (0.043), 40 (0.246), 54 (0.316) and 86 (0.395) are the referents when VRS are assumed.

The production practices of the DMU-70 and its referents are compared in Table 5, and clearly, the use of inputs by the DMU-70 is 'excessive'. The 'excessive' nature of the input use by DMU-70 is borne out when the recommendations by the Central Cotton Research Institute (CCRI, 1994) are considered. According to CCRI in this area, nitrogen plays the dominant role in determining cotton yield and phosphorus contributes little, and to obtain optimal yield, there is no need to plough the land more than four or five times. As is obvious, this farm is not following the recommended practices. However, this particular farm has a greater number of land parcels (three) as compared to its peers (DMUs 6, 46, 54, and 86) which are contiguous farm holdings. This situation may have jeopardized the chances of this farm becoming efficient.

The above comparison would suggest strategies for the DMU-70 to rationalize the use of its inputs. The lambda values obtained from the DEA solution for this farm provide a composite DMU which would produce the equivalent level of output, but by using lesser levels of inputs as shown in Table 5. This information as generated by the DEA modelling approach is intrinsically interesting and the DEA model can be run to examine allocative or economic efficiency of resource use on individual farms, as illustrated in Section 8.

8. Results of allocative efficiency analysis

The interpretation of allocative efficiency depends on the assumptions made about a farmer's behaviour. Farrell (1957) assumed that cost minimization is the basis on which a farmer's allocation decision is taken to obtain a given level of output and the allocative inefficiency is a farmer's inability to equate the ratio of marginal products of inputs to the ratio of their respective prices. Lau and Yotopoulos (1971), Schmidt and Lovell (1979), and Kopp and Diewert (1982) have assumed profit maximizing behaviour and have defined allocative inefficiency as the failure to equate the marginal value product of inputs to their prices. In the DEA model, however, the behavioural assumption is

Table 5
Input use levels of the DMU-70 and its referent DMUs — the VRS case

Variables included in the DEA model	Input use levels of DMU-70	Input use levels of the referent units				Composite DMU
		DMU-6	DMU-40	DMU-54	DMU-86	
Lambda values		0.043	0.246	0.316	0.395	
Outputs						
Cotton yield (kg/ha)	2530.3	2293	3517	1956	2399	2529.5
Inputs						
Number of irrigations	10	5	6	7	5	5.878
Nitrogen fertilizer (kg nutrients/ha)	198.9	85.2	113.7	56.8	170.5	116.9
Phosphatic fertilizer[a] (kg nutrients/ha)	56.8	0	0	0	0	0
Labour use (hrs/ha)	247	139.8	172	170.8	85	135.9
Pesticide costs (Rs. per hecatre)	2842	2440	2656	1260	1297	1669
Tractor time (hrs/ha)	25.5	12.4	3.7	20.6	16.6	14.51

[a] Zero values in the 'phosphatic fertilizer' show that the efficient farmers were not using this input as it is not necessarily required for cotton production.

Table 6
Allocative efficiency scores of the cotton producers

Ranges	Number of DMUs falling in a range	
	The CRS case	The VRS case
Equal to 100%	14	34
Greater than 90% but <100%	8	19
80–<90%	9	25
70–<80%	21	23
60–<70%	22	15
50–<60%	23	1
40–<50%	13	–
Less than 40%	7	–

more subtle as the allocative efficiency is the proportion by which the costs of the levels of inputs on a farm can be reduced without any loss in output. Thus, an efficiency score of 0.8 implies that the DMU concerned could reduce its costs by 20% by choosing a more cost-efficient input mix.

In measuring allocative efficiency of cotton production, the costs of individual inputs used have been estimated by using the actual prices paid by farmers. The variables belonging to the same category were pooled together to reduce the number of cost variables in order to facilitate analysis. The variables defined were expenditure (in Rs. per hectare) on (i) land cultivation; (ii) cotton seed; (iii) thinning; (iv) inter-cultural operations; (v) fertilizer; (vi) irrigation; and (vii) pesticide usage. The results as given in Table 6 show that, assuming VRS, nearly 30% of the DMUs have an efficiency score of 1.

Results of the estimation of both technical and allocative efficiency show that technically efficient farms were also allocatively efficient. However, some units such as the DMU-101 and the DMU-111 were technically efficient but were not so allocatively.

8.1. Sensitivity analysis for an individual DMU's allocative efficiency

The DMU-83 has the lowest allocative efficiency score of 56.67 (assuming VRS) and it can be used to illustrate the use of sensitivity analysis for exploring the avenues for improving the allocative efficiency. The lambda values associated with the solution for this farm show that the DMUs 30, 47, 54, 64, 84, 86 and 113 were its referent units (see Table 7). For most of the inputs, the referent DMUs were spending considerably less than the DMU-83 particularly on pest control, fertilizer, and cultivation. Using lambda values of the referent DMUs, the targets which DMU-83 can aim at become allocatively efficient and are presented in the last column of Table 7. This farm needs to decrease its expenditure on pesticide, irrigation and land preparation operations.

9. Concluding remarks

The preceding analysis points towards the existence of a significant extent of resource use inefficiency on cotton farms in the cotton–wheat production system of Pakistan's Punjab. In many instances, the quanti-

Table 7
Sensitivity analysis for allocative efficiency of cotton production on the DMU-83

Variables	DMU-83	Referent units							
		DMU-30	DMU-47	DMU-54	DMU-64	DMU-84	DMU-86	DMU-113	Target for DMU-83
LAMBDA		0.006	0.084	0.035	0.427	0.151	0.255	0.043	
LANDPREP	1976.8	926.6	1334.3	967.4	1136.7	617.8	1541.9	864.8	1161
SEEDEXP	345.9	259.5	148.3	231.4	216.2	313	129.7	196.4	203.2
INTERCULT	1111.9	370.7	803.1	815.4	716.6	741.3	444.8	543.6	652.9
THINNING	86.50	173	0	148.3	0	86.50	98.80	148.3	50.86
FERTCOST	2762.6	2159.7	2221.4	573.3	1156.4	2421.6	1764.3	2174.5	1622
IRRICOST	2223.9	86.48[a]	86.48[a]	86.48[a]	953.1	501.9	2881	550.7	1252
PESTCOST	3763.3	2005.2	2322.7	1260.2	2619.3	2631.6	1297.3	2616.8	2210
INCOMEHA	47341.7	63343	58323.3	43664.4	45608.5	39180.8	49736.7	58456.1	47341.7

[a] Lower cost of irrigation on these farms shows that canal water was the only source of irrigation at a fixed charge of Rs. 86 per hectare for the season.

ties of inputs used were unjustifiably higher than what would be required to achieve their present levels of crop output. By using the DEA modelling approach for efficiency analysis, it is possible to achieve two types of results. First, it is possible to identify the adjustments that can be made in the use of inputs on inefficient farms by comparing them with their 'peer' farms. Second, the factors that can be manipulated to minimize the excessive use of inputs and hence reduce the costs of production can be established. However, for a meaningful interpretation of the DEA results, it is necessary to consider the totality of recommendation domains for various production practices in specific areas, as without the inclusion of all the relevant and important factors in the analysis, one cannot be assertive about the sources of inefficiencies. Nonetheless, the DEA approach has an undoubted edge over the standard production function analysis for identifying the sources of inefficiencies on individual farms. The DEA results are much easier to interpret and to utilize for investigating avenues for improvements in technology and resource use efficiency on farms.

This exercise in using the DEA modelling approach for measuring efficiency has demonstrated that there was a high degree of allocative inefficiency, as regards costs of production, on cotton-producing farms in Pakistan. However, the efficiency scores for both technical and allocative efficiencies increase with increase in the number of input variables included in the DEA model. The real advantage of DEA modelling is that it allows the specification of a multi-product, multi-input firm (Byrnes et al., 1987). The construction of the 'efficient frontier' for measuring the efficiency is achieved without having to make any pre-supposition regarding the underlying functional form and the statistical errors associated with the specification of such a function are also avoided.

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