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INPUT SUBSTITUTION AND AGRICULTURAL RESEARCH

Carlos A. Baanante and Surjit S. Sidhu*

The purpose of this paper is to describe the nature of the 'green revolution' technology, to study the effects of scale and education and to derive implications for future research directed toward generating technical change for developing agricultures. For this purpose empirical estimates of scale and education effects as well as own- and cross- price elasticities of demand and partial elasticities of input substitution in the production of Mexican wheat varieties (MWVs) are obtained from a cross-section of farm level data from the Indian Punjab.

For empirical analyses of agricultural production, the Cobb-Douglas form of production function has found almost universal acceptability. However, for more than two factors of production, the implied assumptions of separability and constant elasticity of substitution are highly restrictive. This is a crucial point if the basic aim of a research effort is empirical analysis of the structural and input substitution relationships of a particular production technology. The choice of the function and *a priori* restrictions on its form should be scrutinized by empirical analysis. An approach that does not impose restrictions on input substitution possibilities and patterns is required. For this purpose, application of the cost function[1] based on the development of the translog functional forms[2] is considered a more useful approach. In this paper, therefore, the translog cost function, for which the underlying production function is not restricted to any particular functional form, is the analytical tool used for empirical implementation.

In the next section a brief description is provided of the translog cost function model and the relationships linking the parameter estimates to partial elasticities of substitution and elasticities of input demand. Then the data and

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* Economists, International Fertilizer Development Center (IFDC), Muscle Shoals, Alabama, U.S.A. The authors would like to acknowledge the helpful comments from colleagues at IFDC and Hans P. Binswanger, Lawrence J. Lau, and Vernon W. Ruttan and an anonymous referee of this Journal.

1. Hans P. Binswanger, "A Cost Function Approach to the Measurement of Elasticities of Factor Demand and Elasticities of Substitution", *American Journal of Agricultural Economics*, Vol. 56, No. 2, May 1974, pp. 377-386 and "Measured Biases of Technical Change: The United States", in H. P. Binswanger, V. W. Ruttan *et al.* (Eds.): Induced Innovation: Technology, Institutions and Development, The Johns Hopkins University Press, Baltimore, 1978, pp. 215-242. See also J. S. Hekman, "An Analysis of the Changing Location of Iron and Steel Production in the Twentieth Century", *The American Economic Review*, Vol. LXVIII, No. 1, March 1978, pp. 123-133; and Toshiyuki Kako, "Decomposition Analysis of Derived Demand for Factor Inputs: The Case of Rice Production in Japan", *American Journal of Agricultural Economics*, Vol. 60, No. 4, November 1978, pp. 628-635.

2. L. R. Christensen, D. W. Jorgenson and L. J. Lau, "Transcendental Logarithmic Production Frontiers", *The Review of Economics and Statistics*, Vol. LV, No. 1, February 1973, pp. 28-45; W. E. Diewert, "An Application of the Shepherd Duality Theorem: A Generalized Leontief Production Function", *The Journal of Political Economy*, Vol. LXXIX, No. 3, May-June 1971, pp. 481-507 and "Functional Forms for Profit and Transformation Functions", *Journal of Economic Theory*, Vol. 6, 1973, pp. 284-316.

the estimation procedure used in this study are briefly described. In the last section empirical estimates and policy implications for agricultural development and research are discussed.

THE TRANSLOG COST FUNCTION MODEL

For minimization of total costs, C, subject to a production function, there exists a corresponding minimum cost function, C*, which may be written as:

(1) $C^* = f(Q, E, P_1, \ldots, P_n)$

where Q is total output, E is education, and Ps are input prices.

The 'translog' version of the cost function is considered to be one of the more general functions to approximate production and cost relationships in agriculture. As a logarithmic Taylor series expansion, this function can be written as follows:[3]

$$(2)\ \ln C^* = v_o + v_q \ln Q + \sum_i v_i \ln P_i + 1/2 \sum_i \sum_j \gamma_{ij} \ln P_i \ln P_j + \sum_i \gamma_{iq} \ln P_i \ln Q + \sum_i \gamma_{ie} \ln P_i \ln E + \text{remainder} \qquad i = 1, 2, \ldots, n; \quad j = 1, 2, \ldots, n.$$

where v_0, v_q, v_i, γ_{ij}, γ_{iq} and γ_{ie} are parameters of the cost function. Cobb-Douglas is a special case of this function when all $\gamma_{ij} = 0$.

The relevant properties of this function are as follows:[4]

(*a*) The equality of the cross-derivatives,

$$\frac{\partial^2 \ln C^*}{\partial \ln P_i \, \partial \ln P_{j0}} = \frac{\partial^2 \ln C^*}{\partial \ln P_j \, \partial \ln P_{i0}},$$ implies the symmetry

between parameters γ_{ij} and γ_{ji} for all $i \neq j$.

(*b*) C* is homogeneous of degree one in all input prices, which implies

$$\sum_i v_i = 1; \quad \sum_i \gamma_{ij} = 0; \quad \sum_j \gamma_{ji} = 0.$$

(*c*) Partial elasticities of substitution (σ_{ij}) and own- and cross-price elasticities of input demand (η_{ii} and η_{ij}) are related to the γ_{ij} parameters as follows:

$$(3) \quad \sigma_{ij} = \frac{1}{\alpha_i \alpha_j} \gamma_{ij} + 1 \quad \text{for all } i, j; i \neq j,$$

$$(4) \quad \sigma_{ii} = \frac{1}{\alpha_i^2} (\gamma_{ii} + \alpha_i^2 - \alpha_i) \quad \text{for all } i,$$

$$(5) \quad \eta_{ij} = \frac{\gamma_{ij}}{\alpha_i} + \alpha_j \quad \text{for all } i, j; i \neq j,$$

$$(6) \quad \eta_{ii} = \frac{\gamma_{ii}}{\alpha_i} + \alpha_i - 1 \quad \text{for all } i,$$

where α_i and α_j are shares in the total cost of input i and j, respectively.

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3. Binswanger, *op. cit.*; Hekman, *op. cit.*; and Kako, *op. cit.*
4. Binswanger, *op. cit.*; and Kako, *op. cit.*

It is obvious from the above that if parameter estimates γ_{ij} are obtained from (2) and if information on input shares is available, all partial elasticities of substitution and elasticities of input demand can be calculated. For this purpose, the cost function (2) may be estimated directly. It has been shown,[5] using Shepherd's duality theorem, that the first derivatives of (2) with respect to the logarithms of the input factor prices are equal to the respective input shares in the total cost. The cost function thus may be estimated jointly with (n− 1) input share equations.[6] The input share equations can written as:

$$(7) \quad \frac{\partial \ln C^*}{\partial \ln P_i} = \alpha_i = v_i + \sum_j \gamma_{ij} \ln P_j + \gamma_{iq} \ln Q + \gamma_{ie} \ln E \qquad i = 1,2, ---, n.$$

Conceptually, it is equivalent to obtaining cost function estimates by jointly estimating input share equation (7) with or without including the cost equation (2). Operationally, however, it is much simpler to estimate jointly the (n—1) input equations alone.

THE DATA AND THE ESTIMATION PROCEDURE

The basic farm level data for this research pertain to Mexican wheat varieties (MWVs) grown during the crop year 1970-71 in the Indian Punjab. These data were obtained from a stratified random sample spread over four different parts of the State and are thus quite representative of wheat production in the State. The data have earlier been used in Sidhu and Baanante.[7]

A brief description of the variables developed for this research and the notation used are as follows:

Q = physical output of wheat measured in kilograms of wheat per farm, including by-products converted into kilograms of wheat equivalent at current prices.

P_N = the money wage rate of labour per hour. It is obtained by dividing the total labour expenditure for wheat production per farm by the quantity of labour including both family and hired labour.[8]

P_A = the money price of animal power per hour. It is obtained by dividing

5. Y. Mundlak, "Elasticities of Substitution and the Theory of Derived Demand", *The Review of Economic Studies*, Vol. XXXV, No. 102, April 1968, pp. 225-236. D. W. Jorgenson and L. J. Lau, "Duality and Differentiability in Production", *Journal of Economic Theory*, Vol. 9, 1974, pp. 23-42; H. Uzawa, "Duality Principles in the Theory of Cost and Production", *International Economic Review*, Vol. 5, No. 2, May 1964, pp. 216-220; and Binswanger, *American Journal of Agricultural Economics*, May 1974, *op. cit.*

6. L. R. Christensen, D. W. Jorgenson and L. J. Lau, "Conjugate Duality and the Transcendental Logarithmic Production Function (unpublished).

7. S. S. Sidhu and C. A. Baanante, "Farm-Level Fertilizer Demand for Mexican Wheat Varieties in the Indian Punjab", *American Journal of Agricultural Economics*, Vol. 61, No. 3, August 1979, pp. 455-462.

8. The total labour expenditure per farm includes the imputed costs of family labour at the wage rate paid to permanent hired labour. Child and female labour is converted into man equivalents by treating two children (or women) equal to one man.

the total animal power expenditure for wheat production per farm by the hours of use of animal power.

P_F = the money price per kilogram of fertilizer nutrients ($N + P_2O_5 + K_2O$).

P_I = the money price of irrigation water per acre-irrigation. It is obtained by dividing total water costs by the number of acre-irrigations. An acre-irrigation represents the amount of water required to irrigate once an acre of land by the flood irrigation method.

P_L = the average rental price of land per acre per farm. It is obtained by dividing the total rental cost of land under wheat per farm by the number of acres of wheat land per farm. The total rental cost of land services for wheat production per farm includes the actual rent paid for rented-in land in cash or share of the produce and the imputed rental values of owned lands. For imputing rental values of owned lands, the actual rental rates of the fields in close proximity (considered as equivalent in land fertility) are applied. For land producing two crops during the year, half of the annual rent is treated as the share of the wheat crop.

P_K = price of capital equipment and machinery. The quantity of capital equipment and machinery is measured as annualized cost of total expenditures and investments on these inputs. Thus, the implicit price is unity. An interest rate of 10 per cent is used to determine the annuities.

C = total cost of wheat production per farm measured in rupees. It is the sum of expenditures on labour, animal power, fertilizers, irrigation water, land, and annualized cost of capital equipment and machinery.

α_N, α_A, α_F, α_I, α_L, α_K = the expenditure shares (in total cost) of labour, animal power, fertilizer, irrigation water, land, and capital equipment and machinery inputs respectively.

E = the average number of years of schooling per family member (over 13 years of age) of the farm household.

The model consisting of six share equations (7) is estimated with the data pertaining to the MWVs from the Indian Punjab. Since only five of the six equations are linearly independent,[9] the share equation for capital input is dropped.[10] Farms are assumed to be price-takers, and thus all price variables on the right-hand side of the share equations are proper exogenous variables. The inclusion of output on the right-hand side is somewhat problematic. If farmers maximize profits and are not only cost minimizers at fixed output levels, output cannot be considered a truly exogenous variable. Strong correlation between cost and output variables can cause statistical problems in estimating the model. The problem, however, is not as severe if cost function (2) is not included in the estimating model. Inclusion of output in the share equations does, however, afford

9. Diewert, *Journal of Economic Theory*, 1973, *op. cit.*

10. In fact, any one of the six equations can be dropped. This particular equation is excluded because the quantity of capital input is measured as an annual flow, and thus its price is unity.

an important advantage. It permits the study of neutral or non-neutral scale effects (or efficiency differences) across farms. These scale effects should, however, be interpreted with caution since output is not a truly exogenous scale measure. Similarly, including education in the model allows an evaluation of the neutral or non-neutral effects of education on efficiency across farms.

For statistical specification additive errors with zero expectations and finite variance are assumed for each of the five equations of the model. The covariances of the errors of any two of the equations for the same farm may not be zero, but the covariances of the errors of any two equations corresponding to different farms are assumed to be identically zero. Under these assumptions an asymptotically efficient method of estimation[11] is used to estimate jointly the five input share equations (7) by the application of restricted generalized least squares. In addition to the symmetry constraints ($\gamma_{ij} = \gamma_{ji}$ for all $i \neq j$) imposed across equations, the coefficients with respect to the price of capital equipment and machinery are estimated residually using the homogeneity constraint ($\sum_j \gamma_{ij}=0$, for all i, j).

EMPIRICAL ESTIMATES AND CONCLUSIONS

At this stage, it should be pointed out that the implications derived in this section are based on empirical estimates describing the MWV production technology. No comparison of the MWV technology is carried out with the traditional wheat technology. At the time of data collection during 1970-71, and most certainly by now, the MWVs are the dominant wheat varieties grown in the Indian Punjab.

The restricted estimates of the parameters of the translog cost function model obtained by jointly estimating the six share equations (7) are presented in Table I. The estimates of parameters γ_{ij} in Table I and simple averages of input shares are used to compute, from equations (3-6), the elasticities of input demands, and partial elasticities of input substitution, which are presented in Tables III and IV respectively.

The Cobb-Douglas cost function is a special case of the translog cost function, when all $\gamma_{ij} = 0$.[12] Therefore, the estimates of parameters γ_{ij} can be used to test the hypothesis that the cost function (and the underlying production function) for MWVs in the Indian Punjab is of the Cobb-Douglas type. The hypothesis $\gamma_{ij} = 0$ for all i, j was tested using an F-test. The hypothesis was rejected at the one per cent level of significance.[13] This result, obtained under the assumptions of the model used, casts some doubt on the appropriateness of using Cobb-Douglas specification to characterize MWV technology in the Indian Punjab.

11. Arnold Zellner, "An Efficient Method of Estimating Seemingly unrelated Regressions and Tests of Aggregation Bias", *Journal of American Statistical Association*, Vol. 57, No. 2, June 1962, pp. 348-375.

12. Binswanger, *American Journal of Agricultural Economics*, May 1974, *op. cit.*, and Hekman, *op. cit.*

13. The computed F value is 34.49 with 10 and 537 degrees of freedom.

TABLE I—RESTRICTED ESTIMAES OF THE COEFFICIENTS OF THE INPUT SHARE EQUATIONS OF THE TRANSLOG COST FUNCTION, MWVs: 1970-71, PUNJAB, INDIA

Dependent variable	Price of						Intercept	Output	Education
	Labour (P_N)	Animal power (P_A)	Fertilizer (P_F)	Irrigation (P_I)	Land (P_L)	Capital equipment and machinery[a] (P_K)			
Share of :									
Labour (α_N)	0.2072* (9.36)	—0.0531* (—8.06)	—0.0736* (—3.05)	—0.0034 (—0.57)	—0.1002* (—8.45)	0.0231	0.9733* (13.51)	0.0002 (0.04)	—0.0100* (—2.96)
Animal power (α_A)	—0.0531*	0.0321* (3.25)	0.0059 (0.85)	—0.0043 (—1.12)	—0.0246* (3.48)	0.0440	0.6822* (9.09)	—0.0483* (—6.60)	0.0100* (2.03)
Fertilizer (α_F)	—0.0736*	0.0059	0.0378 (0.64)	—0.0192* (—2.88)	0.0048 (—0.35)	0.0539	—0.0379 (—0.43)	0.0175* (3.12)	0.0063** (1.88)
Irrigation (α_I)	—0.0034	—0.0043	—0.0192*	0.0622* (15.37)	—0.0279* (—5.52)	—0.0074	0.0498 (1.36)	0.0087* (2.89)	—0.00006 (—0.03)
Land (α_L)	—0.1002*	—0.0246*	—0.0048	—0.0279*	0.1640* (12.87)	—0.0065	—0.5288* (—6.95)	0.0030 (0.52)	—0.0066** (—1.71)
Capital equipment and machinery (α_K)	0.0231	0.0440	0.0539	—0.0074	—0.0065	—0.1071	—0.1386	0.0189	0.00036

(a) Estimates derived from homogenity constraint.
Asymptotic t-values are in parentheses.
*Significant at 0.05 level of significance ($t_{0.05}$ = 1.96).
**Significant at 0.10 level of significance ($t_{0.10}$ = 1.64).
Number of observations for each equation = 95.

TABLE II—SCALE AND EDUCATION EFFECTS ON INPUT COST SHARES

Type of farmer		Education level*	Output level (kg./farm)	Input cost shares					
Education	Scale			Labour	Animal power	Fertilizer	Irrigation	Land	Capital
Low	Small	0.40	3,400	0.308	0.190	0.073	0.058	0.328	0.043
Average	Small	2.48	3,400	0.290	0.208	0.085	0.058	0.316	0.043
High	Small	4.60	3,400	0.284	0.214	0.089	0.058	0.312	0.043
Low	Average	0.40	13,861	0.308	0.122	0.098	0.070	0.332	0.070
Average	Average	2.48	13,861	0.290	0.140	0.110	0.070	0.320	0.070
High	Average	4.60	13,861	0.284	0.146	0.114	0.070	0.316	0.070
Low	Large	0.40	24,300	0.308	0.095	0.108	0.075	0.334	0.080
Average	Large	2.48	24,300	0.290	0.113	0.120	0.075	0.322	0.080
High	Large	4.60	24,300	0.284	0.119	0.124	0.075	0.318	0.080

*Average number of years of schooling per family member.

TABLE III—DERIVED[a] ESTIMATES OF OWN- AND CROSS-PRICE ELASTICITIES OF INPUT DEMAND, MWVs: 1970-71, PUNJAB, INDIA

Factors	Prices of					
	Labour	Animal power	Fertilizer	Irrigation	Land	Capital equipment and machinery
	(P_N)	(P_A)	(P_F)	(P_I)	(P_L)	(P_K)
Cobb-Douglas case :						
Labour	—0.7112	0.1376	0.1104	0.0701	0.3263	0.0668
Animal power	0.2888	—0.8624	0.1104	0.0701	0.3263	0.0668
Fertilizer	0.2888	0.1376	—0.8896	0.0701	0.3263	0.0668
Irrigation	0.2888	0.1376	0.1104	—0.9299	0.3263	0.0668
Land	0.2888	0.1376	0.1104	0.0701	—0.6737	0.0668
Capital equipment and machinery	0.2888	0.1376	0.1104	0.0701	0.3263	—0.9332
Estimated translog cost function :						
Labour	0.0062	—0.2483*	—0.5562*	0.0216	0.0192	0.4126
	(0.08)	(—11.29)	(—6.70)	(1.08)	(0.47)	
Animal power	0.1049*	—0.6291*	0.1638*	0.0087	0.2509*	0.7254
	(2.19	(—8.74)	(3.28)	(0.32)	(4.92)	
Fertilizer	0.0339	0.1804*	—0.5472	—0.2038*	0.3121*	0.8736
	(0.16)	(2.91)	(—1.02)	(—3.40)	(2.48)	
Irrigation	0.2770*	0.1063*	—0.0635	—0.0425	0.2407*	—0.0439
	(3.30)	(1.93)	(—0.67)	(—0.75)	(3.34)	
Land	—0.0581	—0.0411**	0.0669	—0.3279*	—0.1710*	—0.3050
	(—1.61)	(—1.87)	(1.56)	(—21.86)	(—4.38)	
Capital equipment and machinery	0.6346	0.7962	0.9172	—0.0406	0.2289	—2.5364

(a) Derived from equations 5 and 6 using simple averages of input shares and estimates presented in Table I.

Asymptotic t-values are in parentheses. Standard errors are $SE = \frac{\gamma_{ij}}{\alpha_i}$.

*Significant at 0.05 level of significance ($t_{0 \cdot 05} = 1.96$).
**Significant at 0.10 level of significance ($t_{0 \cdot 10} = 1.64$).

TABLE IV—DERIVED[a] ESTIMATES OF THE PARTIAL ELASTICITIES OF INPUT SUBSTITUTION, MWVs: 1970-71, PUNJAB, INDIA

Factors	Labour (P_N)	Animal power (P_A)	Fertilizer (P_F)	Irrigation (P_I)	Land (P_L)	Capital equipment and machinery (P_K)
Labour	0.0215 (0.08)	—0.337* (—2.04)	—1.308** (—1.73)	0.832* (2.85)	0.063 (0.50)	2.197
Animal power		—4.5731* (—8.76)	1.388* (3.05)	0.554 (1.39)	0.452* (2.88)	5.787
Fertilizer			—4.9606 (—1.02)	—1.493** (—1.72)	0.867* (2.23)	8.313
Irrigation				—0.6122 (—0.74)	—0.244 (—1.10)	—0.581
Land					—0.5253* (—4.41)	0.702
Capital, equipment and machinery						—37.991

(a) Derived from equations 3 and 4 using simple averages of input shares and estimates presented in Table I.

Asymptotic t-values are in parentheses. Standard errors are SE $= \frac{\gamma_{ij}}{\alpha_i \alpha_j}$.

*Significant at 0.05 level of significance ($t_{0.05} = 1.96$).
**Significant at 0.10 level of significance ($t_{0.10} = 1.64$).

Coefficient estimates of the output and education variables presented in Table I should be interpreted as measures of constant rates of change in input shares as logarithms of output (scale) and education variables change. If all γ_{iq} and all γ_{ie} are zero, scale and education effects are neutral. Non-neutrality and biases of the technology, with respect to these variables, are indicated by the presence of coefficient estimates significantly different from zero.[14] From the estimates presented in Table I, the following conclusions can be drawn with respect to scale and education effects in the production of MWVs in the Indian Punjab.

Scale Effects

In the production of MWVs in the Indian Punjab the effects of scale (output level) for animal power, fertilizer, irrigation, and capital equipment and machinery appear to be important. The coefficient estimates for output are significant in the animal power, fertilizer, and irrigation share equations. The output coefficients in animal power, fertilizer, irrigation, and capital equipment and machinery respectively are —0.0483, 0.0175, 0.0087, and 0.0189. Thus for MWV technology, at given input prices and levels of education, the effects of increasing scale of operation (output level) are fertilizer using, irrigation water using, capital equipment and machinery using, and animal power saving. It should also be noted that, as the scale of operation (output level) increases, the shares of labour and land are not affected significantly.

Education Effects

Effects of education on factor shares across farms are significant in the case of labour, animal power, fertilizer, and land. The coefficient estimates for education in these equations are — 0.0100, 0.0100, 0.0063, and — 0.0066 respectively. This means that, at given factor prices and output levels, the effect of more education is labour saving, land saving, animal power using, and fertilizer using.

It is interesting to note from the animal power equation in Table I that at larger output levels (larger farms), holding input prices and education fixed, the scale effect in the MWV technology is animal power saving and that at higher education levels, holding prices and output level constant, the education effect is animal power using. The animal power saving scale effect is probably the result of substitution of capital equipment and machinery for animal power. This supports the well-known fact that subsidisation of capital inputs in the Indian Punjab during the period under investigation was substantially more favourable to the larger farmers.[15] Also it should be noted that, as the scale of operation (output level) increases and as the level of education increases, the MWV technology is fertilizer using. The importance of the above conclusions with res-

14. Note that $\sum_i \gamma_{iq} = 0$; $\sum_i \gamma_{ie} = 0$ by the homogeneity constraint.

15. S. S. Sidhu, "Economics of Technical Change in Wheat Production in the Indian Punjab", *American Journal of Agricultural Economics*, Vol. 56, No. 2, May 1974, pp. 217-226.

pect to scale and education effects is highlighted in Table II for farmers with low, average, and high levels of education and output.

Input Substitution and Demand

In Table III, the elasticities of input demand in the translog case computed at simple averages of input shares are compared with the Cobb-Douglas case ($\gamma_{ij} = 0$ for all i, j). The own-price demand elasticities are smaller (absolute value) in the translog case for all inputs except capital equipment and machinery. This is because only the coefficient γ_{kk} is negative. In fact, the values of own demand coefficients of labour, irrigation (coefficient estimates not significantly different from zero), and land indicate quite inelastic response. Only the demand for capital input indicates a more elastic response than the Cobb-Douglas case ($\gamma_{kk} < 0$).

The translog matrix of input demand elasticities provides a complete description of the structure of input demand in the production of MWVs in the Indian Punjab. Each row represents demand function for the ith factor mentioned on the left-hand side. Each η_{ij} is the elasticity of demand for the ith input with respect to a price change of the jth input, holding other prices, output and education constant. Elasticities in each column represent response of the ith factor to a change in the price of the jth factor. It should be noted that the demand for fertilizer is influenced significantly by changes in all input prices except labour price. Changes in the wage rate of labour do not appear to influence fertilizer demand significantly. On the other hand, a decrease (increase) in fertilizer price leads to a substantial expansion (reduction) in labour demand. It should be pointed out that the demand for labour is influenced much more by the changes in fertilizer and animal power prices than by the changes in the wage rates. Thus, a reduction in fertilizer price through subsidies is expected to expand fertilizer use and employment of labour.[16] This result should be of importance for other densely populated developing countries where MWVs are grown under conditions similar to those of the Indian Punjab. Also a decrease in the price of irrigation water, through policies directed to expand the supply of irrigation water, is expected to increase fertilizer use in the production of MWVs in the Indian Punjab.

The partial elasticity of substitution (σ_{ij}) between inputs i and j measures the change in the demand for the ith input as a result of a change in the price of the jth input normalised by the price of the ith input, holding all input prices (other than the jth input), output, and education constant but allowing other input quantities to vary. Positive (negative) values of σ_{ij} indicate that inputs i and j are substitutes (complements). The σ_{ij} are better measures than η_{ij}

16. Binswanger, *American Journal of Agricultural Economics*, May 1974, *op. cit.* See also E. R. Berndt and L. R. Christensen, "The Internal Structure of Functional Relationships: Separability, Substitution, and Aggregation", *The Review of Economic Studies*, Vol. LX, No. 123, 1973, pp. 403-410; and I. Morrisset, "Some Recent Uses of Elasticity of Substitution—A Survey", *Econometrica*, Vol. 21, 1953, pp. 41-62.

of the strength of substitution or complementarity among inputs since the magnitudes of η_{ij} are influenced by the input cost shares whereas the magnitudes of σ_{ij} are not. The matrix of derived estimates of the partial elasticities of substitution (σ_{ij}), presented in Table IV, characterizes the production technology of MWVs in the Indian Punjab in terms of the nature of input substitution (or complementarity) relationships. This information is helpful to guide efforts directed toward the development of new agricultural technology and to compare the nature of input substitution across technologies for which similar information is available.

The results seem to indicate some substitution possibilities between capital equipment and machinery input and all other inputs except irrigation water. In other words, MWV technology is such that capital equipment and machinery can be easily substituted for labour, animal power, fertilizer, and land and vice versa. In addition, significant substitutability is indicated among input pairs of labour and irrigation, animal power and fertilizer, animal power and land, and fertilizer and land.

On the other hand, the results presented in Table IV also indicate that for input pairs of labour and animal power, labour and fertilizer, and fertilizer and irrigation there exist significant complementary relationships.[17] These results have important implications for agricultural research and development policies of the developing countries. First, they confirm the symbiotic nature of the 'green revolution' technology as the seed-fertilizer-irrigation technology. Second, the existence of strong and significant complementarity between the input pairs of fertilizer and irrigation and fertilizer and labour in the production of MWVs in the Indian Punjab and the fact that the MWVs are highly responsive to fertilizer, suggest that the rate of diffusion of these varieties should be faster in areas where the supply conditions (prices and availability) of these three inputs are favourable. In general, the availability of labour is a less serious constraint. This is especially true in densely populated areas. Even in less densely populated areas the in-migration and substitution of labour by capital equipment are distinct possibilities. Complementarity of labour and fertilizer, thus, is is not a very serious constraint on the diffusion of MWVs and for the expansion of fertilizer use provided fertilizer supplies are available.

The complementarity between fertilizer and irrigation, however, is a different matter. In most low moisture areas the development of irrigation requires long run planning and large investments. Thus, in the absence of irrigation even with assured fertilizer availability, the diffusion of MWVs and expansion in fertilizer use in low moisture areas could be seriously constrained. On the other hand, this will be true even under assured moisture conditions if large investments and long run planning are required to ensure availability of fertilizer. Thus, the fertilizer-irrigation complementarity, as evidenced in this paper, implies

17. This complementarity among labour, fertilizer and irrigation in the MWV technology explains in part the substantial increase in the demand for these inputs after the introduction of these varieties in the Indian Punjab. See Siddhu, *op. cit.*

that heavy investments in irrigation and/or fertilizer supply infrastructure are necessary if seed-fertilizer technologies like the MWVs are to diffuse. This poses a dilemma for the agricultural and economic development of the arid areas of the world, especially the developing countries with limited resources. One of the important challenges for agricultural research, thus, may be to generate at reasonable costs technology appropriate for increasing agricultural production under low moisture conditions.

In order to face this challenge successfully, agricultural research effort should focus on the following problem areas:

(a) Development of biological materials with high response to fertilizer under low moisture conditions.

(b) Development of fertilizer materials to economically increase crop response to fertilizer use under low moisture conditions.

(c) Development of economically efficient agronomic and agro-engineering technologies which increase crop response to fertilizer under low moisture conditions.

Here it is important to emphasize the interrelatedness that exists among these three problem areas and that a carefully planned and well co-ordinated research effort in these three areas is more likely to be successful. Research in these areas which results in a reduction of the complementarity between water and fertilizer is expected to facilitate the development of agriculture in countries where water is a relatively scarce resource. Since agriculture in dry arid areas is in general poor, the income distribution effects of this type of research should be quite favourable within and across developing countries. In addition, the favourable income distribution and employment effects of this research should be reinforced by the existence of complementarity between fertilizer and labour. Research on fertilizer materials and adaptive agronomic and irrigation-engineering technology which may enhance substitution of fertilizer for water could also have favourable diffusion effects in the case of existing high-yielding varieties (HYVs). This again should have favourable income distribution effects.

Investigation of the structure of production and demand of the HYVs has not received sufficient attention in the literature on the 'green revolution'. Evenson,[18] while discussing the diffusion of HYVs, reports a lack of correlation between irrigation infrastructure and agricultural productivity in Indian agriculture. However, the diffusion rates of MWVs in different States of India are fairly well correlated to the irrigation levels. This is what one would expect given that the MWVs are highly fertilizer responsive and given the existence of complementarity between fetilizer and water as the evidence suggests from the present research. Apart from whether there is strong correlation between productivity and irrigation, the MWVs do not appear to be succeeding in dry unirrigated

18. R. Evenson, "The 'Green Revolution' in Recent Development Experience", *American Journal of Agricultural Economics*, Vol. 56, No. 2, May 1974, pp. 387-394, and "Technology Generation in Agriculture", in L. G. Reynold (Ed.): Agriculture in Development Theory, Yale University Press, New Haven, 1975, pp. 192-223.

areas. On the other hand, studies by Hayami,[19] Hayami and Kikuchi,[20] and Hsieh and Ruttan[21] indicate that the development of irrigation infrastructure is a critical condition for increasing food output which reinforces the main implication of this paper, that is, the necessity of producing seed-fertilizer technology appropriate for low moisture conditions.

In summary, it should be emphasized that economics' research on farm production structure has not explicitly included irrigation water as an input, and thus the nature of relatedness of water with fertilizer and other inputs and the consequent implications for future seed-fertilizer-irrigation research remained somewhat obscure. The empirical results presented in this paper support the view that one of the important constraints for expanding the role of fertilizer in wheat production in low moisture regions of the world may be the existence of strong complementarity between fertilizer and water that characterizes the production of present HYVs. Hence, future research should focus on the reduction of this complementarity.

19. Y. Hayami, "Conditions for the Diffusion of Agricultural Technology: An Asian Perspective", *The Journal of Economic History*, Vol. XXXIV, 1974, pp. 131-181.

20. Y. Hayami and M. Kikuchi, "Investment Inducements to Public Infrastructure: Irrigation in the Philippines", *The Review of Economics and Statistics* Vol. LX, No. 1, February, 1978, pp. 70-77.

21. S. C. Hsieh and V. W. Ruttan, "Environmental, Technological and Institutional Factors in the Growth of Rice Production: Philippines, Thailand and Taiwan", *Food Research Institute Studies*, Vol. VII, No. 3, 1967, pp. 307-341; and V. W. Ruttan "Reviewing Agricultural Research Programmes", *Agricultural Administration*, Vol. 5, 1978, pp. 1-19.