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A cross-country comparison of land-fertilizer substitution rates and implications for world food production

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A cross-country comparison of land-fertilizer substitution rates and implications for world food production

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by

Philip Alan Treffeisen

A Thesis Submitted to the

Graduate Faculty in Partial Fulfillment of the

Requirements for the Degree of

MASTER OF SCIENCE

Department: Economics
Major: Agricultural Economics

Signatures have been redacted for privacy

Iowa State University
Ames, Iowa

1980

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TABLE OF CONTENTS

EQUIVALENTS OF WEIGHTS AND MEASURES IN THE ENGLISH AND METRIC SYSTEMS

1 kilogram = 2.2 pounds

1 pound = .454 kilogram

1 hectare = 2.47 acres

1 acre = .405 hectare

1 kilogram per hectare = .891 pound per acre

1 pound per acre = 1.12 kilograms per hectare

INTRODUCTION: THE WORLD FOOD PROBLEM

One of the most pressing problems facing the world today is that of increasing the availability of food in the developing countries of Asia, Africa, and Latin America. There is some evidence that global food shortages are caused artificially, through deliberate restrictions on production, failure to maintain grain reserves at adequate levels, and the simple fact that many countries are unwilling or unable to import sufficient quantities of food to feed their people. Regardless of the causes of shortages, however, the need for rapid worldwide increases in food production cannot be denied. Effective demand for food is increasing at a rate of 2.5 percent per year. Eighty percent of this rise is due to population growth, the rest to increased incomes (Chou et al., 1977). Total world grain production has managed to keep pace with population growth in recent years, but certain regions lag behind. In Africa, for example, per capita food production dropped throughout the decade of the 1970's (FAO, 1978a).

That world food production manages to keep pace with effective demand belies the fact that there are millions in the world who are malnourished because they do not have sufficient income to purchase an adequate diet. The traditional measure of malnutrition has been protein consumption. However, in recent years it has been found that fulfillment of a minimum caloric requirement will most likely eliminate the protein deficit as well. Reutlinger and Selowsky (1976) have developed a methodology for determining minimum caloric requirements which takes into account differences in climate and activity levels. They estimate that in 1975 1.3

billion persons in the "developing market economies" (i.e., excluding China) had diets which failed to meet minimum caloric standards. Using a lower caloric standard, the number was still 900 million. The FAO has arrived at the much lower figure of ten percent of the world's population with an insufficient protein-energy supply (Chou et al., 1977). This is somewhat fewer than 400 million persons, certainly a significant number even if it is smaller than the other estimates.

Cereal grains, particularly rice, wheat, and maize, are a major component of the world's diet. Consumed directly, they provide fifty-three percent of total human caloric intake (Paddock and Paddock, 1967). In addition, a large amount of grain is consumed indirectly through feeding to animals.

Wheat, rice, and maize are all grown over wide areas of the earth's surface, but the major grain exporters are an exclusive club indeed. In 1977 over half of world wheat exports came from Canada and the USA. Australia supplied about twelve percent of the 66 million metric ton total, while France and Argentina each contributed approximately nine percent. These five countries together were responsible for only 28 percent of total wheat production but 87 percent of total wheat exports (FAO, 1978b). Part of the reason for the discrepancy in these figures is that the USSR, the world's largest wheat producer, is a major importer rather than exporter. Due largely to erratic weather conditions, but possibly also to inefficiencies in collectivized agriculture, the Soviet Union often finds it necessary to import massive quantities of wheat. This provokes large increases in the world market price. Developing countries then find themselves able to purchase less grain than anticipated, and at a higher price.

Maize (corn) production has spread from its original home in the Americas to all corners of the globe. Nevertheless, there are only a few countries which produce the crop in quantities which could be termed significant. In 1977 the US produced almost half of the world crop of 350 million metric tons. The next largest producers were China, Brazil, the USSR, and Romania. These five countries together accounted for just over two-thirds of the total production. With respect to exports, the United States was even more dominant. It provided almost 71 percent of total maize exports. Argentina was a distant second (9.6 percent), followed by South Africa and Thailand, each with around three percent of the total (FAO, 1978b). Most maize traded in international markets is for livestock feed.

Rice is generally thought of as a crop of Asia, though it is grown on all of the inhabited continents. The five largest producers in 1977 were all in Asia: China, India, Indonesia, Bangladesh, and Japan. These countries provided seventy-six percent of total world production (FAO, 1978a). In total, Asia produces and consumes ninety percent of the world's rice.

Very little rice leaves its country of origin. Out of a total world production of 336 million metric tons in 1977, fewer than eleven million tons were exported. Half of the exports were from Thailand and the US alone (FAO, 1978a,b).

Rice imports by developing countries are often intended to stave off crisis situations, to mitigate the effects of a bad harvest or to raise grain availability by a small but critical amount. Exports by developing countries are a windfall gain in years of good harvests. World market prices for rice tend to fluctuate wildly, as year-to-year climatic conditions convert countries from net exporters to net importers and vice-versa.

It is obvious that increased grain production in developing countries should be a high-priority matter. The much heralded "green revolution" has brought large increases in production to some countries. However, the new high-yielding varieties require increased use of expensive chemical inputs, particularly fertilizers. Research is needed to determine the optimal allocation of these scarce inputs, and this paper presents such an analysis for fertilizer.

Purpose of Study

The present study compares fertilizer-response functions for wheat, rice, and maize in selected groups of countries. Three levels of fertilizer application are determined for each function: the level for maximum yield, the economic optimal level, and a level corresponding to two-thirds of the optimal. Economic returns above fertilizer cost are determined for each dosage. Then using the methodology of Heady (1963), the response functions are transformed into land-fertilizer equations. The equations for land-fertilizer isoquants are computed at the three yield levels previously determined. Marginal rates of substitution between land and fertilizer are determined at a number of points on the isoquants. The production potential from improved management and increased fertilizer use is estimated, together with the amount of land which could be saved by producing current output with more fertilizer. Finally, the results of the analysis are compared across countries, and implications for global food production are discussed.

REVIEW OF LITERATURE

Fertilizer Response Functions

Heady and Dillon (1961, 1972) provide a review of the development of production function studies. The attempt to express the relationship between fertilizer application and crop yield in algebraic form dates from the mid-nineteenth century. Justus von Leibig in 1855 defined his "law of the minimum" by stating that the lack in the soil of one element necessary for the growth of a plant would make the soil barren for that plant. Yield was proportional to plant nutrients already present in the soil or applied as fertilizer, and when all nutrients were present in sufficient quantities, an additional application of one or more of them would not increase yield. Von Leibig did not specify a particular algebraic form. However, Baule interpreted the law of the minimum to mean that plants used nutrients in a fixed ratio and that yield response would be dependent on the nutrient with the smallest supply relative to the quantity required.

Mitscherlich in 1909 was the first researcher to indicate a specific algebraic form for crop yield response. He suggested the following equation:

$$\log A - \log (A - y) = CX \qquad (1)$$

A is maximum total yield when the nutrient X is not deficient and C indicates the rate at which marginal yield declines. Mitscherlich later altered the equation to allow for negative marginal products (declining total yield):

$$Y = (1 - 10^{-CX})(10^{-KX})(10^{C}) \qquad (2)$$

K defines a "damage factor" which can reduce total yield at high levels of X.

Working independently, Spillman proposed a function similar to that of Mitscherlich:

$$Y = M - AR^X \tag{3}$$

M defines the maximum yield possible from application of the nutrient. A defines the maximum response to the nutrient, and R expresses the ratio by which the marginal productivity of X declines. Total yield without the variable nutrient is $y_0 = M - A$, while the yield response to fertilizer may be expressed as $y = A(1 - R^X)$. Adding the two components gives $Y = y_0 + y = M - A + A(1 - R^X) = M - AR^X$. Y has no maximum value, but is asymptotic to M. Taking the derivative of yield with respect to the input X, we obtain the equation of marginal products:

$$\frac{\partial Y}{\partial X} = -AR^X \ln(R) \tag{4}$$

Since R is a positive fraction, ln(R) will be negative. Multiplication by the negative quantity $-AR^X$ gives positive marginal products, even at very high levels of X. Taking the second derivative of Y with respect to X gives the negative quantity

$$\frac{\partial^2 Y}{\partial X^2} = -AR^X(\ln R)^2 - AR^{X-1} \tag{5}$$

which indicates diminishing (though still positive) marginal products as input levels increase.

As previously mentioned, no maximum yield can be defined for the Spillman function. However, by equating the marginal value product (marginal physical product X the product price) to the fertilizer price, one can determine an optimal level of fertilizer use.

$$(-AR^X \ln(R))P_y = P_X \tag{6a}$$

$$Z = \ln\left(\frac{PX}{-A\ln(R)\ Py}\right)/\ln(R) \tag{6b}$$

The curve of response to the variable factor is asymptotic to A, while the total yield curve is asymptotic to M.

The Spillman function is still in use, but the most common functional forms for expressing yield response to fertilizers are the Cobb-Douglas and the quadratic. A Cobb-Douglas function for fertilizer response has as its generalized form:

$$Y = AX_1^a\ X_2^b\ X_3^c \tag{7}$$

where Y represents yield, A is a constant, subscripted X's are quantities of fertilizer inputs, and the small letters represent elasticities of production, defined as the negative of the percentage change in output divided by the percentage change in input. Having the sum of the elasticities equal to one implies constant returns to scale. Cobb and Douglas originally specified the function in this form, in order that total output might be imputed to the factors of production. In modern usage, however, there are no restrictions on the sum of the exponents. Fertilizer response functions estimated using the Cobb-Douglas form normally have coefficients summing to less than one, indicating decreasing returns to scale from fertilizer use.

The Cobb-Douglas function does not allow for a point of maximum yield. Yield increases indefinitely with larger applications of fertilizer, though at a decreasing rate. In spite of the defect, the Cobb-Douglas function is widely used because it often gives a very good fit even with a small number of observations, and is relatively easy to manipulate compared with some other functional forms.

Using the form of the Cobb-Douglas function in (7), marginal products are computed as follows:

$$\frac{\partial Y}{\partial X_1} = a\ AX_1^{a-1}\ X_2^b\ X_3^c \tag{8a}$$

$$\frac{\partial Y}{\partial X_2} = B\ A\ X_1^a\ X_2^{b-1}\ X_3^c \tag{8b}$$

$$\frac{\partial Y}{\partial X_3} = A\ X_1^a\ X_2^b\ X_3^{c-1} \tag{8c}$$

The equation of an isoquant indicates the combinations of two fertilizer inputs which can be used to obtain a given yield level. Considering a Cobb-Douglas function with two inputs X_1 and X_2, and fixing yield at $\overline{Y}$, we obtain the following equation for the isoquants

$$X_1 = (\overline{Y}/AX_2^b)1/a \tag{9}$$

These isoquants are asymptotic to the X_1 and X_2 axes. In other words, at least some of both nutrients must be present to obtain yield.

The marginal rate of substitution between two inputs is defined as the amount of one input required to replace one unit of the other, maintaining yield at a constant level. Mathematically, it is the negative of the slope of the isoquant:

$$MRS_{X_1X_2} = -\frac{\partial X_1}{\partial X_2} = (b/a)Y^{1/a}\ A^{-1/a}\ X_2^{-(a+b)a} \tag{10}$$

Though the Cobb-Douglas function cannot be used to estimate maximum possible yield, it can be used to determine the optimal input levels and corresponding yield. The criterion for the economic optimum is the same as for the Spillman function: where marginal value product of the input equals the input price. In this case, where

$$(a\ A\ X_1^{a-1}\ X_{2_{b-1}}^{b}\ X_3^{c})P_Y = P_{X_1} \tag{11a}$$

$$(b\ A\ X_1^{a}\ X_2^{b-1}\ X_3^{c})P_Y = P_{X_2} \tag{11b}$$

$$(c\ A\ X_1^{a}\ X_2^{b}\ X_3^{c-1})P_Y = P_{X_3} \tag{11c}$$

where the quantities in parentheses are marginal products, the P_{X_1}'s are prices of fertilizer inputs, and P_Y is the price of output.

This study will make use primarily of the quadratic form of the fertilizer response function. Listed below are the forms of the quadratic function in two and three variables, respectively:

$$Y = b_0 + b_1X_1 + b_2X_2 - b_3X_1^2 - b_4X_2^2 + b_5X_1X_2 \tag{12a}$$

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 - b_4X_1^2 - b_5X_2^2 - b_6X_3^2$$
$$+ b_7X_1X_2 + b_8X_1X_3 + b_9X_2X_3 \tag{12b}$$

The above equations contain an intercept term, linear and quadratic terms for each nutrient, and two-factor interaction terms. A three-factor interaction term could be added in (12b), but most studies have shown such terms not to be statistically significant. The intercept term is an estimate of yield with no fertilizer. Laird et al. (1969) explain that the linear terms represent the slope of the yield function at the origin (i.e., zero levels of the nutrients). The quadratic terms measure the deviation from a linear trend of response to a nutrient. Finally, the interaction terms are a measure of the difference in yield response to a nutrient when another one is present and when it is not.

The quadratic function is fairly easy to manipulate, and it seems to explain many yield-fertilizer relationships quite well. It is normally expected that the linear coefficients will be positive and the quadratic terms negative. The interaction terms may be either positive or negative, depending on how increased dosage of one nutrient affects response to another. The more common sign is positive. As an example of positive NP interaction, the application of ammoniacal nitrogen at planting has been found to improve the absorption of phosphorus by the plant (Tisdale and Nelson, 1975).

The marginal products for the two-nutrient function (12a) are as follows:

$$\frac{\partial Y}{\partial X_1} = b_1 - 2b_3X_1 + b_5X_2 \tag{13a}$$

$$\frac{\partial Y}{\partial X_2} = b_2 - 2b_4X_2 + b_5X_1 \tag{13b}$$

and for the three-nutrient function:

$$\frac{\partial Y}{\partial X_1} = b_1 - 2b_4X_1 + b_7X_2 + b_8X_3 \quad (14a)$$

$$\frac{\partial Y}{\partial X_2} = b_2 - 2b_5X_2 + b_7X_1 + b_9X_3 \quad (14b)$$

$$\frac{\partial Y}{\partial X_3} = b_3 - 2b_6X_3 + b_8X_1 + b_9X_2 \quad (14c)$$

The marginal rate of substitution of X_1 for X_2 ($MRS_{X_1X_2}$) is

$$-\frac{\partial X_2}{\partial X_1} = (-)\ \frac{b_1 - 2b_3X_1 + b_5X_2}{b_2 - 2b_4X_2 + b_5X_1}$$

for the two-nutrient function. The three-nutrient function has the following equations for $MRS_{X_1X_2}$:

$$-\frac{\partial X_2}{\partial X_1} = (-)\ \frac{b_1 - 2b_4X_1 + b_7X_2 + b_8X_3}{b_2 - 2b_5X_2 + b_7X_1 + b_9X_3}$$

for $MRS_{X_1X_3}$:

$$-\frac{\partial X_3}{\partial X_1} = (-)\ \frac{b_1 - 2b_4X_1 + b_7X_2 + b_8X_3}{b_3 - 2b_6X_3 + b_8X_1 + b_9X_2}$$

and for $MRS_{X_2X_3}$:

$$-\frac{\partial X_3}{\partial X_2} = (-)\ \frac{b_2 - 2b_5X_2 + b_7X_1 + b_9X_3}{b_3 - 2b_6X_3 + b_8X_1 + b_9X_2}$$

for $MRS_{X_1X_3}$:

$$-\frac{\partial X_3}{\partial X_1} = (-)\ \frac{b_1 - 2b_4X_1 + b_7X_2 + b_8X_3}{b_3 - 2b_6X_3 + b_8X_1 + b_9X_2}$$

and for $MRS_{X_2X_3}$:

$$-\frac{\partial X_3}{\partial X_2} = (-)\ \frac{b_2 - 2b_5X_2 + b_7X_1 + b_9X_2}{b_3 - 2b_6X_3 + b_8X_1 + b_9X_2}$$

The two-nutrient function has the following equation for isoquants:

$$X_1 = \frac{b_1 + b_5X_2 \pm ((b_1 + b_5X_2)^2 - 4b_3(\bar{Y} - b_0 - b_2X_2 + b_4X_2^2))^{.5}}{2b_3} \quad (17)$$

The isoquant equation for the three-nutrient function is somewhat more complex:

$$X_1 = \frac{b_1 + b_7X_2 + b_8X_3 \pm ((b_1 + b_7X_2 + b_8X_3)^2 - 4b_4(\overline{Y} - b_0}{2b_4}$$

$$\frac{- b_2X_2 - b_3X_3 + b_5X_2^2 + b_6X_3^2 - b_9X_2X_3))^{.5}}{} \qquad (18)$$

Isoquants of quadratic functions touch the input axes rather than being asymptotic to them. Thus, they allow one to obtain particular output levels with only one nutrient input.

The nutrient levels which give maximum yield are found by setting the partial derivatives of yield with respect to the inputs equal to zero and solving the simultaneous equations. If one increases input levels beyond the point at which marginal product is zero, negative marginal product (i.e., a decrease in total yield) will result.

The levels of fertilization for maximum yield are equivalent to the economic optimal (i.e., profit-maximizing) levels only if the cost of fertilizer is zero. If not, and assuming no capital constraints, one should apply the nutrients at the levels at which their marginal value products equal their prices. We have for the two-nutrient case:

$$(b_1 - 2b_3X_1 + b_5X_2)P_Y = P_{X_1} \qquad (19a)$$

$$(b_2 + b_5X_1 - 2b_4X_2)P_Y = P_{X_2} \qquad (19b)$$

and for the three-nutrient case:

$$(b_1 - 2b_4X_1 + b_7X_2 + b_8X_3)P_Y = P_{X_1} \qquad (20a)$$

$$(b_2 + b_7X_1 - 2b_5X_2 + b_9X_3)P_Y = P_{X_2} \qquad (20b)$$

$$(b_3 + b_8X_1 + b_9X_2 - 2b_6X_3)P_Y = P_{X_3} \qquad (20c)$$

where P_Y is the product price and the P_{X_i}'s are the fertilizer input prices.

Under conditions of capital scarcity, a slightly different criterion from the above should be used to determine optimal fertilization levels. In these cases, one should apply fertilizer until the marginal economic return from its use is equal to marginal returns from other nutrients on the farm.

Statistical Estimation of Production Functions

The method used to estimate the response functions in this study is the well-known technique of least-squares regression. Below is a brief summary of the technique. For a more complete discussion, see Heady and Dillon (1972), Ostle and Mensing (1975), and Johnston (1972).

The principal idea behind least-squares regression is to fit a line or curve to a set of data in such a way that the sum of the squared deviations from the line or curve is at a minimum. For example, a simple linear regression model of the form

$$Y = B_0 + B_1X_1 + B_2X_2 + B_3X_3 \qquad (21)$$

can be fit to a set of data by minimizing

$$\sum_{i=1}^{n} (Y_1 - b_0 - b_1X_{1i} - b_2X_{2i} - b_3X_{3i})^2 \qquad (22)$$

where the b's are least-squares estimates of B values and i refers to the ith of n observations. The normal equations are:

$$b_0n + b_1 \sum_{i=1}^{n} X_{1i} + b_2 \sum_{i=1}^{n} X_{2i} + b_3 \sum_{i=1}^{n} X_{3i} = \sum_{i=1}^{n} Y_i \qquad (23a)$$

$$b_0 \sum_{i=1}^{n} X_{1i} + b_1 \sum_{i=1}^{n} X_{1i}^2 + b_2 \sum_{i=1}^{n} X_{1i}X_{2i} + b_3 \sum_{i=1}^{n} X_{1i}X_{3i} = \sum_{i=1}^{n} X_{1i}Y_i \quad (23b)$$

$$b_0 \sum_{i=1}^{n} X_{2i} + b_1 \sum_{i=1}^{n} X_{1i}X_{2i} + b_2 \sum_{i=1}^{n} X_{2i}^2 + b_3 \sum_{i=1}^{n} X_{2i}X_{3i} = \sum_{i=1}^{n} X_{2i}Y_i \quad (23c)$$

$$b_0 \sum_{i=1}^{n} X_{3i} + b_1 \sum_{i=1}^{n} X_{1i}X_{3i} + b_2 \sum_{i=1}^{n} X_{2i}X_{3i} + b_3 \sum_{i=1}^{n} X_{3i}^2 = \sum_{i=1}^{n} X_{3i}Y_i \quad (23d)$$

Estimation of yield response to fertilizer normally involves non-linear models. In the case of the Cobb-Douglas function, however, a (linear) logarithmic transformation is performed. Using the equation in (7), we have

$$\ln Y = \ln A + a\ln X_1 + b\ln X_2 + c\ln X_3 \quad (24)$$

The quadratic function does not require a transformation. It is estimated directly using the normal equations.

Choice of Form

Experience with the Cobb-Douglas and quadratic forms of the fertilizer response function has shown that the Cobb-Douglas gives a good fit more consistently, particularly in cases of a small number of observations.

A three-factor Cobb-Douglas function such as (7) requires the estimation of the four parameters A, a, b, and c. The three-factor quadratic function (12b), on the other hand, requires estimation of the ten parameters b_0 through b_9, and thus provides considerably fewer error degrees of freedom.

Although the Cobb-Douglas may provide a better statistical fit, the quadratic function is more consistent with agronomic principles since it allows for negative marginal product (decreasing total product) at high input levels. At times the estimation procedure results in "incorrect" signs for the quadratic function. The most common problem is that of positive quadratic coefficients. If these are found in conjunction with positive linear coefficients, the function displays increasing marginal returns to fertilizer. Increasing returns to a nutrient indicate that it should have been included in the trials at a higher level, in order to include the region of decreasing marginal returns. On the other hand, positive quadratic coefficients with negative linear ones give an "inverted" response curve. Theoretically, fertilizer would depress yield in the initial stages. After reaching a minimum point, yield would increase at an increasing rate with additional applications of fertilizer. A function of this shape has no agronomic basis.

The "classic" production function which is presented in textbooks of microeconomic theory (Henderson and Quandt, 1971; Ferguson and Gould, 1975), consists of three regions. Region I has increasing marginal products, Region II has positive but declining marginal products, and Region III has negative marginal products (declining total product).

The standard quadratic function does not allow for both increasing and decreasing returns to fertilizer application. However, by grafting two functions, one with increasing and one with decreasing marginal returns, a curve such as that described above is obtained. Fuller (1969) has described a procedure for grafting functions.

The present study makes use of a few already-estimated response functions which have both positive linear and positive quadratic terms. It would appear in this case that recommended fertilization levels should be at least as high as the maximum levels used in the trials, and so these nutrients are fixed at their maximum level for both maximum and economic optimum yield.

Land-Fertilizer Equations

Fertilizer response functions normally represent yield solely as a function of the amount of nutrient applied. In reality, however, yield response is a function also of initial soil fertility, planting time, density of planting, method of fertilizer application, and above all, climatic conditions. Some of the important work on the effect of agro-climatic variables on yield has been done by Jenny (1941), Voss and Pesek (1965), Carmen (1968), Turrent (1968), Darwich (1977) and Tejeda-Sanhueza (1973).

Land is usually considered as an implicit factor of production. Yield is expressed in kilograms per hectare or pounds per acre. However, land may be considered a variable factor of production to the extent that it substitutes for other inputs. In this study we are particularly concerned with substitution between land and fertilizer. Heady (1963) has described a procedure for transforming nutrient response functions into land-nutrient response functions. Bishay (1965) and others have adopted the method in order to obtain empirical estimates of marginal rates of substitution of land for fertilizer.

Quadratic functions

We can illustrate Heady's procedure for estimating land-fertilizer substitution rates with the quadratic function in (25):

$$Y = b_0 + b_1F_1 + b_2F_2 - b_3F_1^2 - b_4F_2^2 + b_5F_1F_2 \tag{25}$$

which is identical to (12a) except that F_i's are used instead of X_i's to refer to fertilizer nutrients. We first convert this equation into a single-nutrient form. This is done by defining $F = \Sigma F_i$, the total sum of the nutrients applied, and $R_i = F_i/F$, the relative proportion of a nutrient in the total fertilizer mix. Fixing the total amount of fertilizer and the relative proportions of the nutrients, and using the relationship $F_i = R_iF$, we change the response function in (25) to the form of (26):

$$Y = b_0 + b_1R_1F + b_2R_2F - b_3R_1^2F^2 - b_4R_2^2F^2 + b_5R_1R_2F^2 \tag{26}$$

Heady suggests that by multiplying the function in (26) by a variable representing land (labelled here as L) and dividing the variable F by L, one obtains an expression for yield response per land area unit. The result is as follows:

$$Y = b_0L + b_1R_1F + b_2R_2F - b_3R_1^2F^2L^{-1} - b_4R_2^2F^2L^{-1} + b_5R_1R_2F^2L^{-1} \tag{27}$$

This function displays decreasing returns to scale for land or fertilizer alone, with the possibility of negative marginal returns with increasing fertilizer use. The function has constant returns to scale, however, when both fertilizer and land are increased proportionally.

The land-fertilizer production function in (27) can be simplified to the form of (28a)

$$Y = b_0L + \alpha F - \beta F^2L^{-1} \tag{28a}$$

where

$$\alpha = b_1R_1 + b_2R_2 \tag{28b}$$

and

$$\beta = b_3R_1^2 + b_4R_2^2 - b_5R_1R_2 \tag{28c}$$

The equation for the marginal rate of substitution of fertilizer for land is:

$$MRS_{FL} = -\frac{\partial L}{\partial F} = -\left(\frac{\partial Y}{\partial F}/\frac{\partial Y}{\partial L}\right) = -(\alpha - 2\beta FL^{-1})/(b_0 + \beta F^2L^{-2}) \tag{29}$$

and the equation for land-fertilizer isoquants is:

$$L = \frac{\overline{Y} - \alpha F \pm ((\overline{Y} - \alpha F)^2 + 4b_0\beta F^2)^{.5}}{b_0} \tag{30}$$

where $\overline{Y}$ is a valid yield level and the other variables have previously been defined.

The properties of the land-fertilizer equation in (28a) are such that a particular yield level is obtainable with exactly one unit of land when the input levels used are those calculated from the original function. The isoquant for maximum yield never has a y-coordinate (land) value less than one, because it represents the maximum product which can be obtained from a unit of land. To increase total product beyond this level requires the addition of more land or both more land and fertilizer. Increasing fertilizer alone will depress total yield, whether land remains constant or is reduced. To maintain a constant yield with additional fertilization requires more land as well, a fact which causes the isoquant to take on a positive slope in that region.

Isoquants other than the one for maximum yield also have positive slopes beyond certain input levels, but their corresponding yield levels can be produced with less than one unit of land.

Cobb-Douglas functions

We can apply a methodology similar to that above to the Cobb-Douglas function in (7):

$$Y = AX_1^a X_2^b X_3^c \tag{7}$$

We first convert the multinutrient function into a one-nutrient form. Using the same symbols as with the quadratic form, we have:

$$Y = A(R_1F)^a(R_2F)^b(R_3F)^c = AR_1^aR_2^bR_3^cF^{a+b+c} \tag{31}$$

We form the land-fertilizer equation by dividing the fertilizer quantity F by L and then multiplying the entire equation by L:

$$Y = ALR_1^aR_2^bR_3^c(F/L)^{a+b+c} = AR_1^aR_2^bR_3^cF^{a+b+c}L^{1-(a+b+c)} \tag{32a}$$

or in natural logarithm form:

$$\ln Y = \ln(A) + \ln(D) + B\ln(F) + (1 - B)\ln(L) \tag{32b}$$

where $D = R_1^aR_2^bR_3^c$ and $B = (a + b + c)$.

The marginal rate of substitution of fertilizer for land is:

$$MRS_{FL} = -\frac{\partial L}{\partial F} = -\left(\frac{\partial Y}{\partial F}/\frac{\partial Y}{\partial L}\right) = \frac{(a + b + c)L}{(a + b + c - 1)F} \tag{33}$$

and the equation for land-fertilizer isoquants is:

$$L = \frac{\bar{Y}^{1/(1-(a+b+c)}}{(AR_1^aR_2^bR_3^cF^{a+b+c})^{1/(1-(a+b+c)}} \tag{34}$$

Empirical studies

A number of empirical estimates of the marginal rate of substitution of fertilizer for land have been made. Heady (1963) reported estimates for corn (maize) from Iowa, Mississippi, Kansas, and North Carolina. Four examples of the results computed are given below.

Table 1. Marginal rates of substitution of fertilizer for land (Heady, 1963)

State	Yield level (kg)	Fertilizer (kg)	Land (ha)	MRS x 1000
Iowa	1095	0.0	.5498	39.4
Mississippi	1040	4.5	.5498	14.5
North Carolina	1922	9.1	1.0000	28.7
Kansas	1845	18.2	2.1215	15.0

Multiplying the marginal rate of substitution by 1000 gives the amount of land in hectares replaced by one metric ton of fertilizer at that point on the isoquant.

Ibach (1967) calculated that 4.2 hectares would have been required to produce crops equal in value to the value added through the use of one metric ton of N, P, and K as applied in the U.S. during the period 1960-64.

Bishay (1965) compared marginal rates of substitution of fertilizer for land and labor for five different countries and nine different crops. He used four different input levels: no fertilizer, the level for maximum yield, a "medium" level, and the economic optimum level. Below are examples of the results he computed at the maximum yield level of fertilization.

Table 2. Marginal rates of substitution of fertilizer for land (Bishay, 1965)

Country	Crop	Amount of F (kg)	Land area (ha)	MRS x 1000
Egypt	maize	36.4	.4452	1.76
Egypt	maize	63.6	.4168	.32
India	rice	18.2	.4128	3.23
India	rice	27.3	.4978	10.26

Khan (1965) and Bose (1970) both computed marginal rates of substitution of fertilizer for land for wheat and rice in India. Over an average of ten and eleven locations, respectively, Khan found that one metric ton of fertilizer substituted for 4.4 hectares of land in rice production and 5.6 hectares of land in wheat production when applied at a rate of 49 kg/ha. Bose calculated that one metric ton of nitrogen replaced 2.8 hectares of land in the production of Dular rice.

Estimates of land-fertilizer substitutability presented in this paper are site-specific. In addition, they refer to a particular isoquant (a given total yield) and a particular point on that isoquant (a specific combination of land and fertilizer). If a conscious decision were made in a particular country to take out some land currently in production and produce an equal or greater amount of food on the remaining land, it would most probably be marginally productive land that would be retired from use. More than one unit of this marginal land would be required to equal the yield capacity of one unit of the better grade of land normally used in fertilizer trials. In this case the results of the trials would tend to underestimate the amount of land replaced by a given quantity of fertilizer.

If a decision were taken to increase food production by augmenting fertilizer use while maintaining constant or increasing the land area in production, the additional land put into production would again probably be of marginal quality. Thus in this case also the results of the present study would tend to underestimate land-fertilizer substitutability.

Sources of Data

The data for this study have been taken from various sources. Some of the functions have been estimated from raw data, while others were originally estimated in coded form and have been reestimated using actual yield and fertilizer input values. A large number of the functions were taken directly from theses of published sources, but there had generally been no economic analysis performed on the data. In the cases in which there had been, the fertilizer and grain prices needed revision. None of the functions had previously been transformed into the land-fertilizer form except those of Khan (1965) and Bose (1970) for India.

Most of the data on fertilizer prices were obtained from the FAO Fertilizer Handbook. Prices received by farmers for grain came from a set of unpublished FAO data, furnished to the author through the courtesy of the Economic Research Service of the U.S. Department of Agriculture.

In the following section, the results of the study are presented by country. A brief description of each country's agricultural sector precedes the data analysis for that country.

LATIN AMERICA

Latin America was at one time the source of a large portion of the world's fertilizer, the huge guano deposits off the Pacific coasts of Peru and Chile. Fertilizer use in Latin America has remained very low, however, and much of the fertilizer is now imported. In 1967 total fertilizer consumption in Latin America was 1.826 million metric tons. Production reached only 795,000 metric tons, out of a potential production and gross capacity of 1.1 million and 1.6 million metric tons, respectively (Yudelman, 1970). In 1976 total fertilizer consumption for the continent of South America was 2.6 million metric tons. This corresponded to 31.3 kilograms per hectare of arable land, compared with an average for the entire world of 58.9 kg/ha (FAO, 1978c).

Yudelman (1970) attributes the low level of fertilizer use in Latin America partly to unfavorable input/product price ratios. These in turn are caused by protection given to domestic input industries and low producer prices for agricultural goods. Small internal markets prevent input industries from taking advantage of economies of scale. This is of course a strong argument in favor of increased economic integration.

The specter of famine does not hang as ominously over Latin America as over Asia and Africa, but the region nevertheless faces a food/population problem. Yudelman reports that at least one-fourth of the Latin American population lives in dire poverty. Malnutrition, particularly among children, is rampant. Population growth for Latin America as a whole has been very rapid, averaging 2.8 percent per year from 1950 to 1975 (Smith, 1976).

Most Latin American countries do not share the good fortune of having ample deposits of petroleum, a basic ingredient in the manufacture of many fertilizers. Mexico and Venezuela are the primary exceptions, both of them major petroleum exporters. Chile has deposits of sodium nitrate, but this material has receded in popularity as a nitrogenous fertilizer (Slack, 1970).

There would appear to be no shortage of arable land in Latin America. Indeed, estimates of the percentage of potentially arable land currently under cultivation have ranged as low as 30 percent (Yudelman, 1970).

To summarize, the most important steps to improve the alimentary situation in the region would be a) a reduction in population growth; b) an increase in the area of land cultivated; and c) a more intensive use of inputs, particularly fertilizers. In the following section we investigate the potential for augmented food production through increased fertilizer application in Argentina, Chile, Peru, and Brazil.

Argentina

Argentina is the world's fourth most important exporter of wheat, after the United States, Canada, and Australia. The eighth largest country in the world in terms of land area, it is endowed with a large fertile plain known as the pampas. Wheat grows well in all sections of the pampas but the semi-arid southeast.

Argentina was the world's leading exporter of wheat during the years after World War I. Total acreage in 1927-1928 exceeded eleven million hectares, compared with 6.4 million hectares in 1976 (Borgstrom, 1973; FAO, 1978a). The reduced wheat acreage is due in part to a transfer of resources into meat production, and has been stimulated by a post-World War II policy of low grain prices for farmers.

Unlike most of Latin America, Argentina has had a fairly low rate of population growth; only about 1.5 percent per year in the 1960's. The slow growth rate has made easier the nation's task of feeding its own people.

Fertilizer use in Argentina has been quite low, even by Latin American standards. In 1976 the consumption of fertilizer per hectare of cultivated land was 2.1 kilograms, compared with 31.3 kg for the continent of South America as a whole and 106.5 kg for the United States (FAO, 1978c).

Darwich (1977) mentions several possible reasons why fertilizer use per hectare has been so low in Argentina. First, the ratio of prices paid by farmers for fertilizer to the prices received for their crops has been too high to make fertilizer use profitable during the years of unfavorable weather to which the pampas are susceptible. For many years the government kept food prices artificially low in an effort to win the support of the urban working classes. In addition, fertilizer prices have been higher than in many other countries. This is particularly true of phosphate, almost all of which is imported.

In spite of droughts and other forms of adverse weather, the soils of the pampas are in general highly fertile and produce at a profitable level without fertilization. However, as soil fertility declines and economic pressures cause the fertilizer/product price ratio to move in a direction favorable to farmers, it can be expected that fertilizer use per land area unit will increase.

The response data for the present study are taken from Darwich's 1977 work. His price data are also used, as they are more recent and appear to be more accurate than those available from the FAO. The prices are \$370 US per metric ton N, \$478 US per metric ton P, and \$82 US per metric ton of wheat. The original study estimates functions for 13 sites in 1972, 42 in 1973, and 15 in 1974. We shall analyze a generalized function for the seventy sites, two functions for 1972, three for 1973, and two for 1974. The site-specific functions were chosen for having correct signs and for being statistically significant in terms of R^2 and the t-values for the regression coefficients.

The generalized function presents yield as a function of fertilizer application and agro-climatic variables. Its form is as follows:

$$Y = 2561 + 4.78N + 7.68P + .0135NP - .0166N^2 - .0331P^2 - 279Pp$$
$$- .177Nd - 9.386cb - 149.05w + 8.51ca - .388sd + 6.51cc \qquad (35a)$$

where N, P, and K are fertilizer inputs and the agro-climatic variables are listed below along with their mean values.

p available phosphorus in the A horizon in ppm (8.09)
d number of water stress days from heading to dough stage (12.60)
cb percent clay in the B horizon (31.63)
w weed infestation, scale of 0 to 5 (1.77)
ca percent clay in the A horizon (22.84)
sd = so x d solum thickness in cm x number of stress days from heading to dough stage (1131.60
cc cation exchange capacity for the A horizon, in mg/100 g of soil (24.81)

Replacing the agro-climatic variables with their mean values, we obtain the following function:

$$Y = 1917 + 2.550N + 5.423P - .017N^2 - .033P^2 + .013NP \tag{35b}$$

A few sites with highly unfavorable soil and climatic conditions depress the average total yield across the sites. Equation (35b) gives a considerably lower maximum yield than most of the sites chosen for the present study. Maximum yield is 2359 kg/ha obtained with applications of 120 kg/ha N and 160 kg/ha P. Returns above fertilizer cost are $98 per hectare. Use of both N and P is found to be uneconomical, however. The point at which the marginal value product of fertilizer equals the input price is where N = 107 kg/ha and P = 101 kg/ha. These input levels give returns above fertilizer costs of $105 per ha, less than the gross revenue without using any fertilizer of $157 per hectare.

The single-site yield response functions are estimated without agro-climatic variables, using the quadratic form. They are listed below.

Year		R^2	
1972	$Y = 2095 + 8.38N^{***} + 12.23P^{***} - .0599N^{2**} - .00764NP - .06949P^{2***}$	.92	(36a)
1972	$Y = 2448 + 3.46N + 16.12P^{***} - .04413N^{2*} - .10177P^{2***} + .02053NP$	.95	(37a)
1973	$Y = 1794 + 8.65N^{***} + 10.74P^{***} - .03506N^{2***} - .09797P^{2***} - .00991NP$	.94	(38a)
1973	$Y = 2146 + 5.95N^{*} + 9.05P^{***} - .03506N^{2} - .05923P^{2*} + .04163NP^{*}$	.90	(39a)
1973	$Y = 2067 + 5.17N + 17.60P^{***} - .07285N^{2**} - .11896P^{2***} + .04474NP$	.92	(40a)
1974	$Y = 2305 + .84N + 18.59P^{***} - .017847N^{2} - .1477P^{2} + .0345NP$	.88	(41a)
1974	$Y = 1759 + 3.18N + 9.95P^{***} - .021805N^{2} - .04305P^{2**} - .03295NP^{**}$	.90	(42a)

where * = significant at .10; ** = significant at .05; and *** - significant at .01.

The amounts of N and P for maximum yield, along with optimum and two-thirds of optimum input levels, are given in Table 3. Input and yield levels are in kg/ha. R refers to economic returns above fertilizer costs. The column (a) refers to the difference between economic returns above fertilizer costs using optimum input levels and total economic returns without application of fertilizer. Thus, in a sense, (a) indicates per hectare returns to optimal fertilizer use. Column (b) lists the ratio of economic returns above fertilizer costs at optimum input levels to economic returns with zero fertilization. Thus, it is an indication of the rate of return to optimal fertilization. As was mentioned in the introduction, the optimal fertilization levels are computed without considering the costs or effects on yield of other inputs.

There is quite a bit of variation in fertilizer response between sites, even within the same year. The site used for function (42a) responds negatively to N, and so this nutrient should not be applied. In addition, the use of N is not economical for the sites used in (37a) and (43a).

Rates of return for fertilizer use are not particularly high, ranging from five to sixteen percent, and it is easy to see why under conditions of uncertainty farmers might be reluctant to apply chemical fertilizers. These rates of return are computed under experiment station conditions, and would probably be lower on even a well-managed commercial farm.

Table 3. Input, yield, and economic return levels corresponding to four fertilization levels; functions (36a)-(42a) (wheat, Argentina)

Maximum yield				Optimum levels				Two-thirds of opt. levels				Zero fert.				
N	P	Y	R[a]	N	P	Y	R	N	P	Y	R	Y	R	(a)[b]	(b)[c]	Function
76	92	2869	$163	29	51	2719	$188	19	34	2563	$187	2095	$172	$16	1.09	(36a)
59	85	3237	$203	0	51	3005	$222	0	34	2878	$220	2448	$201	$21	1.10	(37a)
86	50	2438	$144	41	23	2255	$159	27	15	2128	$157	1794	$147	$12	1.08	(38a)
165	134	3243	$141	46	43	2707	$184	31	29	2547	$184	2146	$176	$8	1.05	(39a)
62	86	2980	$180	21	53	2792	$196	14	35	2617	$193	2067	$169	$27	1.16	(40a)
95	74	3033	$178	0	43	2831	$212	0	29	2720	$209	2305	$189	$23	1.12	(41a)
0	116	2334	$136	0	48	2137	$152	0	32	2033	$151	1759	$144	$8	1.06	(42a)

[a] R = per hectare economic returns above fertilizer costs.

[b] (a) = difference between R for optimum fertilization and R for zero fertilization.

[c] (b) = ratio of R for optimum fertilization to R for zero fertilization.

Land-fertilizer equations for (36a) through (42a) are given below. The functions are labelled with the same numbers as in their original form, with the letters b, c, and d for the maximum yield, economic optimal, and two-thirds of economic optimal input levels, respectively.

For function (36a):

$$Y = 2095L + 10.490F - .034999F^2L^{-1} \qquad F = 168 \qquad (36b)$$

$$Y = 2095L + 10.836F - .037900F^2L^{-1} \qquad F = 80 \qquad (36c)$$

$$Y = 2095L + 10.852F - .038074F^2L^{-1} \qquad F = 53 \qquad (36d)$$

For function (37a):

$$Y = 2448L + 10.929F - .037853F^2L^{-1} \qquad F = 144 \qquad (37b)$$

$$Y = 2448L + 16.120F - .10177F^2L^{-1} \qquad F = 51 \qquad (37c)$$

$$Y = 2448L + 16.120F - .10177F^2L^{-1} \qquad F = 34 \qquad (37d)$$

For function (38a):

$$Y = 1794L + 9.419F - .034309F^2L^{-1} \qquad F = 136 \qquad (38b)$$

$$Y = 1794L + 9.400F - .034309F^2L^{-1} \qquad F = 64 \qquad (38c)$$

$$Y = 1794L + 9.396F - .034284F^2L^{-1} \qquad F = 42 \qquad (38d)$$

For function (39a):

$$Y = 2146L + 7.339F - .012276F^2L^{-1} \qquad F = 299 \qquad (39b)$$

$$Y = 2146L + 7.447F - .012793F^2L^{-1} \qquad F = 89 \qquad (39c)$$

$$Y = 2146L + 7.447F - .012793F^2L^{-1} \qquad F = 60 \qquad (39d)$$

For function (40a):

$$Y = 2067L + 12.392F - .042054F^2L^{-1} \qquad F = 148 \qquad (40b)$$

$$Y = 2067L + 14.070F - .057764F^2L^{-1} \qquad F = 74 \qquad (40c)$$

$$Y = 2067L + 14.045F - .057468F^2L^{-1} \qquad F = 49 \qquad (40d)$$

For function (41a):

$$Y = 2305L + 8.614F - .025480F^2L^{-1} \qquad F = 169 \qquad (41b)$$

$$Y = 2305L + 18.59F - .14770F^2L^{-1} \qquad F = 43 \qquad (41c)$$

$$Y = 2305L + 18.59F - .14770F^2L^{-1} \qquad F = 29 \qquad (41d)$$

For function (42a):

$$Y = 1759L + 9.95F - .043050F^2L^{-1} \qquad F = 116 \qquad (42b)$$

$$Y = 1759L + 9.95F - .043050F^2L^{-1} \qquad F = 48 \qquad (42c)$$

$$Y = 1759L + 9.95F - .043050F^2L^{-1} \qquad F = 32 \qquad (42d)$$

Tables 4-10 list a number of points on the land-fertilizer isoquants for functions 36a-42a, along with the amount of land replaced by one metric ton of fertilizer at these points (the marginal rate of substitution of fertilizer for land multiplied by 1000). As was pointed out in the introduction, these replacement rates of fertilizer for land may underestimate the true values. Both the first land to go out of production as well as any additional land put into production would probably be of an inferior quality to the land represented in the experimental data. A unit of fertilizer would substitute for more of the marginal land than of the experiment station land.

The data show a wide variation in substitution rates between sites. Taking points on these yield isoquants which correspond to the economic optimum levels of fertilization, fertilizer substitutes for land at a rate of between 5.76 (Eq. 40c) and 2.74 (Eq. 41c) ha per metric ton when it is applied in the amount of 40 kg. Remaining on the same isoquants, but applying 100 kg of nutrient, one metric ton of fertilizer replaces up to 2.02 ha of land. For a number of the functions, however, an amount of 100 kg of fertilizer is on a positively-sloped portion of the land-fertilizer isoquant. This means that fertilizer substitutes for a nega-

Table 4. Coordinates of land-fertilizer isoquants, equations 36b-36d (wheat, Argentina)

Quantity of fert. (kg)	36b Yield (kg)	36b Amount of land (ha)	36b Land needed to replace 1 met. T fertilizer (ha)	36c Yield (kg)	36c Amount of land (ha)	36c Land needed to replace 1 met. T fertilizer (ha)	36d Yield (kg)	36d Amount of land (ha)	36d Land needed to replace 1 met. T fertilizer (ha)
0	2869	1.3695	9.39	2719	1.2979	8.71	2563	1.2234	7.75
20		1.2746	7.23		1.2004	6.54		1.1262	5.71
40		1.1916	5.37		1.1169	4.70		1.0440	4.01
50		1.1552	4.56		1.0811	3.91		1.0094	3.29
53[a]		1.1450	4.33		1.0712	3.69		.9999	3.09
60		1.1226	3.83		1.0496	3.21		.9794	2.66
80[b]		1.0689	2.59		.9999	2.04		.9336	1.61
100		1.0308	1.61		.9676	1.14		.9060	.81
120		1.0074	.84		.9511	.44		.8944	.19
140		.9969	.24		.9478	-.11		.8958	-.30
160		.9972	-.25		.9552	-.55		.9074	-.69
168[c]		.9998	-.41		.9605	-.71		.9152	-.86
180		1.0061	-.64		.9707	-.91		.9265	-1.02

[a] Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b] Amount of fertilizer corresponding to the economic optimum level of application.

[c] Amount of fertilizer required to achieve maximum yield.

Table 5. Coordinates of land-fertilizer isoquants, equations 37b-37d (wheat, Argentina)

Quantity of fert. (kg)	37b Yield (kg)	37b Amount of land (ha)	37b Land needed to replace 1 met. T fertilizer (ha)	37c Yield (kg)	37c Amount of land (ha)	37c Land needed to replace 1 met. T fertilizer (ha)	37d Yield (kg)	37d Amount of land (ha)	37d Land needed to replace 1 met. T fertilizer (ha)
0	3237	1.3223	7.81	3005	1.2275	9.92	2878	1.1757	9.10
20		1.2380	6.04		1.1108	6.18		1.0596	5.54
34[a]		1.1856	4.94		1.0494	4.09		.9998	3.58
40		1.1650	4.51		1.0288	3.33		.9801	2.87
51[b]		1.1302	3.77		.9999	2.11		.9532	1.75
60		1.1048	3.22		.9845	1.28		.9398	.98
80		1.0586	2.17		.9739	-.18		.9338	-.37
100		1.0265	1.32		.9893	-1.26		.9533	-1.37
120		1.0076	.65		1.0227	-2.07		.9901	-2.14
140		1.003	.10		1.0683	-2.71		1.0384	-2.75
144[c]		1.0000	.01		1.0786	-2.82		1.0491	-2.85
150		1.0004	-.13		1.0944	-2.98		1.0657	-3.00
160		1.0028	-.34		1.1223	-3.21		1.0945	-3.23

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 6. Coordinates of land-fertilizer isoquants, equations 38b-38d (wheat, Argentina)

Quantity of fert. (kg)	38b			38c			38d		
	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
0	2438	1.359	9.70	2255	1.257	8.28	2128	1.186	7.37
20		1.260	7.31		1.159	6.10		1.088	5.33
40		1.175	5.28		1.076	4.29		1.007	3.66
42[a]		1.167	5.11		1.068	4.13		1.000	3.51
60		1.106	3.63		1.011	2.84		.945	2.35
64[b]		1.095	3.35		1.000	2.59		.935	2.12
80		1.055	2.32		.965	1.71		.903	1.34
100		1.022	1.31		.937	.85		.880	.58
120		1.004	.52		.926	.19		.873	-.01
130		1.001	.20		.925	-.09		.875	-.26
136[c]		1.000	.02		.926	-.24		.877	-.39
140		1.000	-.09		.928	-.33		.879	-.48
160		1.007	-.58		.940	-.75		.895	-.86

[a] Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b] Amount of fertilizer corresponding to the economic optimum level of application.

[c] Amount of fertilizer required to achieve maximum yield.

Table 7. Coordinates of land-fertilizer isoquants, equations 39b-39d (wheat, Argentina)

Quantity of fert. (kg)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
	39b			39c			39d		
0	3243	1.511	7.81	2707	1.261	5.52	2547	1.186	4.89
24		1.428	6.54		1.178	4.45		1.103	3.88
50		1.351	5.39		1.101	3.50		1.027	3.01
60[a]		1.322	4.96		1.073	3.16		1.000	2.70
75		1.279	4.36		1.034	2.69		.961	2.27
89[b]		1.243	3.85		1.000	2.30		.929	1.92
100		1.216	3.47		.976	2.02		.906	1.67
125		1.161	2.71		.928	1.47		.861	1.18
150		1.114	2.07		.891	1.03		.828	.79
175		1.076	1.53		.865	.67		.806	.48
200		1.046	1.10		.848	.38		.793	.24
225		1.024	.74		.840	.15		.789	.03
250		1.010	.44		.838	-.04		.791	-.13
275		1.002	.20		.842	-.21		.798	-.28
200[c]		1.000	.00		.850	-.34		.808	-.40
300		1.000	.01		.851	-.35		.809	-.41
325		1.002	.18		.863	-.47		.824	-.51
350		1.009	.33		.841	-.57		.841	-.61

[a] Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b] Amount of fertilizer corresponding to the economic optimum level of application.

[c] Amount of fertilizer required to achieve maximum yield.

Table 8. Coordinates of land-fertilizer isoquants, equations 40b-40d (wheat, Argentina)

Quantity of fert. (kg)	40b			40c			40d		
	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
0	2980	1.442	12.46	2792	1.351	12.42	2.617	1.266	10.89
20		1.328	9.42		1.224	8.73		1.140	7.48
40		1.228	6.83		1.118	5.76		1.037	4.79
49[a]		1.189	5.82		1.079	4.66		1.000	3.81
60		1.146	4.73		1.039	3.51		.962	2.80
74[b]		1.099	3.54		1.000	2.32		.927	1.76
80		1.082	3.10		.987	1.88		.117	1.38
100		1.038	1.86		.961	.72		.897	.37
120		1.012	.93		.955	-.14		.897	-.37
140		1.001	.22		.965	-.78		.912	-.93
148[c]		1.000	-.02		.973	-1.00		.921	-1.13
160		1.002	-.33		.987	-1.28		.938	-1.38
180		1.013	-.76		1.016	-1.68		.971	-1.74

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 9. Coordinates of land-fertilizer isoquants, equations 41b-41d (wheat, Argentina)

Quantity of fert. (kg)	41b			41c			41d		
	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
0	3033	1.316	6.47	2831	1.228	12.17	2720	1.180	11.23
10		1.279	5.83		1.153	9.19		1.105	8.38
20		1.245	5.22		1.090	6.63		1.043	5.95
29[a]		1.215	4.70		1.046	4.68		1.000	4.13
30		1.212	4.64		1.042	4.49		.996	3.94
40		1.181	4.10		1.007	2.74		.964	2.31
43[b]		1.173	3.94		1.000	2.28		.957	1.89
50		1.153	3.59		.987	1.32		.946	1.00
60		1.127	3.13		.980	.17		.941	-.07
80		1.082	2.30		.995	-1.57		.961	-1.70
100		1.048	1.61		1.039	-2.81		1.009	-2.88
120		1.023	1.03		1.100	-3.72		1.073	-3.75
140		1.008	.56		1.171	-4.41		1.146	-4.42
160		1.001	.16		1.250	-4.94		1.227	-4.93
169		1.000	.00		1.282	-5.13		1.264	-5.12
180		1.001	-.18		1.333	-5.34		1.311	-5.32
200		1.007	-.46		1.420	-5.65		1.399	-5.63

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 10. Coordinates of land-fertilizer isoquants, equations 42b-42d (wheat, Argentina)

Quantity of fert. (kg)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
	42b			42c			42d		
0	2334	1.327	9.96	2137	1.215	8.35	2033	1.156	7.56
20		1.222	7.18		1.111	5.83		1.052	5.18
32[a]		1.167	5.74		1.058	4.56		1.000	3.99
40		1.135	4.88		1.027	3.80		.970	3.29
48[b]		1.106	4.09		1.000	3.13		.944	2.67
60		1.070	3.06		.967	2.25		.913	1.87
80		1.027	1.68		.931	1.09		.881	.81
100		1.005	.64		.916	.21		.871	.02
110		1.001	.21		.916	-.14		.873	-.30
116[c]		1.000	-.02		.918	-.34		.876	-.48
120		1.000	-.16		.919	-.46		.878	-.59
130		1.004	-.49		.926	-.74		.889	-.85
140		1.010	-.78		.936	-.99		.898	-1.08

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

tive quantity of land, up to 2.81 ha per metric ton in the case of equation (41c). For this site, maintaining the economic optimum yield level of 2831 kg with the application of 100 kg of fertilizer would require 1.039 ha. The same yield could be obtained with 43 kg of fertilizer and only one ha of land. The isoquants corresponding to (41b) through (41d) are drawn in Figure 1. It may seem impossible that the isoquant for maximum yield can cross the ones for optimum and two-thirds of optimum fertilization, but this is due to the fact that fertilization for maximum yield requires a completely different nutrient mix (N/P ratio) than do the other two fertilization levels.

The sample of response functions estimated here is admittedly small, and represents results of trials made under more favorable conditions than could be expected on an actual farm. Nevertheless, the functions give an idea of the potential for raising food production through augmented fertilizer use. Using the functions (36a) through (42a) as a guide, the 6.39 million ha sown to wheat in Argentina in 1976 could have produced between 14.91 and 20.72 million metric tons at input levels for maximum yield, 13.66 and 19.20 million metric tons at optimum levels, and 12.99 and 18.39 million metric tons at two-thirds of optimum levels. The amount of fertilizer required would have ranged between 741,000 and 1.911 million metric tons for maximum yield, 275,000 and 569,000 metric tons at optimal levels, and 185,000 and 383,000 metric tons at two-thirds of optimal levels. All of these quantities are substantially greater than the 71,800 metric tons of fertilizer which Argentina used for all purposes in 1976.

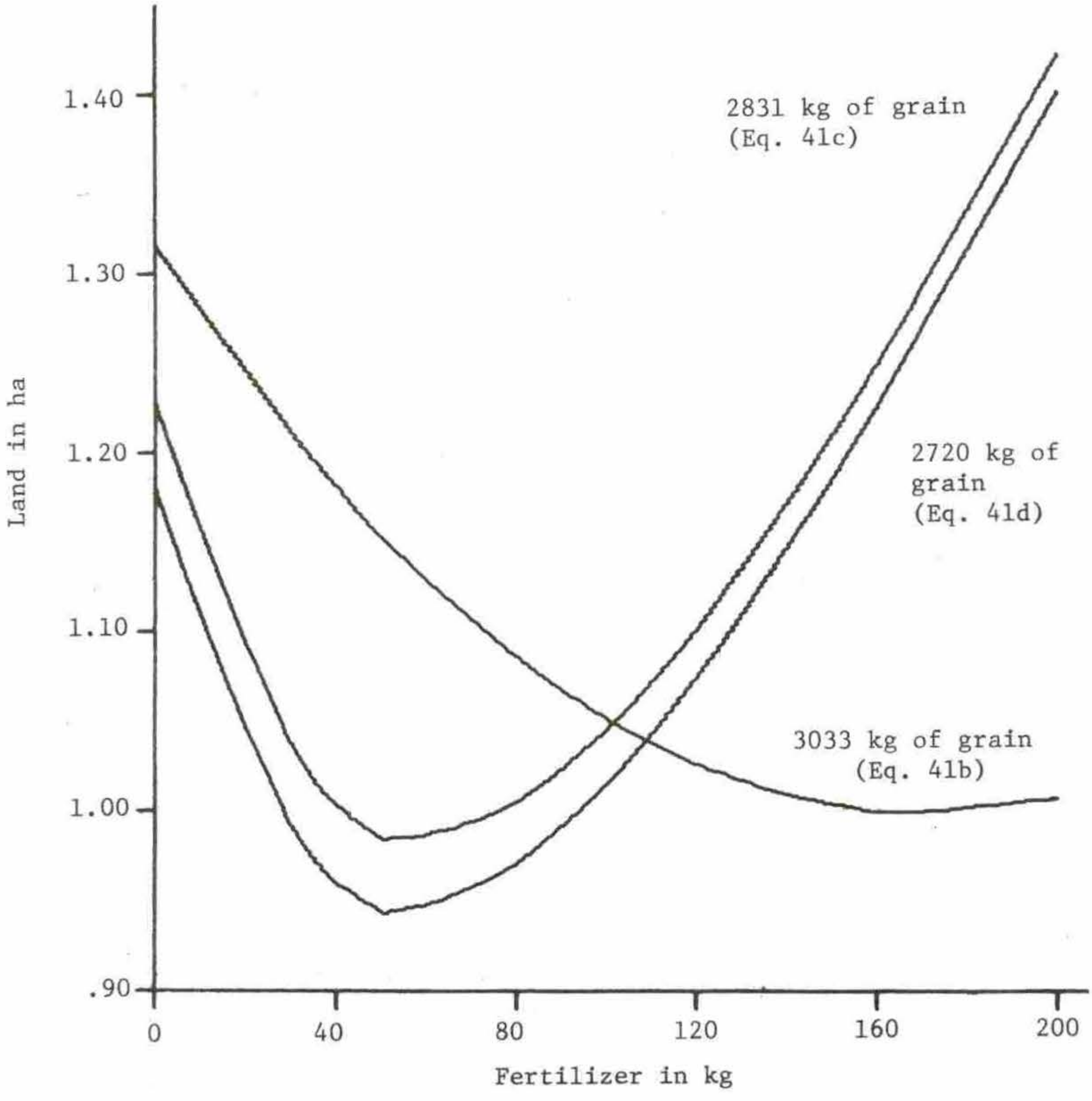

Figure 1. Isoquants corresponding to land-fertilizer equations (41b) through (41d) (wheat, Argentina)

Production of the 1976 wheat crop of eleven million metric tons with increased use of fertilizers would have given substantial savings in land. Instead of using 6.39 million hectares, the crop could have been grown on between 3.39 and 4.71 million ha with fertilizer application for maximum yield, between 3.66 and 5.15 million ha using optimal levels of application, and between 3.82 and 5.41 million ha at two-thirds of the optimum levels. The amount of fertilizer required would have been between 546,000 and 1.013 million metric tons at levels for maximum yield, 247,000 and 326,000 metric tons at economic optimum levels, and 173,000 and 229,000 metric tons for two-thirds of the optimum levels, depending on the experimental site chosen as representative of yield potentials.

Chile

Chile occupies a long, narrow strip of Pacific coast at the southern end of South America. It has a total land area of 74.88 million hectares, of which an estimated 5.83 million are in permanent and temporary crops. The population in 1977 was 10.63 million persons, with 2.17 million in agriculture (FAO, 1978a).

The central part of the country is a rich agricultural district with extensive cultivation of grains, particularly wheat. Farther to the south there is considerable dairy activity, as well as a substantial number of grape and apple orchards. In spite of a rich potential, however, Chile in 1977 imported $315 million US worth of agricultural products and exported only $162 million US worth. The largest single component of the import bill was for cereals, while fruits and vegetables dominated the exports.

Wheat and wheat flour imports alone totalled 657,396 metric tons, slightly over half as much as the 1.2 million metric ton harvest (FAO, 1978b).

The Popular Unity government of Salvador Allende which was in power from 1970 until 1973 was committed to a policy of radical agrarian reform and low food prices to urban consumers. Rural instability led to decreases in agricultural production and mounting import bills (Moss, 1973). The present military government has lifted price controls and reversed some of the land reform measures of its predecessors. These changes have not brought self-sufficiency to Chilean agriculture, however.

The present study analyzes data from some of the many experiments on wheat yield response which have been carried out in Chile. The extremely high rate of inflation which has afflicted the country in recent years makes much price information unreliable. Thus we have chosen to use prices from 1972, a year of economic difficulties, but without the severe inflation of later years. The prices used are \$250 US per metric ton N, \$268 US per metric ton P, and \$75 US per metric ton of wheat. The nitrogen-wheat and phosphate-wheat price ratios are 3.3 and 3.6, respectively, somewhat more favorable than the ratios of 4.5 and 5.8 for Argentina.

Researchers of the Instituto Nacional de Investigaciones Agricolas (INIA, 1973) have estimated generalized response functions for wheat in Chile utilizing agro-climatic variables. The generalized function for central Chile takes the quadratic form:

$$Y = B_0 + B_1N + B_2P + B_3N^2 + B_4P^2 \qquad (43a)$$

where

$$B_0 = 7.918 + .4064n^{***} - .00048n^{2*} + 1.10105A^{***} - .0191A^{2***} + .398Ca^{***} + .0602PR^{***} - .00129E^{2***} - .580DIV^{***} + .0122(DIV)^2 \quad (43b)$$

$$B_1 = .1688^{***} - .0021n^{***} + .00302^{**}DI - .00493^{***}DIV \quad (43c)$$

$$B_2 = .091^{***} - .00567p^{**} \quad (43d)$$

$$B_3 = -.00418^{***} + .00000472n^{**} - .0000106DI^{**} + .0000122DIV^{***} \quad (43e)$$

$$B_4 = -.000260^{***} \quad (43f)$$

where * = significant at .10; ** = significant at .05; and *** = significant at .01.

N and P are applied nitrogen and phosphate. The remaining variables are defined below, with their average values in parentheses.

n	soil nitrogen in ppm (29.5)
p	soil phosphate in ppm (12.3)
A	soil clay in % (32.4)
Ca	soil calcium carbonate in % (2.5)
PR	soil depth in cm (82)
E	length of growing season in days (33.9)
DIV	water-deficient days between flowering and formation of grain (7.7)
DI	water-deficient days between seeding and flowering (5.1)

Using average values for the agro-climatic variables and converting units to kilograms, we obtain the following equation:

$$Y = 3582 + 8.4291N + 2.1259P - .400088N^2 - .0260P^2 \quad (43f)$$

There appear to be some problems involved in using average values. As was the case with the generalized function for Argentina, (43f) gives unrealistically low input and yield levels.

A separate function is estimated for yield response in the Precordillera region. Unlike the function for central Chile, it contains an N x P interaction term. The equation is thus of the form:

$$Y = B_0 + B_1N + B_2P - B_3N^2 - B_4P^2 + B_5NP \qquad (44a)$$

where

$$B_0 = 212.9 + 92.0MO^{**} + 25.1PF^{***} - 101.8E^{**} + 271.4LC^{***} - 35.02(LC)^{2***} + 8.04A^{***} - 5.91ST^{**} \qquad (44b)$$

$$B_1 = 17.1^{***} - .075n^{**} - .127LS^{*} \qquad (44c)$$

$$B_2 = 7.77^{***} + 48E^{***} \qquad (44d)$$

$$B_3 = .0358^{***} \qquad (44e)$$

$$B_4 = .0164^{***} \qquad (44f)$$

$$B_5 = .0120^{***} - .0121A^{***} \qquad (44f)$$

where * = significant at .10; ** = significant at .05; and *** = significant at .01.

The agro-climatic variables are defined below, with average values in parentheses:

MO organic matter in % (11.05)
E time of seeding in days/10 (2.6)
A land previously cultivated or not
n soil nitrogen in ppm (48.3)
LS rainfall between sowing and emergence in dm (6.4)
LC rainfall between emergence and harvest in dm (3.9)
PF depth of A horizon in cm (27.0)
ST granular structure in % (50.5)

Using mean values for the agro-climatic variables, we obtain the following equation:

$$Y = 2088 + 12.684N + 9.018P - .0358N^2 - .0164P^2 + .006NP \qquad (44h)$$

The derivation of maximum, optimum, and two-thirds of optimum yields gives the results shown in Table 11.

The land-fertilizer equations for the three yield levels are given in (44j) through (44l):

Table 11. Input, yield, and economic return levels corresponding to four fertilization levels; function (44i) (wheat, Chile)

Maximum yield				Optimum levels				Two-thirds of opt. levels				Zero fert.				
N	P	Y	R[a]	N	P	Y	R	N	P	Y	R	Y	R	(a)[b]	(b)[c]	Function
203	312	4784	$224	147	196	4489	$247	98	131	3964	$238	2088	$157	$90	1.57	(44i)

[a]R = per hectare economic returns above fertilizer costs.

[b](a) = difference between R for optimum fertilization and R for zero fertilization.

[c](b) = ratio of R for optimum fertilization to R for zero fertilization.

$$Y = 2088L + 10.462F - .010148F^2L^{-1} \qquad F = 515 \qquad (44j)$$

$$Y = 2088L + 10.491F - .010466F^2L^{-1} \qquad F = 343 \qquad (44k)$$

$$Y = 2088L + 10.587F - .010455F^2L^{-1} \qquad F = 229 \qquad (44l)$$

Points on the isoquants are listed in Table 12. The maximum yield of 4784 kg is obtained with one ha of land and 515 kg of fertilizer. Other combinations giving the same output include 1.164 ha and 300 kg of fertilizer, 1.817 ha and 100 kg, and 2.291 ha and no fertilizer. The optimum level of fertilization combines one ha of land with 343 kg of fertilizer to produce 4489 kg of grain. The same quantity of grain is obtained from .958 ha and 400 kg of fertilizer, 1.056 ha and 300 kg, 1.673 ha and 100 kg or 2.150 ha and no fertilizer. The yield corresponding to two-thirds of optimal fertilization is 3964 kg produced with one hectare and 229 kilograms of fertilizer, .886 ha and 300 kg, 1.427 ha and 100 kg, or 1.898 ha and no fertilizer.

Using function (44g) as a measure of potential production, Chile's 689,000 ha dedicated to wheat in 1976 would have yielded 3.34, 3.13, and 2.77 million metric tons at the three different fertilizer levels used in this study. This represents an extremely large increase over the actual 1976 production of 866,000 metric tons. The amounts of fertilizer required would have been 359,000, 239,000, and 160,000 metric tons, respectively, all of which are quantities in excess of the 1976 total fertilizer consumption in Chile of 116,000 metric tons.

With fertilizer use at maximum, optimum, or two-thirds of optimum levels, the 1976 wheat crop could have been produced on an area of

Table 12. Coordinates of land-fertilizer isoquants, equations 44j-44l (wheat, Chile)

Quantity of fert. (kg)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
	44j			44k			44l		
0	4784	2.291	26.30	4489	2.150	23.44	3964	1.898	18.27
50		2.047	19.75		1.903	17.20		1.653	12.86
100		1.817	14.09		1.673	11.92		1.427	8.47
150		1.608	9.56		1.466	7.82		1.230	5.23
200		1.425	6.20		1.291	4.88		1.071	3.06
229[a]		1.335	4.75		1.206	3.65		1.000	2.20
250		1.277	3.88		1.153	2.94		.958	1.72
300		1.164	2.36		1.056	1.71		.886	.91
343[b]		1.095	1.50		1.000	1.03		.851	.47
350		1.086	1.39		.993	.94		.848	.42
400		1.037	.76		.958	.45		.833	.10
450		1.010	.35		.943	.13		.833	-.12
500		1.000	.07		.943	-.10		.845	-.27
515[c]		1.000	.00		.945	-.15		.850	-.31
550		1.002	-.13		.952	-.26		.864	-.39
600		1.013	-.28		.969	-.38		.887	-.48

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

181,000, 193,000, or 218,000 ha rather than the 698,000 ha actually used. Fertilizer requirements would have been 93,000, 66,000, and 50,000 metric tons, respectively.

Tejeda-Sanhueza (1973) estimates yield response of wheat to fertilizer in the region known as the Precordillera, the western foothills of the Andes. His study includes data from 34 sites: 20 from 1968 and 14 from 1969. Three models are estimated: the "inverse polynomial," the "1.25," and the quadratic. In the present study we shall make use only of the results computed using the quadratic form. The variety of wheat is the Capelle Desprez winter variety. The soils, known as Trumaos, are characterized by a high level of K and low availability of P.

Ten sites from 1968 are chosen for the present study. They are presented below in equations (45a) through (54a).

Equation	R^2	
$Y = 1632 + 21.3N^{***} + 14.2P - .0551N^{2***} - .0616P^2 + .0291NP$	.92	(45a)
$Y = 1134 + 31.2N^{***} + 21.3P^{**} - .0823N^2 - 1.023P^{2*} + .0196NP$	.92	(46a)
$Y = 447 + 30.2N^{***} + 7.88P - .0807N^{2***} - .0364P^2 + 0284NP^{*}$	.95	(47a)
$Y = 1193 + 12.39N^{**} + 15.84P^{**} - .0258N^{2*} - .0816P^{2**} + .0412NP^{**}$	.94	(48a)
$Y = 2107 + 26.17N^{***} + 15.60P^{**} - .0615N^{2***} - .0849P^{2**} + .0387NP^{**}$	.96	(49a)

$$Y = 1655 + 23.51N^{***} + 7.86P - .0529N^{2***} - .0373P^{2} + .0302NP^{*} \qquad .96 \qquad (50a)$$

$$Y = 2072 + 25.35N^{***} + 20.99P^{*} - .0675N^{2***} - .1076P^{2*} + .0187NP \qquad .84 \qquad (51a)$$

$$Y = 1199 + 17.36N^{***} + 19.26P^{**} - .0409N^{2**} - .0687P^{2*} - .0058NP \qquad .90 \qquad (52a)$$

$$Y = 1647 + 4.03N + 32.88P^{***} - .0098N^{2} - .1078P^{2***} - .0049NP \qquad .92 \qquad (53a)$$

$$Y = 903 + 25.19N^{***} + 15.40P^{**} - .0687N^{2***} - .0627P^{2*} + .0487NP^{***} \qquad .97 \qquad (54a)$$

where * = significant at .10; ** = significant at .05; and *** = significant at .01.

The levels of N and P for maximum, economic optimum, and two-thirds of economic optimum yield are listed in Table 13.

The range of optimal allocation of N is not excessively wide; between 164 and 234 kg/ha except for the two outlying sites in (48a) and (53a). The range of optimal P values is likewise fairly limited, between 107 and 152 kg/ha with (51a) and (54a) at outlyers. The yield levels corresponding to optimum fertilization range from 4118 (52a) to 6633 (49a) kg/ha. Returns to optimum fertilizer use vary from $149 to $263 per hectare, and the return ratio from 2.20 to 7.24.

The land-fertilizer equations for maximum yield, economic optimum application, and two-thirds of economic optimum application levels are given below for (45a) through (54a).

Table 13. Input, yield, and economic return levels corresponding to four fertilization levels; functions (45a)-(54a) (wheat, Chile)

Maximum yield				Optimum levels				Two-thirds of opt. levels				Zero fert.				
N	P	Y	R[a]	N	P	Y	R	N	P	Y	R	Y	R	(a)[b]	(c)[c]	Function
239	172	5392	$298	198	133	5255	$309	132	89	4601	$288	1632	$122	$187	2.53	(45a)
204	124	5638	$339	182	104	5566	$344	121	69	4850	$315	1134	$85	$259	4.05	(46a)
222	196	4556	$234	190	133	4394	$246	127	89	3715	$223	447	$34	$212	7.24	(47a)
397	197	5221	$240	295	150	4966	$258	197	100	4212	$240	1193	$89	$169	2.90	(48a)
260	151	6693	$397	229	137	6633	$404	153	91	5927	$382	2107	$158	$246	2.56	(49a)
285	221	5876	$310	234	152	5667	$326	156	101	4924	$303	1655	$124	$202	2.63	(50a)
204	115	5864	$358	174	96	5775	$364	116	64	5146	$340	2072	$155	$209	2.35	(51a)
203	132	4228	$231	164	107	4118	$239	109	71	3582	$222	1199	$90	$149	2.66	(52a)
168	149	4431	$250	0	136	4125	$273	0	91	3746	$257	1647	$124	$149	2.20	(53a)
263	225	5949	$320	223	181	5803	$331	149	121	4955	$302	903	$68	$263	4.87	(54a)

[a] R = per hectare economic returns above fertilizer costs.

[b] (a) = difference between R for optimum fertilization and R for zero fertilization.

[c] (b) = ratio of R for optimum fertilization to R for zero fertilization.

For equation (45a):

$$Y = 1632L + 18.3287F - .022339F^2L^{-1} \qquad F = 411 \qquad (45b)$$
$$Y = 1632L + 18.4472F - .022668F^2L^{-1} \qquad F = 331 \qquad (45c)$$
$$Y = 1632L + 18.4408F - .022648F^2L^{-1} \qquad F = 221 \qquad (45d)$$

For equation (46a):

$$Y = 1134L + 27.4578F - .041849F^2L^{-1} \qquad F = 328 \qquad (46b)$$
$$Y = 1134L + 27.6004F - .042321F^2L^{-1} \qquad F = 286 \qquad (46c)$$
$$Y = 1134L + 27.6034F - .042335F^2L^{-1} \qquad F = 190 \qquad (46d)$$

For equation (47a):

$$Y = 447L + 19.7342F - .023693F^2L^{-1} \qquad F = 418 \qquad (47b)$$
$$Y = 447L + 21.0096F - .027214F^2L^{-1} \qquad F = 323 \qquad (47c)$$
$$Y = 447L + 21.0042F - .027200F^2L^{-1} \qquad F = 216 \qquad (47d)$$

For equation (48a):

$$Y = 1193L + 13.5340F - .011401F^2L^{-1} \qquad F = 594 \qquad (48b)$$
$$Y = 1193L + 13.5514F - .011401F^2L^{-1} \qquad F = 445 \qquad (48c)$$
$$Y = 1193L + 13.5516F - .011401F^2L^{-1} \qquad F = 297 \qquad (48d)$$

For equation (49a):

$$Y = 2107L + 22.2866F - .027077F^2L^{-1} \qquad F = 411 \qquad (49b)$$
$$Y = 2107L + 22.2136F - .026908F^2L^{-1} \qquad F = 366 \qquad (49c)$$
$$Y = 2107L + 22.2274F - .026939F^2L^{-1} \qquad F = 244 \qquad (49d)$$

For equation (50a):

$$Y = 1655L + 16.6741F - .016467F^2L^{-1} \qquad F = 506 \qquad (50b)$$
$$Y = 1655L + 17.3470F - .018015F^2L^{-1} \qquad F = 386 \qquad (50c)$$
$$Y = 1655L + 17.3596F - .018048F^2L^{-1} \qquad F = 257 \qquad (50d)$$

For equation (51a):

$$Y = 2072L + 23.7782F - .037277F^2L^{-1} \qquad F = 319 \qquad (51b)$$
$$Y = 2072L + 23.7996F - .037351F^2L^{-1} \qquad F = 270 \qquad (51c)$$
$$Y = 2072L + 23.7996F - .037351F^2L^{-1} \qquad F = 180 \qquad (51d)$$

For equation (52a):

$$Y = 1199L + 18.1086F - .027069F^2L^{-1} \qquad F = 335 \qquad (52b)$$

$$Y = 1199L + 18.1101F - .027074F^2L^{-1} \qquad F = 271 \qquad (52c)$$

$$Y = 1199L + 18.1094F - .027072F^2L^{-1} \qquad F = 180 \qquad (52d)$$

For equation (53a):

$$Y = 1647L + 17.5895F - .027786F^2L^{-1} \qquad F = 317 \qquad (53b)$$

$$Y = 1647L + 32.88F - .1078F^2L^{-1} \qquad F = 136 \qquad (53c)$$

$$Y = 1647L + 32.88F - .1078F^2L^{-1} \qquad F = 91 \qquad (53d)$$

And finally, for equation (54a):

$$Y = 903L + 20.6758F - .021181F^2L^{-1} \qquad F = 488 \qquad (54b)$$

$$Y = 903L + 20.8041F - .021474F^2L^{-1} \qquad F = 404 \qquad (54c)$$

$$Y = 903L + 20.8031F - .021472F^2L^{-1} \qquad F = 270 \qquad (54d)$$

A number of points on the land-fertilizer isoquants are given in Tables 14-23.

With the exception of the land-fertilizer equations corresponding to function (47a), the three yield levels for each function may be obtained without fertilizer by using between two and five hectares of land. However, there is considerable difference in the marginal rates of substitution of fertilizer for land at the same input levels across sites. Taking as an example the isoquants corresponding to maximum yields, at zero input levels one metric ton of fertilizer replaces between 91.92 ha (Eq. 51b) and 4586.30 ha (Eq. 47b) of land. At input levels of 200 kg there is still a large range of "replacement rates": between 4.09 and 58.60 ha are replaced by one metric ton of fertilizer.

Half of the ten functions have intercept terms of greater magnitude than the 1976 average yield for wheat in Chile of 1242 kg/ha. For these sites, high management levels and zero fertilizer application would

Table 14. Coordinates of land-fertilizer isoquants, equations 45b-45d (wheat, Chile)

Quantity of fert. (kg)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
	45b			45c			45d		
0	5392	3.304	122.59	5255	3.220	117.20	4601	2.819	89.81
50		2.755	78.76		2.668	74.17		2.270	53.21
100		2.242	44.25		2.154	40.80		1.768	26.70
150		1.791	21.93		1.707	19.69		1.355	11.51
200		1.438	9.95		1.366	8.68		1.075	4.57
221[a]		1.326	7.03		1.260	6.09		1.000	3.08
250		1.206	4.35		1.149	3.72		.929	1.77
300		1.078	1.88		1.036	1.55		.868	.57
331[b]		1.035	1.06		1.000	.84		.856	.16
350		1.019	.71		.987	.52		.854	-.02
375		1.006	.35		.978	.21		.858	-.21
400		1.001	.09		.976	-.02		.865	-.36
411[c]		1.000	-.01		.977	-.11		.870	-.41
425		1.001	-.11		.979	-.21		.877	-.47
450		1.005	-.27		.986	-.35		.890	-.57
475		1.014	-.40		.996	-.47		.906	-.65
500		1.025	-.50		1.009	-.56		.924	-.71

[a] Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b] Amount of fertilizer corresponding to the economic optimum level of application.

[c] Amount of fertilizer required to achieve maximum yield.

Table 15. Coordinates of land-fertilizer isoquants, equations 46b-46d (wheat, Chile)

Quantity of fert. (kg)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
	46b			46c			46d		
0	5638	4.972	598.52	5566	4.908	586.36	4850	4.277	445.27
50		3.785	304.88		3.716	394.79		3.090	202.03
100		2.688	113.28		2.617	107.16		2.027	61.80
150		1.801	32.01		1.740	29.47		1.281	13.92
190[a]		1.355	10.91		1.311	9.91		1.000	4.32
200		1.281	8.41		1.242	7.63		.961	3.27
250		1.071	2.43		1.048	2.16		.871	.66
286[b]		1.016	.89		1.000	.74		.861	-.08
300		1.007	.52		.992	.40		.864	-.27
325		1.000	.05		.988	-.04		.875	-.53
328[c]		1.000	.00		.988	-.08		.876	-.55
350		1.003	-.28		.993	-.35		.891	-.71
375		1.013	-.51		1.005	-.57		.910	-.85
400		1.028	-.69		1.021	-.73		.934	-.95

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 16. Coordinates of land-fertilizer isoquants, equations 47b-47d (wheat, Chile)

Quantity of fert. (kg)	47b: Yield (kg)	47b: Amount of land (ha)	47b: Land needed to replace 1 met. T fertilizer (ha)	47c: Yield (kg)	47c: Amount of land (ha)	47c: Land needed to replace 1 met. T fertilizer (ha)	47d: Yield (kg)	47d: Amount of land (ha)	47d: Land needed to replace 1 met. T fertilizer (ha)
0	4556	10.192	4586.30	4394	9.830	4541.70	3715	8.311	3245.60
50		8.001	2458.40		7.500	2255.10		5.982	1430.20
100		5.868	952.90		5.246	764.30		3.773	387.40
150		3.878	274.60		3.207	179.30		1.961	61.10
200		2.289	58.60		1.790	31.20		1.109	9.00
216[a]		1.935	34.82		1.532	18.23		1.000	5.40
250		1.446	12.50		1.214	6.70		.881	2.00
300		1.138	3.60		1.033	1.90		.828	.30
323[b]		1.075	2.18		1.000	1.00		.825	-.06
350		1.032	1.20		.981	.40		.831	-.30
400		1.002	0.20		.979	-.20		.858	-.70
418[c]		1.000	.00		.985	-.39		.871	-.74
425		1.000	-.10		.988	-.40		.877	-.80
450		1.005	-.30		1.001	-.60		.897	-.80
475		1.014	-.40		1.017	-.70		.920	-.90
500		1.027	-.55		1.035	-.80		.943	-.10

[a] Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b] Amount of fertilizer corresponding to the economic optimum level of application.

[c] Amount of fertilizer required to achieve maximum yield.

Table 17. Coordinates of land-fertilizer isoquants, equations 48b-48d (wheat, Chile)

Quantity of fert. (kg)	48b			48c			48d		
	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
0	5221	4.376	217.30	4966	4.163	196.80	4212	3.531	141.60
50		3.815	157.75		3.601	140.52		2.971	95.13
100		3.271	105.10		3.058	91.60		2.434	57.20
150		2.753	64.30		2.543	54.47		1.938	30.53
200		2.275	36.20		2.075	29.60		1.512	14.60
250		1.860	19.05		1.679	15.02		1.192	6.54
297[a]		1.551	10.03		1.394	7.68		1.000	3.10
300		1.533	9.60		1.379	7.40		.991	2.90
350		1.302	4.87		1.179	3.64		.882	1.35
400		1.157	2.50		1.061	1.80		.830	.60
445[b]		1.080	1.40		1.000	1.00		.811	.20
450		1.072	1.31		.995	.92		.810	.16
500		1.026	.60		.963	.40		.808	-.10
525		1.013	.42		.956	.22		.812	-.18
550		1.005	.24		.952	.07		.818	-.26
575		1.001	.10		.952	-.04		.826	-.32
594[c]		1.000	.00		.953	-.11		.833	-.36
600		1.000	.00		.954	-.12		.835	-.40

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 18. Coordinates of land-fertilizer isoquants, equations 49b-49d (wheat, Chile)

Quantity of fert. (kg)	49b Yield (kg)	49b Amount of land (ha)	49b Land needed to replace 1 met. T fertilizer (ha)	49c Yield (kg)	49c Amount of land (ha)	49c Land needed to replace 1 met. T fertilizer (ha)	49d Yield (kg)	49d Amount of land (ha)	49d Land needed to replace 1 met. T fertilizer (ha)
0	6693	3.177	106.70	6633	3.148	104.50	5927	2.813	83.48
50		2.660	69.19		2.633	67.57		2.299	51.20
100		2.178	39.50		2.153	38.46		1.828	27.11
150		1.755	20.02		1.733	19.43		1.432	12.53
200		1.422	9.30		1.403	9.00		1.148	5.32
244[a]		1.222	4.61		1.206	4.44		1.000	2.45
250		1.201	4.18		1.186	4.03		.986	2.20
300		1.077	1.80		1.065	1.76		.911	.82
350		1.019	.71		1.009	.67		.887	.14
366[b]		1.010	.47		1.000	.40		.886	-.01
400		1.001	.10		.992	.08		.890	-.24
411[c]		1.000	.00		.991	-.01		.894	-.31
425		1.001	.00		.992	-.12		.899	-.38
450		1.005	-.26		.997	-.27		.910	-.48
475		1.013	-.39		1.006	-.40		.924	-.57
500		1.024	-.50		1.017	-.50		.940	-.64

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 19. Coordinates of land-fertilizer isoquants, equations 50b-50d (wheat, Chile)

Quantity of fert. (kg)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
	50b			50c			50d		
0	5876	3.550	127.00	5667	3.424	122.90	4924	2.975	92.85
50		3.055	88.77		2.909	83.29		2.462	59.27
100		2.581	56.39		2.421	50.65		1.981	33.23
150		2.144	32.60		1.976	27.69		1.559	16.38
200		1.761	17.34		1.600	13.84		1.232	7.34
250		1.458	8.74		1.319	6.58		1.021	3.19
257[a]		1.423	7.92		1.288	5.93		1.000	2.84
300		1.246	4.33		1.139	3.12		.909	1.37
350		1.116	2.15		1.039	1.46		.859	.51
386[b]		1.060	1.28		1.000	.79		.846	.15
400		1.045	1.03		.990	.60		.844	.04
450		1.011	.41		.973	.12		.851	-.24
475		1.003	.20		.972	-.04		.859	-.34
500		1.000	.04		.975	-.17		.869	-.42
506[c]		1.000	.00		.976	-.20		.871	-.44
525		1.001	-.10		.981	-.28		.881	-.49
550		1.005	-.21		.989	-.37		.894	-.54
600		1.019	-.37		1.011	-.51		.925	-.64

[a] Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b] Amount of fertilizer corresponding to the economic optimum level of application.

[c] Amount of fertilizer required to achieve maximum yield.

Table 20. Coordinates of land-fertilizer isoquants, equations 51b-51d (wheat, Chile)

Quantity of fert. (kg)	51b			51c			51d		
	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
0	5864	2.830	91.92	5775	2.787	89.23	5146	2.484	70.85
50		2.276	52.97		2.233	50.95		1.933	37.72
100		1.783	25.50		1.742	24.21		1.459	16.25
150		1.398	10.60		1.362	9.92		1.122	5.97
180[a]		1.236	6.02		1.205	5.59		1.000	3.16
200		1.157	4.09		1.129	3.77		.947	2.02
250		1.041	1.45		1.020	1.30		.885	.48
270[b]		1.019	.87		1.000	.76		.878	.13
275		1.015	.75		.996	.65		.878	.06
300		1.002	.27		.986	.19		.880	-.24
319[c]		1.000	.00		.985	-.06		.887	-.41
325		1.000	-.07		.986	-.13		.890	-.46
350		1.005	-.33		.992	-.38		.905	-.63
375		1.016	-.53		1.004	-.56		.923	-.76
400		1.031	-.68		1.020	-.71		.944	-.87

[a] Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b] Amount of fertilizer corresponding to the economic optimum level of application.

[c] Amount of fertilizer required to achieve maximum yield.

Table 21. Coordinates of land-fertilizer isoquants, equations 52b-52d (wheat, Chile)

Quantity of fert. (kg)	52b Yield (kg)	52b Amount of land (ha)	52b Land needed to replace 1 met. T fertilizer (ha)	52c Yield (kg)	52c Amount of land (ha)	52c Land needed to replace 1 met. T fertilizer (ha)	52d Yield (kg)	52d Amount of land (ha)	52d Land needed to replace 1 met. T fertilizer (ha)
0	4228	3.526	187.80	4118	3.435	178.17	3582	2.987	134.80
50		2.791	105.42		2.700	98.47		2.257	68.02
100		2.122	47.68		2.035	43.53		1.617	26.25
150		1.582	17.96		1.506	15.96		1.160	8.26
180[a]		1.350	9.55		1.285	8.37		1.002	4.03
200		1.236	6.26		1.179	5.44		.934	2.49
250		1.020	2.16		1.029	1.82		.857	.59
271[b]		1.035	1.32		1.000	1.08		.849	.18
275		1.030	1.20		.996	.96		.848	.12
300		1.009	.56		.979	.40		.849	-.20
325		1.001	.13		.974	.01		.858	-.43
335[c]		1.000	.00		.975	-.11		.863	-.51
350		1.002	-.18		.978	-.27		.872	-.61
375		1.009	-.41		.987	-.48		.890	-.74
400		1.021	-.58		1.001	-.64		.911	-.85

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 22. Coordinates of land-fertilizer isoquants, equations 53b-53d (wheat, Chile)

Quantity of fert. (kg)	53b Yield (kg)	53b Amount of land (ha)	53b Land needed to replace 1 met. T fertilizer (ha)	53c Yield (kg)	53c Amount of land (ha)	53c Land needed to replace 1 met. T fertilizer (ha)	53d Yield (kg)	53d Amount of land (ha)	53d Land needed to replace 1 met. T fertilizer (ha)
0	4431	2.690	77.30	4125	2.505	125.23	3746	2.274	103.27
50		2.176	44.99		1.608	35.32		1.394	25.48
91[a]		1.796	25.40		1.157	8.38		1.000	5.22
100		1.720	22.08		1.102	5.94		.960	3.52
136[b]		1.453	12.10		1.000	.98		.902	.08
150		1.366	9.44		.993	.08		.906	-.57
200		1.144	3.74		1.037	-1.57		.973	-1.82
250		1.037	1.33		1.131	-2.25		1.078	-2.37
275		1.013	.69		1.186	-2.46		1.137	-2.54
300		1.002	.23		1.245	-2.60		1.199	-2.67
317[c]		1.000	.01		1.287	-2.68		1.242	-2.74
325		1.001	-.10		1.307	-2.72		1.262	-2.77
350		1.006	-.35		1.370	-2.81		1.327	-2.84
375		1.017	-.54		1.435	-2.88		1.393	-2.90
400		1.033	-.69		1.500	-2.93		1.460	-2.95

[a] Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b] Amount of fertilizer corresponding to the economic optimum level of application.

[c] Amount of fertilizer required to achieve maximum yield.

Table 23. Coordinates of land-fertilizer isoquants, equations 54b-54d (wheat, Chile)

Quantity of fert. (kg)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
	54b			54c			54d		
0	5949	6.588	993.77	5803	6.426	951.46	4955	5.487	693.67
100		5.352	334.77		4.179	309.05		3.257	184.87
200		2.400	56.41		2.243	48.45		1.510	19.55
250		1.717	19.22		1.597	16.00		1.091	5.81
270[a]		1.526	12.55		1.424	10.39		1.000	3.73
300		1.319	6.84		1.240	5.65		.915	1.99
350		1.126	2.72		1.074	2.22		.850	.64
400		1.040	1.10		1.003	.85		.834	.03
404[b]		1.035	1.02		1.000	.78		.834	.00
450		1.006	.34		.979	.19		.842	-.29
488[c]		1.000	.00		.977	-.10		.856	-.45
500		1.001	-.08		.979	-.17		.862	-.49

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

possibly supply above-average yields. The ten sites as a whole indicate that total production could be augmented substantially by increased fertilizer application. At input levels for maximum yield, optimum levels, and two-thirds of optimum levels, the 698,000 ha sown to wheat in 1976 could have produced between 2.95 and 4.67 million metric tons, 2.87 and 4.63 million metric tons, and 2.50 and 4.14 million metric tons, respectively. Fertilizer requirements would have ranged from 221,000 metric tons to 415,000 metric tons at input levels for maximum yield, 95,000 to 311,000 metric tons at optimal levels, and 64,000 to 207,000 metric tons at two-thirds of optimal levels.

The actual output of wheat in Chile was 866,000 metric tons in 1976. With high levels of management and increased fertilization, the amount of land required could have been reduced substantially from the actual area of 698,000 ha. Fertilization at maximum yield levels would have required between 129,000 and 205,000 ha, at optimum levels between 131,000 and 210,000 ha, and at two-thirds of optimal levels, between 146,000 and 242,000 ha.

Mujica-Ateaga (1965) describes the results of field experiments conducted by the Facultad de Agronomiá of the Universidad Católica de Chile to determine optimum dosages of N and P for wheat, maize, and potatoes. In many of the experiments it was found that use of one of the nutrients, usually P, was not economical. Selected functions from the study follow below.

$$Y = 1885 + 5.057N^{***} + 2.470P - .004371N^{2***} - .003975P^{2***} + .001409NP^{***} \qquad R^2 = .51 \qquad (55a)$$

Response of wheat at Pirque, Santiago Province, 1962-1963 season.

$$Y = 3569 + 6.148N^{***} - 3.23415P - .593054N^{2} + .69944P^{2} + .217211NP \qquad .60 \qquad (56)$$

Response of wheat, Calera de Tango, 1964-1965. Since P and P^2 had "wrong" signs and had insignificant coefficients, the function was reestimated without P:

$$Y = 3588 + 5.702N^{***} - .005263N^{2***} \qquad .58 \qquad (56a)$$

$$Y = 4145 + 2.399N^{*} + 8.588P^{**} - .192836N^{2} - 1.475788P^{2***} - 7.417235NP^{***} \qquad .72 \qquad (57)$$

Response of wheat, Calera de Tango, 1964-1965. In this case, response to N was judged insignificant, and the function was estimated with P only:

$$Y = 4614 + 9.335P^{***} - .016862P^{2***} \qquad (57a)$$

where * = significant at .10; ** = significant at .05; and *** = significant at .01.

The input levels for maximum yield, economic optimum, and two-thirds of economic optimum yield are given in Table 24.

Equation (55a) reaches the point of maximum yield at very high input levels. Economic optimum levels are much lower, indicating a fairly flat response surface at higher input levels. Equations (56a) and (57a) also show a considerable difference between levels for maximum yield and optimum levels. The three functions in general give much lower values for yield and economic return than do the other ones from Chile. The reason for this is uncertain, but differences in initial soil fertility, climatic factors, and management level may be partly responsible.

The land-fertilizer equations for the three yield levels are listed below:

Table 24. Input, yield, and economic return levels corresponding to four fertilization levels; functions (55a)-(57a) (wheat, Chile)

Maximum yield				Optimum levels				Two-thirds of opt. levels				Zero fert.				
N	P	Y	R[a]	N	P	Y	R	N	P	Y	R	Y	R	(a)[b]	(c)[c]	Function
657	487	4975	\$78	324	0	3655	\$193	216	0	3218	\$187	1885	\$141	\$52	1.37	(55a)
542	0	5132	\$249	225	0	4605	\$289	150	0	4325	\$287	3588	\$269	\$20	1.07	(56a)
9	277	5906	\$369	0	171	5717	\$383	0	114	5459	\$379	4614	\$346	\$37	1.11	(57a)

[a]R = per hectare economic returns above fertilizer costs.

[b](a) = difference between R for optimum fertilization and R for zero fertilization.

[c](b) = ratio of R for optimum fertilization to R for zero fertilization.

For equation (55a);

$$Y = 1885L + 5.407F - .002365F^2L^{-1} \qquad F = 144 \qquad (55b)$$
$$Y = 1885L + 7.586F - .006557F^2L^{-1} \qquad F = 324 \qquad (55c)$$
$$Y = 1885L + 7.588F - .006557F^2L^{-1} \qquad F = 216 \qquad (55d)$$

For equation (56a):

$$Y = 3588L + 5.702F - .005263F^2L^{-1} \qquad F = 542 \qquad (56b)$$
$$Y = 3588L + 5.702F - .005263F^2L^{-1} \qquad F = 225 \qquad (56c)$$
$$Y = 3588L + 5.702F - .005263F^2L^{-1} \qquad F = 150 \qquad (56d)$$

For equation (57a):

$$Y = 4614L + 9.335F - .016862F^2L^{-1} \qquad F = 277 \qquad (57b)$$
$$Y = 4614L + 9.335F - .016862F^2L^{-1} \qquad F = 171 \qquad (57c)$$
$$Y = 4614L + 9.335F - .016862F^2L^{-1} \qquad F = 114 \qquad (57d)$$

Coordinates of the land-fertilizer isoquants are listed in Tables 25-27. To produce a quantity of grain equivalent to maximum per hectare yield requires between 1.280 ha (Eq. 57b) and 2.639 ha (Eq. 55b) of land when no fertilizer is used. The amount of land replaced by one metric ton of fertilizer at an application level approaching zero is between 3.31 and 19.98 ha. At 200 kg of fertilizer application, a quantity equivalent to maximum per hectare yield is produced with between 1.019 and 2.090 ha and one metric ton of fertilizer substitutes for between .53 and 10.93 ha.

Quantities of grain equivalent to optimum yields may be obtained from zero fertilization and between 1.239 and 1.939 ha of land, depending on the site. The amount of land replaced by one metric ton of fertilizer at application levels approaching zero is between 3.11 and 15.13 ha. At fertilization levels of 100 kg, optimum yield equivalents require between 1.071 and 1.559 ha, and with 200 kg they require between .983 and 1.246

Table 25. Coordinates of land-fertilizer isoquants, equations 55b-55d (wheat, Chile)

Quantity of fert. (kg)	55b			55c			55d		
	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
0	4975	2.639	19.98	3655	1.939	15.13	3218	1.707	11.73
50		2.492	17.52		1.743	11.52		1.512	8.60
100		2.358	15.16		1.559	8.40		1.331	5.99
150		2.222	12.96		1.392	5.88		1.170	3.98
200		2.090	10.93		1.246	3.96		1.037	2.53
216[a]		2.048	10.32		1.204	3.47		1.000	2.17
250		1.962	9.10		1.126	2.58		.934	1.55
300		1.840	7.48		1.034	1.63		.863	.91
324[b]		1.784	6.78		1.000	1.30		.839	.69
350		1.724	6.08		.970	1.00		.819	.49
400		1.616	4.89		.929	.57		.796	.22
500		1.425	3.07		.897	.06		.792	-.12
600		1.273	1.88		.906	-.21		.820	-.32
700		1.161	1.13		.938	-.38		.864	-.45
800		1.085	.66		.983	-.49		.917	-.53
900		1.037	.37		1.036	-.57		.975	-.60
1000		1.011	.18		1.094	-.62		1.037	-.64
1100		1.001	.04		1.155	-.67		1.101	-.68
1144[c]		1.000	.00		1.183	-.68		1.130	-.69
1200		1.001	-.05		1.219	-.70		1.168	-.71

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 26. Coordinates of land-fertilizer isoquants, equations 56b-56d (wheat, Chile)

Quantity of fert. (kg)	56b Yield (kg)	56b Amount of land (ha)	56b Land needed to replace 1 met. T fertilizer (ha)	56c Yield (kg)	56c Amount of land (ha)	56c Land needed to replace 1 met. T fertilizer (ha)	56d Yield (kg)	56d Amount of land (ha)	56d Land needed to replace 1 met. T fertilizer (ha)
0	5132	1.430	3.25	4605	1.283	2.62	4325	1.205	2.31
50		1.354	2.70		1.207	2.13		1.129	1.85
100		1.283	2.21		1.137	1.70		1.060	1.45
150[a]		1.219	1.77		1.076	1.32		1.000	1.11
200		1.163	1.39		1.023	1.00		.949	.83
225[b]		1.138	1.22		1.000	.87		.928	.70
250		1.115	1.06		.980	.74		.909	.59
300		1.076	.79		.946	.52		.879	.40
350		1.046	.56		.922	.34		.859	.25
400		1.024	.38		.907	.20		.847	.12
450		1.009	.22		.899	.07		.843	.01
500		1.002	.09		.897	-.03		.845	-.08
542[c]		1.000	.00		.900	-.10		.850	-.14
550		1.000	-.02		.901	-.11		.852	-.15
600		1.003	-.11		.910	-.19		.863	-.22

[a] Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b] Amount of fertilizer corresponding to the economic optimum level of application.

[c] Amount of fertilizer required to achieve maximum yield.

Table 27. Coordinates of land-fertilizer isoquants, equations 57b-57d (wheat, Chile)

Quantity of fert. (kg)	57b Yield (kg)	57b Amount of land (ha)	57b Land needed to replace 1 met. T fertilizer (ha)	57c Yield (kg)	57c Amount of land (ha)	57c Land needed to replace 1 met. T fertilizer (ha)	57d Yield (kg)	57d Amount of land (ha)	57d Land needed to replace 1 met. T fertilizer (ha)
0	5906	1.280	3.31	5717	1.239	3.11	5459	1.183	2.83
50		1.187	2.39		1.146	2.22		1.090	1.19
100		1.111	1.62		1.071	1.48		1.017	1.30
114[a]		1.093	1.44		1.053	1.31		1.000	1.14
125		1.080	1.30		1.041	1.17		.988	1.01
150		1.055	1.01		1.016	.90		.965	.76
171[b]		1.037	.79		1.000	.70		.950	.58
175		1.034	.76		.997	.66		.947	.54
200		1.019	.53		.983	.45		.935	.35
225		1.008	.34		.974	.27		.927	.18
250		1.002	.16		.969	.11		.924	.03
275		1.000	.01		.968	-.04		.925	-.10
277[c]		1.000	.00		.968	-.05		.926	-.11
300		1.001	-.13		.971	-.17		.930	-.22

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

ha. The amounts of land replaced by one metric ton of fertilizer are between 1.48 and 8.40 ha and .45 and 3.96 ha, respectively, depending on the site.

Yield levels corresponding to two-thirds of optimal fertilization require between 114 and 216 kg on one ha of land. With no fertilization, between 1.183 and 1.707 ha are needed. One metric ton of fertilizer replaces between 2.83 and 11.73 ha at an application level approaching zero. At an application level of 100 kg the land requirement is between 1.017 and 1.331 ha, and one metric ton of fertilizer substitutes for from 1.30 to 5.99 ha, again depending on the site.

The 1976 Chilean wheat production of 866,000 metric tons which was produced on 698,000 hectares of land could have been augmented substantially, applying the results of the above equations. Total production could have ranged between 3.47 and 4.12 million metric tons at maximum yield levels, 2.55 and 3.99 million metric tons at optimal levels of fertilization, and 2.25 and 3.81 million metric tons at two-thirds of optimal fertilization levels. However, fertilizer requirements would have increased considerably as well. The function estimated in (55a) has a very flat response surface at higher input levels, with the result that maximum yield per hectare is not reached until an application of 1144 kg of fertilizer. Applying this amount of nutrient to the entire wheat production area would have required 799,000 metric tons of fertilizer, almost seven times more than the country's total consumption in 1976. Using equation (57a) as a guide, on the other hand, fertilization of the entire area at maximum yield levels would have required 193,000 metric tons of nutrient.

Fertilizer requirements for the total area at optimal and two-thirds of optimal application levels would have been from 119,000 to 126,000 metric tons and from 80,000 to 84,000 metric tons, respectively.

Using fertilizer levels for maximum yield, the actual 1976 Chilean crop could have been produced with from 147,000 to 174,000 ha, a considerable savings of land over the 698,000 ha actually used. At optimal input levels the amount of land needed would have been between 151,000 and 237,000 ha, and at two-thirds of optimal levels between 159,000 and 269,000 ha of land would have been required, depending on the site. The amount of fertilizer necessary to obtain the crop from this reduced quantity of land would have had an extremely wide range, due to the flatness of the response curve in (55a). Using the site for equation (56a) as a basis for estimating yield response, total 1976 production would have required 169,000, 188,000, and 200,000 ha of land at the three fertilization levels, along with 92,000, 42,000, and 30,000 metric tons of fertilizer, respectively.

Peru

Peru is situated on the Pacific Coast of South America, north of Chile. The country has a land area of 138 million hectares and had a population of slightly over 16 million inhabitants in 1977, forty-two percent of whom were classified as agricultural (FAO, 1978a).

Peru had an estimated 904,000 ha of land planted to cereals in 1977; this figure included 410,000 in maize, 140,000 in wheat, and 125,000 in rice. Yields for maize were 1707 kg/ha, slightly below the average for South America of 1849 kg/ha, but considerably above the figure for Mexico of 1217 kg/ha (FAO, 1978a). As in most of Latin America, maize in Peru is generally grown on small plots on a noncommercial basis.

Wheat is cultivated in areas of higher elevation. Average yields in Peru in 1977 were 1071 kg/ha, slightly under the average for South America of 1117 kg/ha, and only one-third of Mexico's high 3367 kg/ha yields (which are in turn due to introduction of high-yielding varieties) (FAO, 1978a).

Peru's rice cultivation is found primarily in the northern coastal and the Selva Alta (high jungle) regions. The average yield in 1977 of 4640 kg/ha was the highest of any country in the Americas besides the United States (FAO, 1978a).

In none of the above-mentioned grains is Peru self-sufficient. Imports in 1976 reached 602,000 metric tons of wheat, 280,000 metric tons of maize, and almost 82,000 metric tons of rice (FAO, 1978b).

Fertilizer consumption in 1976 was 38.7 kilograms per hectare of arable land the permanent crops. While this figure was slightly above the average for South America as a whole, it was below that for many countries with a modern, commercialized agricultural sector. Thus, it would appear that the potential for raising crop yields through increased fertilizer use is significant.

The present study examines data on rice yield response to fertilizer in the northern coastal and Selva Alta regions. The data are from a study by Carmen (1968). Most fertilizer experiments with rice have used only N, but these included P and K as well. Response functions were estimated in the original study, but using orthogonal coding. In order to obtain meaningful results it was necessary to reestimate all of the functions using original values.

Carmen found that climatic variables had great influence on yield. Regressing yield on temperature variables alone gave R^2 values as high as .43. As expected, however, N was the most important factor in increasing rice yields. Application solely of N gave predicted yields in the range of 3920 to 5720 kg/ha. Additional yields required application of P and K.

The reestimated functions chosen for the present study are listed below:

$$\underline{R^2}$$

$$Y = 2688 + 41.748N^{***} + .011P + 9.975K - .076N^{2*} - .009P^2 - .060K^2 - .047NP + .019NK + .037PK \qquad .73 \qquad (81a)$$

$$Y = 3269 + 45.79^{***} + 13.32P - 20.86K^{**} - .105N^{2***} - .075P^2 + .114K^{2**} - .002NP - .022NK + .043PK \qquad .86 \qquad (82a)$$

$$Y = 2243 + 31.97N^{***} - 4.44P + 5.68K - .051N^{2*} + .069P^2 - .032K^2 + .010NP + .030NK - .029PK \qquad .85 \qquad (83a)$$

$$Y = 3605 + 15.66N^{**} + 22.29P^{**} - 4.97K - .081N^{2***} - .077P^2 + .055K^2 - .043NP^{**} - .056PK^{*} + .024NK \qquad .53 \qquad (84a)$$

where * = significant at .10; ** = significant at .05; and *** = significant at .01.

It will be noted that three of the above equations have positive quadratic terms for one nutrient, accompanied by either positive or negative linear and interaction terms. If all the terms involving a particular nutrient are positive, we have increasing returns, and the nutrient in question should be applied at least to the level corresponding to the maximum level used in the experiment. A positive quadratic term combined with a negative linear one, on the other hand, means that the nutrient has a negative effect until higher levels of application are reached. As there would appear to be no agronomic justification for such behavior, in the present study we shall fix the input level of such nutrients at zero.

The three input levels for the equations (58a) through (61a) are given in Table 28, along with the corresponding yield and return levels. Prices used are \$342 US per metric ton N, \$322 US per metric ton P, \$242 US per metric ton K, and \$129 US per metric ton of rice.

It will noted that optimal input levels include all three nutrients for one of the functions, N and P for two others, and N and K for one. The land-fertilizer equations are as follows:

For equation (58a):

$$Y = 2688L + 31.994F - .038F^2L^{-1} \qquad F = 420 \qquad (58b)$$

$$Y = 2688L + 32.534F - .039F^2L^{-1} \qquad F = 383 \qquad (58c)$$

$$Y = 2688L + 32.534F - .039F^2L^{-1} \qquad F = 255 \qquad (59d)$$

For equation (59a):

$$Y = 3269L + 36.569F - .060F^2L^{-1} \qquad F = 303 \qquad (59b)$$

$$Y = 3269L + 37.608F - .064F^2L^{-1} \qquad F = 274 \qquad (59c)$$

$$Y = 3269L + 37.640F - .064F^2L^{-1} \qquad F = 183 \qquad (59d)$$

Table 28. Input, yield, and economic return levels corresponding to four fertilization levels; functions (58a)-(61a) (rice, Peru)

Maximum yield					Optimum levels				
N	P	K	Y	R[a]	N	P	K	Y	R
291	0	129	9402	$1082	272	0	111	9362	$1088
217	86	0	8815	$1035	205	69	0	8777	$1040
392	6	265	9266	$995	354	7	222	9163	$1005
63	127	0	5575	$649	50	115	0	5483	$653

[a]R = per hectare economic returns above fertilizer costs.

[b](a) = difference between R for optimum fertilization and R for zero fertilization.

[c](b) = ratio of R for optimum fertilization to R for zero fertilization.

Two-thirds of opt. levels					Zero fert.				
N	P	K	Y	R	Y	R	(a)[b]	(b)[c]	Function
181	0	74	8419	$1006	2688	$347	$741	3.14	(58a)
137	46	0	8013	$972	3269	$422	$618	2.46	(59a)
236	5	148	8105	$927	2243	$289	$716	3.48	(60a)
33	77	0	5184	$633	3605	$465	$188	1.40	(61a)

For equation (60a):

$$Y = 2243L + 21.126F - .016F^2L^{-1} \qquad F = 663 \qquad (60b)$$

$$Y = 2243L + 21.517F - .017F^2L^{-1} \qquad F = 583 \qquad (60c)$$

$$Y = 2243L + 21.506F - .017F^2L^{-1} \qquad F = 389 \qquad (60d)$$

For equation (61a):

$$Y = 3605L + 20.089F - .053F^2L^{-1} \qquad F = 190 \qquad (61b)$$

$$Y = 3605L + 20.281F - .054F^2L^{-1} \qquad F = 165 \qquad (61c)$$

$$Y = 3605L + 20.301F - .054F^2L^{-1} \qquad F = 110 \qquad (61d)$$

Coordinates on the land-fertilizer isoquants are listed in Tables 29-32. A quantity of grain equivalent to maximum per hectare yield may be produced with a zero application of fertilizer and between 1.530 and 4.131 hectares of land, according to the site. Approaching a zero application level, one metric ton of fertilizer substitutes for between 13.04 and 145.62 ha of land. To produce these amount of rice using 100 kg of nutrient requires from 1.106 to 2.367 ha of land, and the amount of land replaced by one metric ton of fertilizer is from 3.10 to 52.52 ha. Similarly wide ranges are observed for the other two yield levels. The amounts of rice corresponding to optimum per hectare yields require the use of between 1.521 and 4.085 ha if no fertilizer is used, while amounts corresponding to two-thirds of optimum application need between 1.438 and 3.132 ha. The reason for such wide ranges of land-fertilizer substitution is that the function estimated in equation (61a) does not have a very great response to fertilizer. As such, it is probably not representative of conditions in the area under study.

Considering only the sites used to estimate equations (58c) through (60a), the area of 133,000 ha dedicated to rice cultivation in Peru in

Table 29. Coordinates of land-fertilizer isoquants, equations 58b-58d (rice, Peru)

Quantity of fert. (kg)	58b Yield (kg)	58b Amount of land (ha)	58b Land needed to replace 1 met. T fertilizer (ha)	58c Yield (kg)	58c Amount of land (ha)	58c Land needed to replace 1 met. T fertilizer (ha)	58d Yield (kg)	58d Amount of land (ha)	58d Land needed to replace 1 met. T fertilizer (ha)
0	9402	3.498	145.62	9362	3.483	146.82	8419	3.132	118.73
50		2.915	93.69		2.890	93.52		2.541	71.86
100		2.367	52.57		2.335	51.70		1.994	36.99
150		1.881	25.91		1.844	24.99		1.530	16.34
200		1.495	11.60		1.460	10.96		1.196	6.57
250		1.237	5.02		1.208	4.66		1.007	2.60
255[a]		1.218	4.62		1.190	4.28		.994	2.37
300		1.092	2.17		1.071	1.98		.920	.97
350		1.024	.86		1.009	.75		.891	.20
383[b]		1.004	.37		.992	.28		.889	-.10
400		1.000	.18		.989	.11		.892	-.22
420[c]		.998	.00		.989	-.06		.898	-.33
450		1.001	-.21		.994	-.26		.911	-.47

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 30. Coordinates of land-fertilizer isoquants, equations 59b-59d (rice, Peru)

Quantity of fert. (kg)	59b Yield (kg)	59b Amount of land (ha)	59b Land needed to replace 1 met. T fertilizer (ha)	59c Yield (kg)	59c Amount of land (ha)	59c Land needed to replace 1 met. T fertilizer (ha)	59d Yield (kg)	59d Amount of land (ha)	59d Land needed to replace 1 met. T fertilizer (ha)
0	8815	2.697	81.34	8777	2.685	82.93	8013	2.451	69.18
50		2.158	46.04		2.133	45.90		1.901	36.13
100		1.687	21.66		1.653	20.87		1.436	15.16
150		1.329	8.81		1.298	8.17		1.118	5.43
183[a]		1.173	4.66		1.150	4.21		1.000	2.62
200		1.117	3.32		1.098	2.95		.962	1.75
250		1.022	1.07		1.015	.86		.913	.30
274[b]		1.004	.49		1.001	.32		.911	-.09
300		.997	.05		.998	-.09		.917	-.39
303[c]		.997	.01		.999	-.13		.919	-.42
350		1.009	-.48		1.017	-.60		.949	-.78

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 31. Coordinates of land-fertilizer isoquants, equations 60b-60d (rice, Peru)

Quantity of fert. (kg)	60b Yield (kg)	60b Amount of land (ha)	60b Land needed to replace 1 met. T fertilizer (ha)	60c Yield (kg)	60c Amount of land (ha)	60c Land needed to replace 1 met. T fertilizer (ha)	60d Yield (kg)	60d Amount of land (ha)	60d Land needed to replace 1 met. T fertilizer (ha)
0	9266	4.131	160.74	9163	4.085	160.09	8105	3.613	125.19
50		3.665	121.73		3.611	120.06		3.140	90.45
100		3.211	86.39		3.150	84.04		2.683	60.37
150		2.776	57.43		2.709	54.89		2.251	37.13
200		2.368	35.83		2.298	33.54		1.859	21.10
250		1.999	21.11		1.932	19.33		1.527	11.24
300		1.686	11.91		1.627	10.69		1.273	5.80
350		1.441	6.60		1.394	5.83		1.101	3.00
389[a]		1.298	4.17		1.262	3.65		1.014	1.81
400		1.265	3.67		1.232	3.21		.996	1.57
450		1.149	2.07		1.128	1.78		.932	.80
500		1.077	1.17		1.066	.97		.907	.35
550		1.035	.62		1.032	.49		.897	.07
583[b]		1.019	.38		1.019	.27		.897	-.06
600		1.014	.28		1.016	.18		.898	-.12
650		1.006	.05		1.012	-.03		.908	-.25
663[c]		1.005	.00		1.013	-.08		.912	-.28
700		1.007	-.11		1.018	-.18		.923	-.34

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 32. Coordinates of land-fertilizer isoquants, equations 61b-61d (rice, Peru)

Quantity of fert. (kg)	61b: Yield (kg)	61b: Amount of land (ha)	61b: Land needed to replace 1 met. T fertilizer (ha)	61c: Yield (kg)	61c: Amount of land (ha)	61c: Land needed to replace 1 met. T fertilizer (ha)	61d: Yield (kg)	61d: Amount of land (ha)	61d: Land needed to replace 1 met. T fertilizer (ha)
0	5515	1.530	13.04	5483	1.521	13.01	5184	1.438	11.64
50		1.280	6.99		1.269	6.90		1.188	5.95
75		1.182	4.78		1.171	4.69		1.093	3.94
100		1.106	3.10		1.095	3.01		1.022	2.45
110[a]		1.081	2.56		1.071	2.48		1.000	1.98
125		1.052	1.87		1.042	1.79		.974	1.38
150		1.019	.97		1.011	.90		.949	.60
165[b]		1.008	.55		1.000	.49		.942	.24
175		1.003	.31		.997	.25		.940	.03
190[c]		1.001	.00		.995	-.06		.942	-.24
200		1.002	-.19		.997	-.24		.945	-.39

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

1976 could have yielded considerably more than the actual amount of 570,000 metric tons. Applying fertilizer at levels for maximum yield, the amounts for the three functions would have been: for (58a), 1.250 million metric tons; for (59a), 1.127 million metric tons; and for (60a), 1.232 million metric tons. Fertilizer requirements would have been 55,860, 40,300, and 88,180 metric tons, respectively. These represent a substantial amount when compared with fertilizer consumption of 128,909 metric tons for all crops in 1976 (FAO, 1978c).

Fertilization of the total area of optimal levels would have given crops of 1.245, 1.167, and 1.219 million metric tons, respectively, almost as great as the amounts obtained with maximum yields. The amounts of fertilizer required would have been about ten percent less, however: 50,940, 36,440, and 77,540 metric tons.

Two-thirds of optimal fertilization levels would have given total crops of 1.120, 1.066, and 1.078 million metric tons, while the amounts of nutrient needed would have been 33,920, 24,340, and 51,740 metric tons, respectively.

Total 1976 rice production could have been obtained from a reduced quantity of land by augmenting fertilizer use. Using fertilization for maximum yield, the 570,000 metric tons would have required 63,000 ha and 25,460 metric tons of fertilizer (Eq. 58a), 64,660 ha and 19,590 metric tons (Eq. 59a) or 61,520 ha and 40,780 metric tons of fertilizer (Eq. 60a). Production with optimum fertilization would have necessitated use of more land, but would have reduced fertilizer requirements. The optimum land-fertilizer combinations for the total crop would have been 60,880 ha and 23,320 metric tons of fertilizer (Eq. 58a), 64,940 ha and 17,790 metric tons of fertilizer (Eq. 59a), and 62,210 ha and 36,270 metric tons of fertilizer (Eq. 60a). This amount of land required is half of the actual figure, but the savings come at the cost of substantial fertilizer use.

Brazil

Brazil is the giant of South America. With 116 million inhabitants on 846 million hectares (1977), it is the world's fifth largest country in size and sixth largest in population (FAO, 1978a).

Although Brazil has earned fame as an emerging industrial power, its population is forty percent agricultural. The country is the world's leading producer of coffee, sugar, and beans (*Phaseolus vulgaris*), and is a major producer of many other crops as well. Its agricultural exports in 1977 were valued at $7.25 billion US, while agricultural imports amounted to $967 million US. The crop with the largest share in the export bill was coffee, with a total value of $2.3 billion US. With respect to cereals, imports were valued at $340 million US and exports at $223 million US. Rice and maize account for virtually the total value of grain exports. Wheat is imported in large quantities, as production (2.1 million metric tons in 1977) falls far short of demand (FAO, 1978a,b).

Brazil does not face the problems of land scarcity of many other countries. The FAO has estimated that over eighty percent of the land is suitable for some agricultural activity (Weil et al., 1975). About 38 percent of the country is classified as farmland, but much of this is fallow.

Cereal yields in Brazil are generally below world averages. This fact may be attributed to environmental factors and management practices. Fertilizer use, though low, is still above the average for South America.

Brazil is the second largest producer of maize in the world. The crop is grown throughout the country, but is concentrated in the south. Total production in 1977 was 19.12 million metric tons, of which 1.42 million metric tons were exported. Average yield was only 1637 kg/ha, below the South American average of 1849 kg/ha and little more than half the world average of 2952 kg/ha.

The present study uses data from the work of Perrin (1976) on response of maize to fertilizer in Minas Gerais state during the years 1967-1969. The complete quadratic model is given in equation (62):

$$\begin{aligned} Y = {} & 23.302 - 11.52(NA) + 48.99(PA) - 1.12(KA) + 6.67(PS) \\ & + 73.39(KG) - 8518.18(PH) - .0181(NA)^2 - .0869(PA^2 \\ & + .0042(KA)^2 + .0460(PS)^2 - .1953(KS)^2 + 721.5745(PH)^2 \\ & - .0023(NA)(PA) - .0139(NA)(KA) + .0794(PA)(KA) \\ & + 4.3470(NA)(PH) - .1302(PA)(PS) - .0420(KA)(KS) \\ & - 6.0331(PA)(PH) \qquad R^2 = .65 \quad (62) \end{aligned}$$

The definitions of the variables and their average values are given below:

NA applied N in kg/ha (74.67)
PA applied P in kg/ha (68.67)
KA applied K in kg/ha (33.49)
PS soil P in ppm (13.24)
KS soil K in ppm (85.68)
PH soil PH in PH units (5.28)

Fixing the levels of soil P, soil K, and soil PH at their mean values, one obtains an equation which exhibits a negative yield effect of applied K except at very high doses. Since this type of response would appear to be inappropriate, we fix the level of applied K at zero. The resulting equation is given in (63a):

$$Y = 3393 + 11.43N + 14.92P - .0181N^2 - .0869P^2 - .0023NP \qquad (63a)$$

Using 1972 prices of $132 US per metric ton N, $176 US per metric ton P, and $41 US per metric ton of maize, this equation has input and yield levels for maximum, optimum, and two-thirds of optimum yield as shown in Table 33.

The land-fertilizer equations for the three yield levels take the following form:

$$Y = 3393L + 12.159F - .0155F^2L^{-1} \qquad F = 383 \qquad (63b)$$

$$Y = 3393L + 12.149F - .0155F^2L^{-1} \qquad F = 281 \qquad (63c)$$

$$Y = 3393L + 12.152F - .0155F^2L^{-1} \qquad F = 188 \qquad (63d)$$

These equations give values on the land-fertilizer isoquants as shown in Table 34. Maximum yield of 5778 kg can be produced with one hectare of land and 393 kg of fertilizer. Other combinations of land and fertilizer which produce the same amount of grain include 1.146 ha and 200 kg, 1.378 ha and 100 kg, or 1.708 ha and no fertilizer application. The optimum yield of 5585 kg is obtained from one hectare of land and 281 kg of fertilizer, .988 ha and 300 kg, 1.323 ha and 100 kg, or 1.646 ha and no fertilizer. The yield level corresponding to two-thirds of optimal fertilization, 5131 kg, is produced with one hectare of land and 188 kg of fertilizer, .982 ha and 200 kg, 1.192 ha and 100 kg, or 1.512 ha and no fertilizer.

If all of the land which Brazil used for maize in 1976 had yielded the optimal level of (63b), total production would have been 62.4 million metric tons, i.e., 3.5 times the actual level. This would have required

Table 33. Input, yield, and economic return levels corresponding to four fertilization levels; function (63a) (maize, Brazil)

Maximum yield				Optimum levels				Two-thirds of opt. levels				Zero fert.				
N	P	Y	R[a]	N	P	Y	R	N	P	Y	R	Y	R	(a)[b]	(b)[c]	Function
311	82	5778	$181	223	58	5585	$189	149	39	5131	$184	3393	$139	$50	1.36	(63a)

[a]R = per hectare economic returns above fertilizer costs.

[b](a) = difference between R for optimum fertilization and R for zero fertilization.

[c](b) = ratio of R for optimum fertilization to R for zero fertilization.

Table 34. Coordinates of land-fertilizer isoquants, equations 63b-63d (maize, Brazil)

Quantity of fert. (kg)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
	63b			63c			63d		
0	5778	1.703	10.39	5585	1.646	9.70	5131	1.512	8.19
50		1.531	7.62		1.475	7.03		1.342	5.77
100		1.378	5.30		1.323	4.83		1.192	3.83
150		1.248	3.51		1.195	3.15		1.071	2.39
188[a]		1.167	2.48		1.117	2.20		1.000	1.61
200		1.146	2.21		1.097	1.95		.982	1.40
250		1.073	1.30		1.028	1.12		.925	.74
281[b]		1.042	.89		1.000	.75		.905	.45
300		1.028	.69		.988	.56		.896	.30
350		1.005	.26		.970	.17		.889	-.01
393[c]		1.000	.00		.968	-.08		.894	-.20
400		1.000	-.04		.968	-.10		.896	-.23
450		1.008	-.26		.979	-.31		.913	-.40

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

fertilizer consumption of 3.14 million metric tons, an enormous amount considering that the total use of fertilizers for all crops in Brazil was only 2.37 million metric tons in 1976. At two-thirds of the optimal fertilization levels, 57.4 million metric tons of maize would have been produced, with a requirement of 2.10 million metric tons of fertilizer.

The 1976 maize crop of 17.84 million metric tons could have been produced with 3.19 or 3.48 million ha, using optimal or two-thirds of the optimal levels of fertilization. This represents a substantial saving of land over the 11.18 million ha actually in cultivation. However, the fertilizer requirements would have been substantial: 896,000 and 654,000 metric tons, respectively.

ASIA

The impact of petroleum price increases on the price of fertilizer has been felt perhaps more severely in the developing countries of Asia than in other parts of the world. Two-thirds of the wheat and one-fourth of the rice acreage in the continent are planted in high-yielding varieties, which require large amounts of fertilizer. A large proportion of this fertilizer must be imported. The countries of Asia spent $713 million US on fertilizer imports in 1971. With the petroleum price rise of 1973-1974, nitrogen fertilizer prices skyrocketed. At the same time, prices of phosphate and potash were also high. The result was a total import bill for fertilizers in 1975 of more than $3 billion US. Prices have fallen since then, and a number of countries have moved toward increased self-sufficiency. However, it is an inescapable fact that fertilizer use, and by implication, expense on fertilizers, will have to increase dramatically if the countries of Asia are to feed themselves (Ping, 1979). At the present time, fertilizer consumption per hectare in Asia is only twenty percent of that in the industrialized countries (FAO, 1978c).

India

The mention of India often conjures up an image of desperately poor rural villages and an economy based on subsistence agriculture. This is only one side of the picture, however. In actual fact, the country is one of the world's major industrial powers. With a population of 650 million and a total land area of almost 300 million hectares, India is the world's second largest country in population (after China), and the seventh largest in land area (after the USSR, Canada, China, the USA, Brazil, and Australia) (FAO, 1978a).

With its high population density, India needs to make the fullest use possible of its land. Over half of the total land area is cropped, but in general yields are very low. Subsistence farming on small plots characterizes the activity of most of the two-thirds of the population which is agricultural.

There are signs of change, however. Introduction of high-yielding varieties, irrigation, and other forms of improved technology have boosted India's food production, especially in areas such as the Punjab. The year 1977 was a particularly good year, with total cereal production of 132.58 million metric tons, eight percent higher than in 1976. Total wheat imports were only 547,000 metric tons, less than one-tenth of what they had been during the previous two years (FAO, 1978a,b).

India is the world's fourth largest producer of nitrogenous fertilizers and the sixth largest producer of phosphatic fertilizers. However, in 1978 the country still had to import one-third of its total fertilizer consumption of 4.3 million metric tons. Fertilizer use dropped ten percent after prices nearly doubled in 1974, but six price decreases since then have stimulated increased consumption (Ping, 1979). Even so, fertilizer use of 202 kilograms per hectare of arable land and permanent crops in 1976 was less than two-thirds of the average for Asia as a whole, and only seven percent of the level for the Republic of Korea (FAO, 1978c).

To summarize, India is caught in a difficult situation. It must increase its use of fertilizers if it is to feed its growing population.

However, this will require a rise in fertilizer imports or a massive effort aimed at increasing internal production.

India is fortunate among "developing" countries in that it has research facilities equal in quality to those in the "developed" world. Considerable work has been done on yield response to fertilizer in the country, and data from some of these studies are used in the present paper.

In 1977, India had 39.5 million ha of land sown to rice. Total production was 74 million metric tons, the largest of any country except China. Average yields were 1973 kg/ha, below the world average of 2566 kg/ha, and far below yields of input-intensive Japanese and Korean agriculture, 6166 and 6780 kg/ha, respectively.

During the same year, India's wheat production was 29 million metric tons, grown on a land area of almost 21 million ha, to give an average yield of 1394 kg/ha. While below the world average of 1664 kg/ha, this figure was higher than the average 1335 kg/ha wheat yield for Asia as a whole.

The work of Khan (1965) in estimating marginal rates of substitution between fertilizer and land for wheat and rice has already been mentioned. In the present study we reestimate land-fertilizer relationships from his data, using newer prices. A series of response functions for rice in different states is given below; information on the statistical significance of the equations is available only for the first two.

Madras $$Y = 204 + 2.429N + 7.711P - .015988N^2 - .105476P^2 + .04267NP \qquad R^2 = .95 \quad (64a)$$

Madhya Pradesh $Y = 286 + 2.229N + 10.679P - .024668N^2 - .132037P^2 + .04676NP$ $R^2 = .95$ (65a)

West Bengal $Y = 645 + 3.965N - .027N^2$ (66a)

Bihar $Y = 652 + 7.13N - .060N^2$ (67a)

West Bengal $Y = 570 + 5.025N - .033N^2$ (68a)

Orissa $Y = 647 + 6.623N - .056N^2$

The above equations give maximum yield levels which are considerably below modern-day average yields for India. Technological change has most probably rendered these functions, originally estimated more than thirty years ago, obsolete. Thus any further analysis would give invalid results.

Saxena and Sirohi (1967) present the results of research conducted at the Indian Agricultural Research Institute (IARI) on the yield response of wheat to N. Some estimated response functions are given below in equations (70a) through (82a). The functions (70a) through (76a) are computed from results averaged over thirteen centers nationwide. Beside each of these equations is listed the variety of wheat employed in the fertilizer response trials. The functions (77a) through (82a) are computed from the results of trials using the Sonora 64 variety in different regions of India. These regions are listed after the equations.

$Y = 1451 + 21.88N - .183N^2$	several N.P. varieties	(70a)
$Y = 1664 + 28.22N - .128N^2$	Sonora 63	(71a)
$Y = 1620 + 29.36N - .151N^2$	Sonora 64	(72a)
$Y = 1500 + 33.36N - .164N^2$	Lerma Rojo	(73a)
$Y = 1607 + 30.41N - .201N^2$	C. 306	(74a)
$Y = 1665 + 24.39N - .130N^2$	N.P. 876	(75a)

$Y = 1588 + 20.51N - .124N^2$	N.P. 887	(76a)
$Y = 2098 + 23.85N - .086N^2$	Sonora 64, Northwest Plains	(77a)
$Y = 991 + 18.96N - .089N^2$	Sonora 64, Central Peninsular	(78a)
$Y = 1683 + 20.69N - .071N^2$	Sonora 64, Northeast Plains	(79a)
$Y = 1228 + 6.33N - .018N^2$	Sonora 64, Peninsular	(80a)
$Y = 1695 + 8.15N - .043N^2$	Sonora 64, Central	(81a)
$Y = 1969 + 22.56N - .084N^2$	Sonora 64, average over all regions	(82)

The regression coefficients are quite similar across regions. Only (77a) and (78a) have intercepts outside the range of 1000-2000 kg/ha. Equations (80a) and (81a) have considerably less linear response to N than the other functions, but also smaller negative quadratic terms to depress yield.

The N levels for maximum, optimum, and two-thirds of optimum yield are shown in Table 35. Prices used are $525 US per metric ton N and $173 US per metric ton of wheat.

Except for (80a) and (81a), returns to optimal fertilizer use are substantial. In the majority of cases there is not a large difference between optimal levels and the levels for maximum yield. Fertilizer quantities for maximum yield vary between 60 and 176 kg/ha, and the optimum levels range from 51 to 124 kg/ha. Excluding (80a), the range of maximum yield is from 2001 to 3752 kg/ha, of yields from optimum fertilization, from 1973 to 3728 kg/ha, and of yields for two-thirds of optimum fertilizer application, from 1800 to 3466 kg/ha.

Since the original functions contain only one nutrient, the land-fertilizer equations have the same coefficients at different input levels:

Table 35. Input, yield, and economic return levels corresponding to four fertilization levels; functions (70a)-(82a) (wheat, India)

Maximum yield			Optimum levels			Two-thirds of opt. levels			Zero fert.				
N	Y	R[a]	N	Y	R	N	Y	R	Y	R	(a)[b]	(b)[c]	Function
60	2105	$333	51	2091	$335	34	1983	$325	1451	$251	$84	1.33	(70a)
110	3219	$499	98	3200	$502	65	2958	$478	1664	$288	$214	1.74	(71a)
97	3047	$476	87	3031	$479	58	2815	$457	1620	$280	$199	1.71	(72a)
102	3196	$499	92	3181	$502	61	2925	$474	1500	$260	$242	1.93	(73a)
76	2757	$437	68	2745	$439	45	2568	$421	1607	$278	$161	1.58	(74a)
94	2809	$437	82	2791	$440	55	2613	$423	1665	$288	$152	1.53	(75a)
83	2436	$378	70	2416	$381	47	2278	$369	1588	$275	$106	1.39	(76a)
139	3752	$576	122	3728	$581	81	3466	$558	2098	$363	$218	1.60	(77a)
107	2001	$290	89	1973	$295	59	1800	$280	991	$171	$124	1.73	(78a)
146	3190	$475	124	3157	$481	83	2911	$460	1683	$291	$190	1.65	(79a)
176	1785	$216	92	1658	$239	61	1547	$236	1228	$212	$27	1.13	(80a)
95	2081	$310	59	2026	$320	39	1947	$316	1695	$293	$27	1.09	(81a)
134	3484	$532	116	3456	$537	77	3208	$515	1969	$341	$196	1.57	(82a)

[a] R = per hectare economic returns above fertilizer costs.

[b] (a) = difference between R for optimum fertilization and R for zero fertilization.

[c] (b) = ratio of R for optimum fertilization to R for zero fertilization.

For equation (70a):

$$Y = 1451L + 21.88F - .183F^2L^{-1} \qquad F = 60 \tag{70b}$$
$$Y = 1451L + 21.88F - .183F^2L^{-1} \qquad F = 51 \tag{70c}$$
$$Y = 1451L + 21.88F - .183F^2L^{-1} \qquad F = 34 \tag{70d}$$

For equation (71a):

$$Y = 1664L + 28.22F - .128F^2L^{-1} \qquad F = 110 \tag{71b}$$
$$Y = 1664L + 28.22F - .128F^2L^{-1} \qquad F = 98 \tag{71c}$$
$$Y = 1664L + 28.22F - .128F^2L^{-1} \qquad F = 65 \tag{71d}$$

For equation (72a):

$$Y = 1620L + 29.36F - .151F^2L^{-1} \qquad F = 97 \tag{72b}$$
$$Y = 1620L + 29.36F - .151F^2L^{-1} \qquad F = 87 \tag{72c}$$
$$Y = 1620L + 29.36F - .151F^2L^{-1} \qquad F = 58 \tag{72d}$$

For equation (73a):

$$Y = 1500L + 33.36F - .164F^2L^{-1} \qquad F = 102 \tag{73b}$$
$$Y = 1500L + 33.36F - .164F^2L^{-1} \qquad F = 92 \tag{73c}$$
$$Y = 1500L + 33.36F - .164F^2L^{-1} \qquad F = 61 \tag{73d}$$

For equation (74a):

$$Y = 1607L + 30.41F - .201F^2L^{-1} \qquad F = 76 \tag{74b}$$
$$Y = 1607L + 30.41F - .201F^2L^{-1} \qquad F = 68 \tag{74c}$$
$$Y = 1607L + 30.41F - .201F^2L^{-1} \qquad F = 45 \tag{74d}$$

For equation (75a):

$$Y = 1665L + 24.39F - .130F^2L^{-1} \qquad F = 94 \tag{75b}$$
$$Y = 1665L + 24.39F - .130F^2L^{-1} \qquad F = 82 \tag{75c}$$
$$Y = 1665L + 24.39F - .130F^2L^{-1} \qquad F = 55 \tag{75d}$$

For equation (76a):

$$Y = 1588L + 20.51F - .124F^2L^{-1} \qquad F = 83 \tag{76b}$$
$$Y = 1588L + 20.51F - .124F^2L^{-1} \qquad F = 70 \tag{76c}$$
$$Y = 1588L + 20.51F - .124F^2L^{-1} \qquad F = 47 \tag{76d}$$

For equation (77a):

$$Y = 2098L + 23.85F - .086F^2L^{-1} \qquad F = 139 \qquad (77b)$$
$$Y = 2098L + 23.85F - .086F^2L^{-1} \qquad F = 121 \qquad (77c)$$
$$Y = 2098L + 23.85F - .086F^2L^{-1} \qquad F = 89 \qquad (77d)$$

For equation (78a):

$$Y = 991L + 18.96F - .089F^2L^{-1} \qquad F = 107 \qquad (78b)$$
$$Y = 991L + 18.96F - .089F^2L^{-1} \qquad F = 89 \qquad (78c)$$
$$Y = 991L + 18.96F - .089F^2L^{-1} \qquad F = 59 \qquad (78d)$$

For equation (79a):

$$Y = 1683L + 20.69F - .071F^2L^{-1} \qquad F = 146 \qquad (79b)$$
$$Y = 1683L + 20.69F - .071F^2L^{-1} \qquad F = 124 \qquad (79c)$$
$$Y = 1683L + 20.69F - .071F^2L^{-1} \qquad F = 83 \qquad (79d)$$

For equation (80a):

$$Y = 1228L + 6.33F - .018F^2L^{-1} \qquad F = 176 \qquad (80b)$$
$$Y = 1228L + 6.33F - .018F^2L^{-1} \qquad F = 92 \qquad (80c)$$
$$Y = 1228L + 6.33F - .018F^2L^{-1} \qquad F = 61 \qquad (80d)$$

For equation (81a):

$$Y = 1695L + 8.15F - .043N^2 \qquad F = 95 \qquad (81b)$$
$$Y = 1695L = 8.15F - .043N^2 \qquad F = 59 \qquad (81c)$$
$$Y = 1695L + 8.15F - .043N^2 \qquad F = 39 \qquad (81d)$$

For equation (82a):

$$Y = 1969L + 22.56F - .084F^2L^{-1} \qquad F = 134 \qquad (82b)$$
$$Y = 1969L + 22.56F - .084F^2L^{-1} \qquad F = 116 \qquad (82c)$$
$$Y = 1969L + 22.56F - .084F^2L^{-1} \qquad F = 77 \qquad (82d)$$

Points on the land-fertilizer isoquants are given in Tables 36-48. Referring to them, we see that to produce quantities of grain equivalent to maximum per hectare yield without fertilizer requires between 1.228 and 2.131 ha of land, depending on the site. At an application level of 50 kg

Table 36. Coordinates of land-fertilizer isoquants, equations 70b-70d (wheat, India)

Quantity of fert. (kg)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
	70b			70c			70d		
0	2105	1.451	31.74	2091	1.441	31.32	1983	1.367	28.16
34[a]		1.074	7.14		1.065	6.96		1.000	5.67
50		1.009	2.00		1.002	1.90		.946	1.19
51[b]		1.007	1.76		1.000	1.67		.945	.98
60[c]		1.000	-.04		.993	-.11		.943	-.59
100		1.095	-4.22		1.090	-4.24		1.055	-4.35

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 37. Coordinates of land-fertilizer isoquants, equations 71b-71d (wheat, India)

Quantity of fert. (kg)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
	71b			71c			71d		
0	3219	1.934	63.47	3200	1.923	62.72	2958	1.778	53.59
50		1.241	14.25		1.231	13.62		1.104	10.21
65[a]		1.122	7.64		1.113	7.45		1.000	5.26
98[b]		1.006	1.15		1.000	1.08		.919	.27
100		1.004	.94		.998	.87		.919	.10
110[c]		1.000	.02		.994	-.03		.922	-.62
150		1.046	-2.05		1.041	-2.07		.987	-2.29

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 38. Coordinates of land-fertilizer isoquants, equations 72b-72d (wheat, India)

Quantity of fert. (kg)	72b: Yield (kg)	72b: Amount of land (ha)	72b: Land needed to replace 1 met. T fertilizer (ha)	72c: Yield (kg)	72c: Amount of land (ha)	72c: Land needed to replace 1 met. T fertilizer (ha)	72d: Yield (kg)	72d: Amount of land (ha)	72d: Land needed to replace 1 met. T fertilizer (ha)
0	3047	1.881	64.11	3031	1.871	63.44	2815	1.738	54.72
50		1.173	11.36		1.165	11.44		1.053	8.33
58[a]		1.112	7.90		1.104	7.73		1.000	5.57
87[b]		1.006	1.18		1.000	1.12		.924	.29
97[c]		1.000	.02		.995	-.03		.926	-.64
100		1.000	-.27		.995	-.31		.929	-.87
150		1.089	-2.89		1.085	-2.91		1.039	-3.07

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 39. Coordinates of land-fertilizer isoquants, equations 73b-73d (wheat, India)

Quantity of fert. (kg)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
	73b			73c			73d		
0	3196	2.131	100.96	3181	2.121	100.02	2925	1.950	84.57
50		1.239	16.18		1.231	15.89		1.089	11.36
61[a]		1.133	9.55		1.125	9.35		1.000	6.33
92[b]		1.005	1.17		1.000	1.10		.915	.11
100		1.000	.18		.995	.13		.918	-.64
102[c]		1.000	-.03		.995	-.08		.919	-.80
150		1.078	-2.75		1.074	-2.77		1.022	-2.98

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 40. Coordinates of land-fertilizer isoquants, equations 74b-74d (wheat, India)

Quantity of fert. (kg)	74b Yield (kg)	74b Amount of land (ha)	74b Land needed to replace 1 met. T fertilizer (ha)	74c Yield (kg)	74c Amount of land (ha)	74c Land needed to replace 1 met. T fertilizer (ha)	74d Yield (kg)	74d Amount of land (ha)	74d Land needed to replace 1 met. T fertilizer (ha)
0	2757	1.716	55.70	2745	1.708	55.21	2568	1.598	48.32
20		1.374	27.46		1.366	27.13		1.259	22.58
40		1.135	10.85		1.129	10.67		1.035	8.25
45[a]		1.095	8.28		1.089	8.13		1.000	6.11
50		1.063	6.17		1.058	6.05		.973	4.38
60		1.021	3.04		1.016	2.95		.941	1.82
68[b]		1.005	1.27		1.000	1.21		.932	.37
76[c]		1.000	-.05		.996	-.10		.934	-.73
80		1.001	-.59		.997	-.63		.938	-1.18
100		1.033	-2.51		1.030	-2.53		.981	-2.81

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 41. Coordinates of land-fertilizer isoquants, equations 75b-75d (wheat, India)

Quantity of fert. (kg)	75b: Yield (kg)	75b: Amount of land (ha)	75b: Land needed to replace 1 met. T fertilizer (ha)	75c: Yield (kg)	75c: Amount of land (ha)	75c: Land needed to replace 1 met. T fertilizer (ha)	75d: Yield (kg)	75d: Amount of land (ha)	75d: Land needed to replace 1 met. T fertilizer (ha)
0	2809	1.687	41.69	2791	1.676	41.16	2613	1.569	36.08
25		1.357	20.66		1.346	20.30		1.242	16.94
50		1.128	8.22		1.118	8.02		1.027	6.22
55[a]		1.097	6.63		1.088	6.46		1.000	4.90
75		1.019	2.28		1.012	2.19		.939	1.33
82[b]		1.007	1.29		1.000	1.21		.932	.51
94[c]		1.000	-.02		.994	-.07		.932	-.56
100		1.002	-.53		.996	-.58		.937	-.99
125		1.035	-2.03		1.030	-2.06		.981	-2.27
150		1.095	-2.93		1.090	-2.95		1.048	-3.07

[a] Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b] Amount of fertilizer corresponding to the economic optimum level of application.

[c] Amount of fertilizer required to achieve maximum yield.

Table 42. Coordinates of land-fertilizer isoquants, equations 76b-76d (wheat, India)

Quantity of fert. (kg)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
	76b			76c			76d		
0	2436	1.534	30.39	2416	1.521	29.89	2278	1.435	26.58
25		1.250	14.59		1.238	14.26		1.154	12.10
47[a]		1.086	6.19		1.075	6.00		1.000	4.76
50		1.071	5.39		1.060	5.21		.985	4.10
70[b]		1.009	1.53		1.000	1.43		.938	.80
75		1.003	.87		.994	.78		.935	.24
83[c]		1.000	-.03		.992	-.10		.937	-.53
100		1.013	-1.44		1.006	-1.48		.958	-1.74
120		1.052	-2.55		1.046	-2.57		1.004	-2.73

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 43. Coordinates of land-fertilizer isoquants, equations 77b-77d (wheat, India)

Quantity of fert. (kg)	77b			77c			77d		
	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
0	3752	1.788	36.36	3725	1.776	35.84	3466	1.652	31.03
25		1.521	22.60		1.508	22.20		1.386	18.53
50		1.299	12.57		1.287	12.29		1.171	9.79
75		1.138	6.28		1.127	6.11		1.025	4.58
81[a]		1.110	5.27		1.101	5.09		1.000	3.73
100		1.044	2.72		1.035	2.62		.948	1.73
122[b]		1.008	.97		1.000	.91		.925	.35
125		1.005	.72		.997	.66		.924	.15
139[c]		1.000	-.01		.994	-.05		.927	-.45
150		1.003	-.47		.996	-.50		.934	-.81

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 44. Coordinates of land-fertilizer isoquants, equations 78b-78d (wheat, India)

Quantity of fert. (kg)	78b Yield (kg)	78b Amount of land (ha)	78b Land needed to replace 1 met. T fertilizer (ha)	78c Yield (kg)	78c Amount of land (ha)	78c Land needed to replace 1 met. T fertilizer (ha)	78d Yield (kg)	78d Amount of land (ha)	78d Land needed to replace 1 met. T fertilizer (ha)
0	2001	2.019	78.00	1973	1.991	75.83	1800	1.816	63.12
25		1.576	38.32		1.549	36.87		1.379	28.57
50		1.243	15.03		1.219	14.26		1.070	10.03
59[a]		1.160	10.25		1.137	9.66		1.000	6.50
75		1.061	4.80		1.041	4.46		.927	2.62
89[b]		1.016	2.05		1.000	1.83		.902	.67
100		1.002	.64		.987	.48		.900	-.35
107[c]		1.000	-.04		.986	-.17		.905	-.85
125		1.013	-1.29		1.001	-1.37		.931	-1.80
150		1.058	-2.34		1.048	-2.39		.989	-2.62

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 45. Coordinates of land-fertilizer isoquants, equations 79b-79d (wheat, India)

Quantity of fert. (kg)	79b Yield (kg)	79b Amount of land (ha)	79b Land needed to replace 1 met. T fertilizer (ha)	79c Yield (kg)	79c Amount of land (ha)	79c Land needed to replace 1 met. T fertilizer (ha)	79d Yield (kg)	79d Amount of land (ha)	79d Land needed to replace 1 met. T fertilizer (ha)
0	3190	1.895	44.17	3157	1.876	43.26	2911	1.730	36.78
25		1.605	27.54		1.585	26.84		1.441	21.90
50		1.358	15.34		1.340	14.85		1.203	11.49
75		1.175	7.71		1.159	7.41		1.037	5.37
83[a]		1.132	6.06		1.116	5.81		1.000	4.10
100		1.063	3.46		1.049	3.29		.946	2.13
124[b]		1.012	1.21		1.000	1.11		.915	.43
125		1.011	1.14		.999	1.04		.914	.38
146[c]		1.000	-.01		.990	-.08		.916	-.51
150		1.000	-.18		.990	-.24		.919	-.64
175		1.016	-1.01		1.007	-1.05		.945	-1.30
200		1.048	-1.56		1.040	-1.58		.985	-1.75

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 46. Coordinates of land-fertilizer isoquants, equations 80b-80d (wheat, India)

Quantity of fert. (kg)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
	80b			80c			80d		
0	1785	1.454	10.89	1658	1.350	9.40	1547	1.260	8.18
25		1.332	8.09		1.229	6.82		1.139	5.80
50		1.226	5.74		1.125	4.70		1.037	3.88
61[a]		1.185	4.86		1.086	3.92		1.000	3.19
75		1.139	3.87		1.043	3.06		.959	2.43
92[b]		1.093	2.85		1.000	2.19		.920	1.68
100		1.075	2.44		.984	1.83		.906	1.37
125		1.031	1.39		.948	.94		.877	.61
150		1.008	.60		.931	.28		.867	.05
176[c]		1.000	.00		.931	-.23		.873	-.40
200		1.006	-.43		.942	-.60		.889	-.72

[a] Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b] Amount of fertilizer corresponding to the economic optimum level of application.

[c] Amount of fertilizer required to achieve maximum yield.

Table 47. Coordinates of land-fertilizer isoquants, equations 81b-81d (wheat, India)

Quantity of fert. (kg)	81b: Yield (kg)	81b: Amount of land (ha)	81b: Land needed to replace 1 met. T fertilizer (ha)	81c: Yield (kg)	81c: Amount of land (ha)	81c: Land needed to replace 1 met. T fertilizer (ha)	81d: Yield (kg)	81d: Amount of land (ha)	81d: Land needed to replace 1 met. T fertilizer (ha)
0	2081	1.228	7.25	2026	1.195	6.87	1947	1.149	6.34
25		1122	4.55		1.090	4.26		1.044	3.85
39[a]		1.076	3.31		1.045	3.06		1.000	2.72
50		1.048	2.46		1.017	2.25		.973	1.96
59[b]		1.030	1.85		1.000	1.67		.957	1.85
75		1.009	.92		.980	.78		.940	.59
95[c]		1.000	-.01		.974	-.11		.936	-.24
100		1.000	-.21		.975	-.30		.938	-.42
125		1.016	-1.06		.993	-1.11		.960	-1.19
150		1.050	-1.71		1.029	-1.74		.999	-1.78
175		1.095	-2.23		1.076	-2.24		1.048	-2.26
200		1.149	-2.64		1.131	-2.64		1.105	-2.65

[a] Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b] Amount of fertilizer corresponding to the economic optimum level of application.

[c] Amount of fertilizer required to achieve maximum yield.

Table 48. Coordinates of land-fertilizer isoquants, equations 82b-82d (wheat, India)

Quantity of fert. (kg)	82b			82c			82d		
	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
0	3484	1.769	35.87	3456	1.755	35.30	3208	1.629	30.41
25		1.501	22.02		1.487	21.58		1.362	17.88
50		1.280	12.03		1.267	11.72		1.149	9.24
75		1.124	5.87		1.112	5.68		1.008	4.19
77[a]		1.114	5.51		1.102	5.33		1.000	3.90
100		1.036	2.42		1.025	2.31		.938	1.46
116[b]		1.009	1.07		1.000	.99		.922	.39
125		1.002	.49		.994	.43		.921	-.06
134[c]		1.000	.01		.992	-.04		.923	-.45
150		1.005	-.66		.998	-.69		.936	-.99

[a] Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b] Amount of fertilizer corresponding to the economic optimum level of application.

[c] Amount of fertilizer required to achieve maximum yield.

the range is from 1.048 to 1.280 ha. Amounts of wheat equal to optimum per hectare yields are obtainable with no fertilizer and between 1.196 and 2.121 ha, and with 50 kg of fertilizer and from 1.017 to 1.950 ha. Finally, the range of land required to obtain yields corresponding to two-thirds of optimal fertilizer use is from 1.149 to 1.950 ha with zero fertilizer application and from .973 to 1.203 ha with fertilizer application of 50 kg.

The 1976 Indian wheat crop amounted to 28.85 million metric tons. This was grown on an area of 20.45 million ha, to give a yield of 1410 kg/ha. If all of the land sown had responded in the same way as expressed in the functions, total production would have been between 36.50 and 76.73 million metric tons, depending on the site. Fertilizer requirements would have been substantial, from 1.227 to 3.599 million metric tons. Optimal fertilization of the area would have provided between 33.91 and 72.24 million metric tons of wheat, with a requirement of between 1.043 and 2.536 million metric tons of nutrients. Fertilization at two-thirds of the optimal levels would have provided from 31.64 to 70.88 million metric tons of grain and would have used between 695,000 and 1.697 million metric tons of fertilizer.

The 1976 Indian wheat crop could have been produced on a reduced quantity of land by utilizing improved management and augmented fertilizer use. The equations (70a) through (82a) indicate that at nutrient application levels for maximum yield, between 7.69 and 16.16 million ha of land and 1.069 and 2.845 million metric tons of fertilizer would have been needed. The ranges using optimal and two-thirds of optimal fertilization levels would have been 7.74-17.40 and 8.32-18.65 million ha, while the amounts of fertilizer needed would have been between 944,000 and 1.601 million metric tons and between 674,000 and 1.138 million metric tons, respectively.

Bose (1970) describes the results of studies on the response of high-yielding varieties of rice in West Bengal. At that time, yields in upland areas were only about 672 kg/ha, compared with 1120 kg/ha for the country as a whole. The low rice yields in West Bengal have been due to low soil fertility, which is in turn caused by several factors. Excessive rainfall during June through September leaches out nutrients, and the extremely warm temperatures which prevail during most of the year promote oxidation.

An N response function is estimated for the improved local variety of rice, Dular. It takes the following form:

$$Y = 1265 + 52.52N - .5075N^2 \qquad (83a)$$

Input levels for maximum, optimum, and two-thirds of optimum yield are shown in Table 49. The prices are \$525 US per metric ton N and \$183 US per metric ton rice.

The land-fertilizer equations for the three input levels are:

$$Y = 1265L + 52.52F - .5075F^2L^{-1} \qquad F = 52 \qquad (83b)$$
$$Y = 1265L + 52.52F - .5075F^2L^{-1} \qquad F = 49 \qquad (83c)$$
$$Y = 1265L + 52.52F - .5075F^2L^{-1} \qquad F = 33 \qquad (83d)$$

The functions give coordinates of land-fertilizer isoquants as shown in Table 50. It may be seen that fertilizer substitutes for land at a fairly high rate at low levels of application. To obtain grain equivalent

Table 49. Input, yield, and economic return levels corresponding to four fertilization levels; equation 83a (rice, India)

Maximum yield			Optimum levels			Two-thirds of opt. levels			Zero fert.				
N	Y	R[a]	N	Y	R	N	Y	R	Y	R	(a)[b]	(b)[c]	Function
52	2624	$452	49	2620	$453	33	2445	$430	1265	$231	$222	1.96	(83a)

[a] R = per hectare economic returns above fertilizer costs.

[b] (a) = difference between R for optimum fertilization and R for zero fertilization.

[c] (b) = ratio of R for optimum fertilization to R for zero fertilization.

Table 50. Coordinates of land-fertilizer isoquants, equations 83b-83d (rice, India)

Quantity of fert. (kg)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
	83b			83c			83d		
0	2624	2.074	178.64	2620	2.071	178.10	2445	1.933	155.10
33[a]		1.101	14.74		1.099	14.63		1.000	10.46
49[b]		1.002	1.16		1.000	1.12		.932	-.30
50		1.002	.01		1.001	1.08		.932	-.65
52[c]		1.000	-.10		.999	-.13		.935	-1.31
100		1.218	-7.21		1.217	-7.22		1.180	-7.36

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

to maximum per hectare yield without fertilizer application requires 2.074 ha; and at this point on the isoquant one metric ton of fertilizer replaces 178.64 ha.

Regarding equation (83a) as a measure of yield potential, India's total 1976 rice production could have reached 101.31 million metric tons at fertilizer application rates for maximum yield, 101.16 million metric tons at optimum rates, and 94.4 million metric tons at two-thirds of the optimum rates. The amount of fertilizer needed would have been 2.01, 1.89, and 1.27 million metric tons, respectively. These figures compare with a total fertilizer consumption in India of 3.41 million metric tons in 1976.

The 1976 crop of 64.36 million metric tons could have been produced with 24.53, 24.56, or 26.32 million ha through application of the three respective fertilization levels. The amounts of fertilizer used would have been 1.276 million, 1.203 million, and 869,000 metric tons, respectively.

Pakistan

Pakistan is India's western neighbor, the former territory of East Pakistan having become the independent nation of Bangladesh in 1971. Pakistan had a population of slightly over 75 million in 1977, an increase of more than three percent over the previous year. Total land area is almost 78 million nectares, but only about one-fourth of this is cropped (FAO, 1978a). Much of the country is arid and mountainous.

Wheat is the most important cereal crop in Pakistan, followed by rice. Wheat yields in 1976 were 1430 kg/ha; slightly higher than the average for India of 1381 kg/ha, but far below the US average of 2050 kg/ha. Rice yields were 2400 kg/ha, above those India (1873 kg/ha) and the Philippines (1959 kg/ha), but far below yields for the input-intensive agricultures of Japan (5952 kg/ha) and Korea (6023 kg/ha).

Wheat production is not sufficient to meet demand, but Pakistan is normally a rice exporter. Pakistan in 1977 produced 9.2 million metric tons of wheat, a record harvest. Imports were only 315,000 metric tons, one-third the level they had been during the previous two years. Rice production reached 7.15 million metric tons, also a record level, and allowing the country to raise its exports to 945,000 metric tons.

The index of total food production in Pakistan rose from 101 in 1970 to 127 in 1977 (1969-71 = 100). However, food production per capita stagnated at an index level of 102 (FAO, 1977a). It is clear that the present demographic explosion cannot continue without serious consequences. To meet a rising demand for food, new lands will have to be cultivated and yields on those presently utilized will have to be increased, primarily through augmented fertilizer use and increased use of irrigation.

The data for the present study come from various sources. Prices from the year 1975 are used. Expressed in US dollars, they are \$335 per metric ton N, \$237 per metric ton P, \$101 per metric ton wheat, and \$189 per metric ton rice.

Ahmad and Shakoor (1976) have studied fertilizer response of several semi-dwarf, high-yielding varieties of wheat in Pakistan. For the Mutant 17 variety they estimate the following function:

$$Y = 2627 + 24.68N^{***} + 8.03P^{*} - .118N^{2***} - .071P^{2*} + .050NP^{**} \qquad R^2 = .94 \qquad (84a)$$

and for the Mutant 432 variety:

$$Y = 3531 + 20.39N^{***} + 10.69P^{**} - .136N^{2***} - .043P^{2} + .035NP^{*} \qquad R^2 = .90 \qquad (85a)$$

where * = significant at .10 level; ** = significant at .05 level; and *** = significant at .01 level.

Quadratic and Cobb-Douglas functions are fit for the Chenab 70 variety as well, but are not used in the present study because they give negative yield effects of nitrogen except at very high input levels. The input, yield, and economic return levels for maximum, optimum, and two-thirds of optimum yield for functions (84a) and (85a) are shown in Table 51.

It should be noted that these functions give yields with zero fertilizer application which are higher than the average 1976 wheat yields for Pakistan of 1422 kg/ha. This is an indication of potential yield increases through improved management.

The land-fertilizer equations for the three fertilization levels are given below:

For equation (84a):

$$Y = 2627L + 17.271F - .038058F^2L^{-1} \qquad F = 227 \qquad (84b)$$

$$Y = 2627L + 17.654F - .039870F^2L^{-1} \qquad F = 185 \qquad (84c)$$

Table 51. Input, yield, and economic return levels corresponding to four fertilization levels; functions (84a)-(85a) (wheat, Pakistan)

Maximum yield				Optimum levels				Two-thirds of opt. levels				Zero fert.				
N	P	Y	R[a]	N	P	Y	R	N	P	Y	R	Y	R	(a)[b]	(b)[c]	Function
126	101	4586	$397	107	78	4528	$403	71	52	4195	$388	2627	$265	$138	1.52	(84a)
96	164	5383	$473	79	129	5313	$480	53	86	4990	$466	3531	$357	$123	1.34	(85a)

[a] R = per hectare economic returns above fertilizer costs.

[b] (a) = difference between R for optimum fertilization and R for zero fertilization.

[c] (b) = ratio of R for optimum fertilization to R for zero fertilization.

$$Y = 2627L + 17.637F - .039786F^2L^{-1} \qquad F = 123 \qquad (84d)$$

and for equation (85a):

$$Y = 3531L + 14.269F - .027489F^2L^{-1} \qquad F = 260 \qquad (85b)$$

$$Y = 3531L + 14.376F - .027922F^2L^{-1} \qquad F = 208 \qquad (85c)$$

$$Y = 3531L + 14.386F - .027963F^2L^{-1} \qquad F = 139 \qquad (85d)$$

Coordinates of the land-fertilizer isoquants are listed in Tables 52-53. The magnitude of fertilizer substitution for land is similar for both equations. The isoquants for (84b) through (84d) are somewhat more steep than those for (85b) through (85d), meaning that fertilizer response is greater with the former function. This is understandable, since the intercept of (84a) is of smaller magnitude than that of (85a), indicating lesser soil fertility. At zero application rates one metric ton of fertilizer replaces 20.04 hectares on the maximum yield isoquant of equation (84d), but only 9.39 hectares on the isoquant of (85b).

If there is a potential for yield increases through improved management, even more potential exists with increased use of fertilizers. Taking functions (84a) and (85a) as the lower and upper bounds of yield potential, Pakistan's 6.11 million hectares dedicated to wheat in 1976 could have produced between 28.02 and 32.89 million metric tons at fertilization levels for maximum yield, from 27.67 to 32.46 million metric tons at optimum input levels, and between 25.63 and 30.49 million metric tons at two-thirds of optimum levels. The amount of fertilizer required for these production levels would have had the ranges 1.39-1.59 million metric tons, 1.130-1.27 million metric tons, and .75-.85 million metric tons, respectively. This would have meant a huge increase in the

Table 52. Coordinates of land-fertilizer isoquants, equations 84b-84d (wheat, Pakistan)

Quantity of fert. (kg)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
	84b			84c			84d		
0	4586	1.746	20.04	4528	1.724	19.97	4195	1.597	17.12
50		1.442	11.18		1.414	10.89		1.291	8.89
100		1.208	5.32		1.180	5.02		1.067	3.84
123[a]		1.131	3.59		1.105	3.32		1.000	2.43
150		1.065	2.14		1.043	1.91		.949	1.29
185[b]		1.017	.90		1.000	.73		.919	.34
200		1.007	.52		.992	.37		.916	.05
227[c]		1.000	.00		.989	-.14		.921	-.35
250		1.004	-.34		.996	-.46		.933	-.63
300		1.034	-.85		1.032	-.95		.977	-1.04

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 53. Coordinates of land-fertilizer isoquants, equations 85b-85d (wheat, Pakistan)

Quantity of fert. (kg)	85b Yield (kg)	85b Amount of land (ha)	85b Land needed to replace 1 met. T fertilizer (ha)	85c Yield (kg)	85c Amount of land (ha)	85c Land needed to replace 1 met. T fertilizer (ha)	85d Yield (kg)	85d Amount of land (ha)	85d Land needed to replace 1 met. T fertilizer (ha)
0	5383	1.524	9.39	5313	1.505	9.22	4990	1.413	8.14
50		1.337	6.06		1.316	5.90		1.226	5.05
100		1.186	3.56		1.165	3.42		1.079	2.81
139[a]		1.100	2.18		1.080	2.06		1.000	1.62
150		1.080	1.87		1.062	1.76		.983	1.36
200		1.021	.79		1.005	.71		.937	.46
208[b]		1.016	.66		1.000	.58		.933	.35
250		1.001	.10		.987	.04		.928	-.11
260[c]		1.000	.00		.987	-.06		.930	-.20
300		1.008	-.36		.997	-.40		.945	-.50

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

country's fertilizer consumption, as actual total use for all crops in 1976 was only 627,000 metric tons.

The 1976 wheat crop of 8.69 million metric tons could have been obtained with from 1.61 million ha (Eq. 85b) to 1.89 million ha (Eq. 84b) through fertilization for maximum yield. Optimum and two-thirds of optimum input levels would have allowed production with between 1.64 and 1.92 million ha and 1.74 and 2.07 million ha, respectively. The amounts of total fertilizer application for the three yield levels would have been 429,000 and 419,000 metric tons, 341,000 and 355,000 metric tons, and 242,000 and 255,000 metric tons, respectively. The functions are such that to produce the total quantity with optimum or two-thirds of optimum input levels requires both more land and more total fertilizer on the site used to estimate function (84a) than on the site for (85a). At maximum yield levels, however, (84a) requires more land but less fertilizer than (85a) to produce the entire crop.

Khan and Ali (1976) estimate yield response of rice in irrigated areas of the Punjab region. A quadratic form is rejected because of "wrong" signs, and instead a Cobb-Douglas is used. With input and yield values converted into kg/ha, it takes the following form:

$$Y = 1837N^{.079733}P^{.035269} \qquad (86a)$$

As there is no maximum yield level defined for a Cobb-Douglas function, only optimum and two-thirds of optimum yield levels are listed in Table 54. As in the case of wheat, 1975 prices are used. They are \$335 US per metric ton N, \$237 US per metric ton P, and \$189 US per metric ton of rice paddy.

Table 54. Input, yield, and economic return levels corresponding to two fertilization levels; function (86a (rice, Pakistan)

Optimal levels				Two-thirds of optimal levels				
N	P	Y	R[a]	N	P	Y	R	Function
144	90	3200	$535	96	60	3054	$531	(86a)

[a]R = per hectare economic returns above fertilizer costs.

The Cobb-Douglas form tends to underestimate yields at low input levels and overestimate them at high levels. Fixing nutrient levels at zero gives a yield of zero, while yield continues to increase even as unreasonably high levels of fertilizer are applied.

The general form of the land-fertilizer equation for a Cobb-Douglas function is given in (32a). The exact forms for the input levels used in (86a) above are as follows:

$$Y = 1709F^{.115002}L^{.884998} \qquad F = 234 \qquad (86b)$$

$$Y = 1709F^{.115002}L^{.884998} \qquad F = 156 \qquad (86c)$$

Some points on the land-fertilizer isoquants are listed in Table 55. An input level of zero causes division by zero in the isoquant equation, and so a level of one is used instead.

Optimum yield is produced on one ha of land with 234 kg of fertilizer. Alternate combinations include 2.031 ha with one kg of fertilizer, 1.117 ha with 100 kg, and 1.020 ha with 200 kg. Fertilizer substitutes for land at these points at the rate of one metric ton replacing 263.98, 1.45, and .66 ha, respectively. Land requirements to produce the yield of 2812 kg corresponding to two-thirds of optimal fertilization are only slightly less than for optimum yield of 2949 kg.

Table 55. Coordinates of land-fertilizer isoquants, equations 86b-86c (rice, Pakistan)

Quantity of fert. (kg)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
		86b		86c		
1	3200	2.031	263.98	3054	1.927	250.41
20		1.376	8.94		1.306	8.48
40		1.258	4.09		1.193	3.88
50		1.222	3.18		1.159	3.01
60		1.193	2.58		1.132	2.45
80		1.149	1.87		1.090	1.77
100		1.117	1.45		1.059	1.38
120		1.090	1.18		1.034	1.12
140		1.069	.99		1.014	.94
150		1.059	.92		1.005	.87
156[a]		1.054	.88		1.000	.83
160		1.050	.85		.996	.81
180		1.035	.75		.981	.71
200		1.020	.66		.968	.63
220		1.008	.59		.956	.56
234[b]		1.000	.56		.948	.53
240		.997	.54		.945	.51
250		.991	.51		.940	.49

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

Philippines

The Philippine Islands are located in the Pacific Ocean to the southeast of China. They have a total land area of almost 30 million hectares, 27 percent of which is in cultivation. The population was 75 million in 1977, and growing at a rate of 3.3 percent per annum. Forty-eight percent of the population is agricultural (FAO, 1978a).

Rice production in the Philippines reached 7.15 million metric tons in 1977. This figure represented seventy percent of total cereal production. However, production fell slightly short of demand, and the country imported 31,000 metric tons of rice that year (FAO, 1978a,b).

The main constraint on increased rice production in the Philippines is yield levels, which remain low in spite of the large amount of research conducted at the International Rice Research Institute in Los Banos, and in spite of widespread adoption of high-yielding varieties. Average yields in 1977 were 2400 kg/ha, considerably less than half the levels for Japan and Korea. It is a well-known fact that high-yielding varieties require high levels of management and large amounts of fertilizer in order to perform well, but at 33.6 kilograms per hectare of cultivated land, fertilizer consumption in the Philippines was only twelve percent the level of Korea and eight percent the level of Japan in 1976 (FAO, 1978c).

Mandac and Herdt (1978) suggest two possible explanations of the yield gap in the Philippines, the difference between maximum possible and actual yields. One is, not surprisingly, a low level of management among farmers. The other is that farmers act to maximize profit rather than yield. The first condition corresponds to technical inefficiency, the second to economic efficiency. Mandac and Herdt find a low level of both technical and economic efficiency, thus accepting the first hypothesis and rejecting the second.

Data for the present study were provided by Dr. Randolph A. Barker, formerly of IRRI, and are for rice response to N. Prices used are from 1977. They are \$671 US per metric ton N and \$100 US per metric ton of rice. Below are listed functions for the response of Indica rice at the Maligaya Rice Research Institute and at IRRI during the 1966 and 1967 wet and dry seasons. The fertilizer/rice price ratio is very high, a fact which may offer an explanation for the low level of per hectare fertilizer application in the country.

$$Y = 3061 + 56.823N^{***} - .248N^{2***} \qquad R^2 = .99 \qquad (87a)$$

$$Y = 3767 + 39.115N^{***} - .119N^2 \qquad R^2 = .95 \qquad (88a)$$

$$Y = 4436 + 21.666N^{***} - .139N^2 \qquad R^2 = .95 \qquad (89a)$$

where * = significant at .10 level and *** = significant at .01 level.

These functions have input, yield, and return levels for maximum, optimum, and two-thirds of optimum yield as shown in Table 56.

In none of the above cases is yield and input levels for maximum and optimum yield very different. The site in (89a) is the least responsive to fertilizer, and gives the lowest returns to optimal fertilizer use, both as an absolute amount and as a percentage above fertilizer costs.

It is interesting to note that all of the above functions give predicted yields with zero fertilizer application which are higher than the average yields reported for the country. While this may be due in part to the soils on the experimental sites being highly fertile, or to the inappropriateness of the estimated functions at low input levels, it may

Table 56. Input, yield, and economic return levels corresponding to four fertilization levels; functions (87a)-(89a) (rice, Philippines)

Maximum yield			Optimum levels			Two-thirds of opt. levels			Zero fert.				
N	Y	R[a]	N	Y	R	N	Y	R	Y	R	(a)[b]	(b)[c]	Function
115	6313	$554	101	6270	$559	67	5755	$531	3061	$306	$253	1.83	(87a)
164	6981	$588	136	6886	$597	91	6341	$573	3767	$377	$220	2.71	(88a)
78	5280	$476	54	5201	$484	36	5036	$479	4436	$444	$40	1.09	(89a)

[a] R = per hectare economic returns above fertilizer costs.

[b] (a) = difference between R for optimum fertilization and R for zero fertilization.

[c] (b) = ratio of R for optimum fertilization to R for zero fertilization.

also be another indication that poor management is a contributing factor to low rice yields in the Philippines.

Since the functions measure the response to only one nutrient, the land-fertilizer equations for the three yield levels all take the same form:

For equation (87a):

$$Y = 3061L + 56.823F - .248F^2L^{-1} \qquad F = 115 \qquad (87b)$$

$$Y = 3061L + 56.823F - .248F^2L^{-1} \qquad F = 101 \qquad (87c)$$

$$Y = 3061L + 56.823F - .248F^2L^{-1} \qquad F = 67 \qquad (87d)$$

For equation (88a):

$$Y = 3767L + 39.115F - .119F^2L^{-1} \qquad F = 164 \qquad (88b)$$

$$Y = 3767L + 39.115F - .119F^2L^{-1} \qquad F = 136 \qquad (88c)$$

$$Y = 3767L + 39.115F - .119F^2L^{-1} \qquad F = 91 \qquad (88d)$$

And for equation (89a):

$$Y = 4436L + 21.666F - .139F^2L^{-1} \qquad F = 78 \qquad (89b)$$

$$Y = 4436L + 21.666F - .139F^2L^{-1} \qquad F = 54 \qquad (89c)$$

$$Y = 4436L + 21.666F - .139F^2L^{-1} \qquad F = 36 \qquad (89d)$$

These equations give coordinates on land-fertilizer isoquants as shown in Tables 57-59.

The low responsiveness of the site in equation (89a) is seen in the relative flatness of its isoquants compared with those of the other two equations. To obtain the equivalent of maximum per hectare yield at zero input levels requires only 1.190 ha in the case of equation (89b), while 1.853 and 2.063 ha are needed for equations (88b) and (87b), respectively.

Table 57. Coordinates of land-fertilizer isoquants, equations 87b-87d (rice, Philippines)

Quantity of fert. (kg)	87b			87c			87d		
	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
0	6316	2.063	79.04	6270	2.048	77.89	5755	1.880	65.62
50		1.292	17.06		1.279	16.62		1.131	12.13
67[a]		1.139	8.59		1.127	8.32		1.000	5.65
100		1.010	1.41		1.001	1.32		.912	.37
101[b]		1.008	1.30		1.000	1.20		.912	.28
115[c]		1.000	-.03		.993	-.10		.916	-.72
150		1.037	-1.86		1.031	-1.89		.972	-2.16

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 58. Coordinates of land-fertilizer isoquants, equations 88b-88d (rice, Philippines)

Quantity of fert. (kg)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
	88b			88c			88d		
0	6981	1.853	35.66	6886	1.828	34.70	6341	1.683	29.42
50		1.391	14.54		1.367	13.97		1.228	10.93
91[a]		1.138	5.47		1.117	5.18		1.000	3.67
100		1.102	4.29		1.082	4.04		.970	2.77
136[b]		1.016	1.26		1.000	1.13		.912	.50
150		1.004	.56		.989	.46		.908	-.02
164[c]		1.000	.01		.986	-.06		.912	-.44
200		1.018	-.93		1.007	-.97		.944	-1.18

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 59. Coordinates of land-fertilizer isoquants, equations 89b-89d (rice, Philippines)

Quantity of fert. (kg)	89b			89c			89d		
	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
0	5280	1.190	6.92	5201	1.172	6.71	5036	1.135	6.29
36[a]		1.053	2.92		1.036	2.79		1.000	2.53
50		1.023	1.77		1.006	1.66		.972	1.45
54[b]		1.016	1.47		1.000	1.37		.966	1.18
78[c]		1.000	.00		.985	-.06		.954	-.18
100		1.012	-1.02		.998	-1.06		.967	-1.13
150		1.099	-2.60		1.088	-2.61		1.065	-2.62

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

The amounts of land replaced by one metric ton of fertilizer at these points are 6.92, 35.66, and 79.04 ha, respectively.

The amount of land required to obtain the equivalent of optimum yield without fertilizer varies from 1.172 to 2.048 ha. At input levels of 50 kg, the range is between 1.906 and 1.279 ha.

Using functions (87a-d) through (89a-d) as a guide, there exists in the Philippines a great potential for increased rice production, reduction in the land area required for rice cultivation, or both. The 3.55 million ha under cultivation in 1976 could have yielded between 18.74 and 24.78 million metric tons at input levels for maximum yield, between 18.46 and 24.45 million metric tons at optimal fertilization levels, and from 17.88 to 22.51 million metric tons at two-thirds of optimal fertilization levels. These are large increases over the actual production of 6.45 million metric tons. The range of fertilizer requirements for the three application levels would have been 277,000-582,000 metric tons, 192,000-483,000 metric tons, and 128,000-323,000 metric tons.

The 1976 rice crop could have been grown on only 924,000 and 1.222 million hectares at fertilization levels for maximum yield. Optimum and two-thirds of optimum fertilization would have required from 937,000 to 1.240 million and from 1.017 million to 1.281 million ha, respectively. Fertilizer requirements would have ranged from 152,000 down to 95,000 metric tons at application levels for maximum yield. Optimum application would have been from 127,000 down to 67,000 metric tons; two-thirds of optimal application from 93,000 to 46,000 metric tons.

Korea

North and South Korea occupy a peninsula which juts out from nothern China. The South, known as the Republic of Korea, had a population of 36 million in 1977, forty percent of which was classified as agricultural. The total land area is 9.8 million hectares, twenty-three percent of which are in crops (FAO, 1978a). Rice is by far the most important cereal crop cultivated in Korea. The heaviest concentration of rice cultivation is in the region known as the southwestern agricultural basins. There the climate is mind enough for two crops per year (Stamp, 1967).

The Republic of Korea is an example of high input agriculture. Fertilizer use in 1976 was 287.40 kilograms per hectare of arable land and permanent crops. These were the highest levels in Asia after Japan and Singapore. The government subsidizes the manufacture of fertilizer, keeping the price paid by farmers low. Korea exported one-third of its total fertilizer production in 1978 (Ping, 1979).

Korea's rice yields are very high: 6780 kilograms per hectare in 1977. Nevertheless, production is not quite sufficient to meet demand. Production in the years 1975, 1976, and 1977 was 6.5, 7.2, and 8.3 million metric tons, while imports amounted to 483,000, 179,000, and 64,000 metric tons, respectively.

Workers of the Institute of Agricultural Science in Su-Won have done research on yield response of rice to fertilizer. Using data provided by them, we estimate the following function for the IRRI 67 variety:

$$Y = 5580 + 15.12N^{***} + 3.38P + 4.80K^{**} - .024N^{2***} - .003P^{2} - .032K^{2*} - .006NP \qquad R^2 = .99 \qquad (90a)$$

where * = significant at .10 level; ** = significant at .05 level; and *** = significant at .01 level.

NK and PK interactions were eliminated because of problems with the matrix used in estimating the regression coefficients. These interactions normally have very small coefficients and levels of significance, and as such influence predicted yields very little.

Prices used in the present study are \$363 US per metric ton N, \$205 US per metric ton P, \$151 US per metric ton K, and \$274 US per metric ton of rice paddy. The input and yield levels for maximum, optimum, and two-thirds of optimum yield are given in Table 60.

The land-fertilizer equations for the three yield levels are as follows:

$$Y = 5580L + 8.678F - .006790F^2L^{-1} \qquad F = 638 \qquad (90b)$$

$$Y = 5580L + 9.752F - .008644F^2L^{-1} \qquad F = 505 \qquad (90c)$$

$$Y = 5580L + 9.752F - .008644F^2L^{-1} \qquad F = 336 \qquad (90d)$$

These equations give coordinates on the land-fertilizer isoquants as shown in Table 61. It will be noted that response to fertilizer is not very great, and that the isoquants are therefore quite flat.

To produce the equivalent of maximum per hectare yield without fertilizer requires 1.497 ha. The amounts of gain obtained with optimum and two-thirds of optimum per hectare fertilization require 1.487 and 1.412 ha, respectively, when no fertilizer is used. The amounts of land replaced by one metric ton of fertilizer at application levels approaching zero are 3.48, 3.87, and 3.49 ha for the respective yield levels.

Table 60. Input, yield, and economic return levels corresponding to four fertilization levels; function (90a) (rice, Korea)

Maximum yield					Optimum levels				
N	P	K	Y	R[a]	N	P	K	Y	R
279	284	75	8353	$2118	266	173	66	8300	$2132

[a]R = per hectare economic returns above fertilizer costs.

[b](a) = difference between R for optimum fertilization and R for zero fertilization.

[c](b) = ratio of R for optimum fertilization to R for zero fertilization.

Two-thirds of opt. levels					Zero fert.				
N	P	K	Y	R	Y	R	(a)[b]	(b)[c]	Function
177	115	44	7880	$2065	5580	$1529	$603	1.39	(90a)

Table 61. Coordinates of land-fertilizer isoquants, equations 90b-90d (rice, Korea)

Quantity of fert. (kg)	90b Yield (kg)	90b Amount of land (ha)	90b Land needed to replace 1 met. T fertilizer (ha)	90c Yield (kg)	90c Amount of land (ha)	90c Land needed to replace 1 met. T fertilizer (ha)	90d Yield (kg)	90d Amount of land (ha)	90d Land needed to replace 1 met. T fertilizer (ha)
0	8353	1.497	3.48	8300	1.487	3.87	7880	1.412	3.49
100		1.350	2.48		1.324	2.61		1.250	2.31
200		1.226	1.66		1.190	1.64		1.118	1.40
250		1.173	1.33		1.136	1.25		1.066	1.06
300		1.128	1.04		1.091	.94		1.024	.77
336[a]		1.099	.86		1.065	.74		1.000	.60
350		1.089	.80		1.056	.67		.992	.54
400		1.059	.60		1.029	.46		.969	.35
450		1.035	.43		1.011	.29		.954	.20
500		1.018	.29		1.001	.14		.947	.07
505[b]		1.017	.27		1.000	.13		.947	.06
550		1.007	.17		.996	.03		.946	-.03
600		1.001	.07		.998	-.07		.950	-.12
638[c]		1.000	.00		1.002	-.14		.956	-.18
650		1.000	-.02		1.004	-.16		.959	-.20

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Quantities equivalent to maximum yield may be produced with, among other combinations, 200 kg of fertilizer and 1.226 ha of land, 400 kg of fertilizer and 1.059 ha, or 500 kg and 1.018 ha. The amounts of land replaced by one metric ton of fertilizer at these points on the isoquant are 1.66, .60, and .29 ha, respectively.

There is not nearly as much potential in Korea as in other Asian countries for improving rice yields through increased fertilizer use, since both yield and fertilization levels are among the highest in the world. Given that function (90a) has an intercept term of 5580, almost as great in magnitude as the country's average yield level of 5966 kg/ha, there is probably more potential for increasing yields through better management practices than through augmenting fertilizer application.

Using function (90a) as a guide, the total area of 1.21 million hectares dedicated to rice production in Korea in 1976 could have produced 10.11 million metric tons of grain at input levels for maximum yield, 10.04 million metric tons at optimal fertilization levels, and 9.53 million metric tons at two-thirds of optimal levels. The amounts of fertilizer required would have been 772,000, 611,000, and 407,000 metric tons, respectively. Actual rice production was 7.25 million metric tons. Total fertilizer consumption for all crops was 643,000 metric tons, most of this of course used for rice.

The differences between actual and potential production in this case are not as dramatic as for some other countries. The reduction in land required to produce the 1976 crop is not as substantial either. The areas needed at the three input levels would have been 868,000, 873,000, and

920,000 hectares and the amounts of fertilizer 554,000, 441,000, and 309,000 metric tons, respectively.

It may be concluded that marginal returns to additional fertilizer use would not be very great in Korea, and that increases in worldwide fertilizer use would best be applied in other countries.

Thailand

Thailand is a southeast Asian nation bordered by Cambodia, Vietnam, and Laos on the east, Burma on the west, and Malysia to the south. The country has a land area of 51 million hectares, of which approximately one-third are cultivated. The total population in 1977 was 45 million, 78 percent agricultural (FAO, 1978a).

Rice is by far Thailand's most important grain, comprising almost ninety percent of total cereal production in 1977. Rice production was 13.59 million metric tons in that year. Thailand and the United States together vie for the position of the world's largest rice exporter. In 1976 the USA was in first place. In 1977 Thailand was the leader, with exports of 2.94 million metric tons. This figure represented twenty-two percent of the nation's total production (FAO, 1978a,b).

Rice yields in Thailand are quite low. At 1813 kg/ha in 1977, they were slightly below the levels of India. Fertilizer use was also quite low; only 13.4 kg per ha of cultivated land (FAO, 1978a,c). The obvious implication is that Thailand could easily augment its exportable surplus of rice by increasing fertilizer application.

The data for Thailand were again provided by Dr. Barker. Among the data were functions estimated from fertilizer trials on farmers' fields, but these contained only linear terms for P and K, and no maximum or optimum levels could be obtained for these nutrients.

It was decided instead to use functions estimated from trials at the Banghen Rice Experiment Station. This is in line with the methods followed up to now, the use of data corresponding to high levels of management. The functions are listed below:

$$Y = 2460 + 23.09N^{***} + 16.94P^{**} - .112N^{2***} - .0757P^{2**} + .0841NP^{***} \qquad R^2 = .95 \qquad (91a)$$

$$Y = 2266 + 40.83N^{***} + 20.31P^{**} - .210N^{2***} - .0619P^{2} - .0265NP \qquad R^2 = .89 \qquad (92a)$$

where * = significant at .10; ** = significant at .05; and *** = significant at .01.

Both equations are highly significant, and have regression coefficients similar in magnitude. Input, yield, and return levels for maximum yield, optimum, and two-thirds of optimum fertilization are listed in Table 62. The prices used are \$791 US per metric ton N, \$923 US per metric P, and \$110 US per metric ton of rice.

In both cases the optimal levels of P are considerably lower than the levels for maximum yield. There is not as much difference for the two levels of N. The implication is that the marginal physical product and therefore the marginal value product of P declines rather quickly relative to the marginal value product of N.

Table 62. Input, yield, and economic return levels corresponding to four fertilization levels; functions (91a)-(92a) (rice, Thailand)

Maximum yield				Optimum levels				Two-thirds of opt. levels				Zero fert.				
N	P	Y	R[a]	N	P	Y	R	N	P	Y	R	Y	R	(a)[b]	(b)[c]	Function
183	213	6387	$361	116	121	5753	$429	77	81	4974	$411	2460	$271	$158	1.58	(91a)
89	145	5538	$405	75	80	5217	$441	50	53	4615	$419	2266	$249	$192	1.77	(92a)

[a] R = per hectare economic returns above fertilizer costs.

[b] (a) = difference between R for optimum fertilization and R for zero fertilization.

[c] (b) = ratio of R for optimum fertilization to R for zero fertilization.

The land-fertilizer equations are listed below. Coordinates on the land-fertilizer isoquants are found in Tables 63-64.

For equation (91a):

$$Y = 2460L + 19.7819F - .024915F^2L^{-1} \qquad F = 396 \qquad (91b)$$

$$Y = 2460L + 19.9504F - .025549F^2L^{-1} \qquad F = 237 \qquad (91c)$$

$$Y = 2460L + 19.9369F - .025483F^2L^{-1} \qquad F = 158 \qquad (91d)$$

And for equation (92a):

$$Y = 2266L + 28.1138F - .060389F^2L^{-1} \qquad F = 234 \qquad (92b)$$

$$Y = 2266L + 30.2396F - .072279F^2L^{-1} \qquad F = 155 \qquad (92c)$$

$$Y = 2266L + 30.2704F - .072490F^2L^{-1} \qquad F = 103 \qquad (92d)$$

The maximum yield in equation (91a), 6387 kg/ha, is produced on one hectare of land with 396 kilograms of fertilizer. It may also be produced with 2.596 ha of land and no fertilizer, or 1.300 ha and 200 kg of fertilizer. The optimal level of fertilization is 237 kg/ha, which gives a yield of 5753 kg/ha. This same amount can be produced with no fertilizer on 2.339 ha of land or with 150 kg of fertilizer on 1.302 ha, or with .905 ha and 350 kg of fertilizer. Using two-thirds of the optimal per hectare fertilizer application (158 kg) gives a yield of 4974 kg on one hectare of land. This same quantity of grain may be obtained from 2.022 ha using no fertilizer, 1.292 ha using 100 kg of fertilizer, or .782 ha using 300 kg of fertilizer. Equation (92a) gives similar results. The maximum yield of 5538 kg is obtained from one ha of land and 234 kg of fertilizer, or alternatively, from 2.444 ha and no fertilizer or 1.394 ha and 100 kg of fertilizer.

Table 63. Coordinates of land-fertilizer isoquants, equations 91b-91d (rice, Thailand)

Quantity of fert. (kg)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
	91b			91c			91d		
0	6387	2.596	54.21	5753	2.339	44.35	4974	2.022	33.13
100		1.847	21.51		1.593	15.64		1.292	9.83
150		1.538	11.69		1.302	7.85		1.032	4.40
158[a]		1.495	10.53		1.263	6.98		1.000	3.84
200		1.300	5.92		1.096	3.66		.875	1.82
237[b]		1.175	3.48		1.000	2.01		.815	.87
250		1.141	2.87		.976	1.61		.803	.65
300		1.051	1.31		.921	.59		.782	.05
350		1.010	.47		.905	.03		.791	-.29
396[c]		1.000	.01		.912	-.29		.812	-.50
400		1.000	-.02		.914	-.31		.815	-.52
500		1.031	-.54		.967	-.68		.888	-.78

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Table 64. Coordinates of land-fertilizer isoquants, equations 92b-92d (rice, Thailand)

Quantity of fert. (kg)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)	Yield (kg)	Amount of land (ha)	Land needed to replace 1 met. T fertilizer (ha)
	92b			92c			92d		
0	5538	2.444	74.10	5217	2.302	70.74	4615	2.037	55.41
100		1.394	13.18		1.228	9.31		1.016	5.52
103[a]		1.372	12.34		1.208	8.62		1.000	5.05
150		1.119	4.12		1.011	2.31		.865	.98
155[b]		1.102	3.63		1.000	1.96		.860	.76
200		1.014	.94		.961	.03		.857	-.50
234[c]		1.000	-.03		.974	-.69		.887	-1.01
250		1.003	-.33		.987	-.92		.905	-1.18

[a]Amount of fertilizer corresponding to two-thirds of the economic optimum level of application.

[b]Amount of fertilizer corresponding to the economic optimum level of application.

[c]Amount of fertilizer required to achieve maximum yield.

Given that experiment station fertilizer trials are usually conducted under management and soil conditions more favorable than those found at the farm level, the true maximum and economic optimal yield levels are probably quite a bit lower than equations (91a) and (92a) indicate. However, from these data we may obtain a rough idea of rice production potentials in Thailand. If the 7.5 million ha planted to rice in 1977 had produced the optimal yields of 5753 kg/ha predicted for equation (91a), total production would have been approximately 43 million metric tons, three times the actual level. However, the total amount of fertilizer required would have been 1.8 million metric tons, more than seven times the amount of fertilizer used for all purposes in Thailand in 1976.

Alternatively, using the optimal levels from (91a), the 1977 production of 13.59 million metric tons could be obtained with 2.4 million ha of land and 560,000 metric tons of fertilizer. Under a capital shortage situation requiring the employment of two-thirds of the optimum input levels, the total production would be obtainable from 2.7 million ha of land and 432,000 metric tons of fertilizer.

The site used to estimate equation (92a) gives lower yield levels than does the other. Maximum per hectare yield of 5538 kilograms may be produced with one hectare of land and 234 kilograms of fertilizer, or 1.394 ha and 100 kg, or 2.444 ha and no fertilizer. Optimum yield of 5217 kilograms is obtainable from one hectare of land and 155 kg of fertilizer, or 1.228 ha and 100 kg, or .961 ha and 200 kg. To produce the yield level with zero application of fertilizer, 2.302 hectares are required. The yield of 4615 kg corresponding to that obtainable on one hectare of land with 103 kg of fertilizer (two-thirds of optimal application) can also be produced with .865 ha and 150 kg of fertilizer, or 2.037 ha and no fertilizer.

Using function (92a) as a basis for national average yield response of rice, the 1977 crop would have reached 39 million metric tons with optimal fertilization levels and 34.6 metric tons with two-thirds of the optimal levels. The amounts of fertilizer used would have been 809,000 or 771,000 metric tons, respectively. The actual crop of 13.59 million metric tons could have been produced with 2.60 million ha and 403,000 metric tons of fertilizer or with 2.94 million ha and 303,000 metric tons of fertilizer.

The slopes of the isoquants indicate that the site in (92a) is somewhat more responsive to fertilizer than the site in (91a) at zero or very low levels of application, but that this situation is reversed at higher input levels.

Once again in the case of these functions we observe that predicted yields without fertilizer (2460 and 2266 kg/ha, respectively) are above the reported average national yield in 1977, in this case 1813 kg/ha. There would appear to be potential for increasing yield through means other than augmenting fertilizer use, such as the introduction of improved varieties and the application of better management practices.

SUMMARY AND CONCLUSIONS

The purpose of this study was to compare fertilizer response functions from a group of developing countries, in order to measure yield potential and the extent to which fertilizer might serve as a substitute for land. Functions were taken from published and unpublished sources, and others were estimated from raw data. Data used were from Argentina (wheat), Chile (wheat), Peru (rice), Brazil (maize), India (wheat and rice), Pakistan (wheat and rice), the Philippines (rice), Korea (rice), and Thailand (rice).

Input and yield levels corresponding to maximum yield, optimal fertilization, and two-thirds of optimal fertilization were calculated for the functions, along with economic returns above fertilizer costs. The functions were then converted into the land-fertilizer form using the methodology of Heady (1963). This involved considering yield as a function of the application of a given fertilizer mix, as well as of the amount of land employed in conjunction with thus nutrient. Alternative combinations of land and fertilizer were presented which would produce the three yield levels mentioned above. The marginal rates of substitution of fertilizer for land corresponding to these points were also listed.

Considering the response functions as representative of conditions in their respective countries of origin, it was possible to estimate the production potential and fertilizer requirements at the three nutrient application levels and using the land area sown to the grain in 1976.

Also computed were savings in land and increases in fertilizer requirements resulting from producing the 1976 crop at the three input levels previously determined.

With a limited amount of data, this paper showed the tremendous potential for augmenting grain yields through improved management and increased fertilizer application. Experimental results giving yields from optimal fertilization of twice the actual national average level were not uncommon. The larger yields could be used to raise total production, to produce the same amount on less land, or to increase production and partially reduce the amount of land sown.

The results of this study showed differences between yield levels for maximum yield and economic optimum yields to be slight. Often the return levels were not significantly different either. However, fertilizer is a scarce resource whose price to farmers may not reflect actual social cost of its production and consumption. Under these conditions, it is especially important to use fertilizer for optimum economic return rather than for maximum yield.

Differences in yield level resulting from optimum and two-thirds of optimum fertilization were sometimes substantial, but yields at two-thirds of the optimum levels were still considerably above national average yields in many cases.

As much as the potential for increased food production, this paper revealed the tremendous need for more detailed and systematic studies of yield response to fertilizer. Many studies on fertilizer response do not lend themselves easily to economic analysis. They may not include agroclimatic variables, or may have so many that the precision gained from using them is outweighed by the difficulty in computing their values. Many fertilizer trials do not include sufficient input levels to allow for a satisfactory estimation of the response function. In particular, failure to include plots at low input levels may result in an overestimation of the intercept term and of yield at low levels of fertilization. On the other hand, failure to include sufficiently high input levels may result in a function which does not capture the region of declining marginal yields.

In order to extract a maximum amount of information from a global comparison of response functions, a "catalog" of such functions should be developed. These functions would include as much as possible the same agro-climatic variables, and would be estimated over several growing seasons. Fertilizer response functions are normally estimated on experiment station plots, under conditions of high management levels. To the extent that these management levels cannot reasonably be duplicated at the farm level, the estimated functions overestimate the potential increase in food production from augmented fertilizer application. For this reason, it may be advisable for purposes of the "catalog" to utilize experiments conducted at the farm level, with a level of management which is advanced but not unrealistically high for commercial agricultural production.

BIBLIOGRAPHY

Ahmed, Munir; and Shakoor, Abdul. "Semi-Dwarf (HYV) Wheats and their Fertilizer Requirements." In Proceedings of Wheat Production Seminar 1976. Esso Pakistan Fertilizer Company, Ltd. Karachi, Pakistan: Esso Pakistan, 1976.

Araos F., José Fernando. Fertilización de Trigo en Suelos Regados de Ñuble. Chillán, Chile: Instituto de Investigaciones Agropecuarias, 1970.

Bishay, Fahmi Kamel. "Marginal Rates of Substitution Between Land, Labor, and Fertilizer in Relation to the Optimum Planning of Resource Combinations." Ph.D. dissertation, Iowa State University, 1965.

Borgstrom, Georg. Focal Points, A Global Food Strategy. New York: Macmillan Publishing Co., 1973.

Bose, Sati Prasad. "Fertilizer Production Functions up to Fourth Order from Experimental Data Applied in Profit Maximization, Supply-Demand Relationships and Marginal Rates of Substitution for Land." M.S. thesis, Iowa State University, 1970.

Carmen, Miguel Leonidas. "Yield of Rice as Affected by Fertilizer Rates, Soil, and Meteorological Factors." Ph.D. dissertation, Iowa State University, 1968.

Chaudhari, A. K.; and Sirohi, A. S. "Notes: Allocation of Fertilizers among Crops and Regions in Uttar Pradesh." Indian Journal of Agricultural Economics 28 (July-September 1973): 46-61.

Chen, Hung-Teh. "An Economic Analysis of Rice Production and the Application of Fertilizer Nutrients in Taiwan." Journal of Agricultural Economics, Taiwan Provincial Chung Hsing University 2 (July 1963): 35-51.

Chinese-American Joint Commission on Rural Reconstruction. "Soils and Fertilizer Uses in Taiwan, Republic of China." Plant Industry Series No. 20, 1961.

Chou, Marylin; Harmon, David P., Jr.; Kahn, Herman; and Wittwer, Sylvan H. World Food Prospects and Agricultural Potential. New York: Praeger Publishers, 1977.

Darwich, Nestor Alejandro. "Analysis of the Response of Wheat to N and P Fertilization under Nonuniform Environmental Conditions in Southeast Buenos Aires Province, Argentina." Ph.D. dissertation, Iowa State University, 1977.

Department of Agricultural Economics, University of Agriculture. Derivation of Fertilizer-Crop Response and Optimum Levels of Fertilization for Various Crops/Areas: Rice. Lyallpur, Pakistan: University of Agriculture, 1975. (a)

Department of Agricultural Economics, University of Agriculture. Derivation of Fertilizer-Crop Response and Optimum Levels of Fertilization for Various Crops/Areas: Wheat. Lyallpur, Pakistan: University of Agriculture, 1975. (b)

Ferguson, Charles E; and Gould, John P. Microeconomic Theory. Homewood, Illinois: R. D. Irwin, 1975.

Food and Agricultural Organization of the United Nations. FAO Production Yearbook 1977. Rome: FAO, 1978. (a)

Food and Agricultural Organization of the United Nations. FAO Trade Yearbook 1977. Rome: FAO, 1978. (b)

Food and Agricultural Organization of the United Nations. Annual Fertilizer Review 1977. Rome: FAO, 1978. (c)

Fuller, Wayne A. "Grafted Polynomials as Approximating Functions." Australian Journal of Agricultural Economics 13 (June 1969): 35-46.

Heady, Earl O. "Marginal Rates of Substitution between Technology, Land, and Labor." American Journal of Agricultural Economics 45 (February 1963): 137-145.

Heady, Earl O.; and Dillon, John L. Agricultural Production Functions. Ames: Iowa State University Press, 1961, 1972.

Henderson, James M.; and Quandt, Richard E. Microeconomic Theory, A Mathematical Approach. New York: McGraw-Hill, 1958, 1971.

Ibach, Donald Brian. Fertilizer Use in the United States by Crops and Areas; 1964 Estimates. Washington, D.C.: U.S. Department of Agriculture, Economic Research Service, 1967.

Institute of Agricultural Science, Office of Rural Development. Experiment and Research Report. Su-Won, Korea: Institute of Agricultural Science, 1978.

Instituto de Investigaciones Agropecuarias. Investigación Agropecuaria. Santiago, Chile: Lord Cochrane, 1971.

Instituto Nacional de Investigaciones Agricolas. Productividad de los Suelos Chilenos. Santiago, Chile: INIA, 1973.

International Food Policy Research Institute. Recent and Prospective Developments in Food Consumption: Some Policy Issues. Research Report 2. International Food Policy Research Institute, Stanford University, 1977.

Jenny, H. Factors of Soil Formation. New York: McGraw-Hill, 1941.

Johnston, J. Econometric Methods. New York: McGraw-Hill, 1963, 1972.

Khan, Ahmed Saeed; and Ali, Asghar. "Production Function Analysis of Nitrogenous and Phosphatic Fertilizers in Rice Production in the Irrigated Areas of the Punjab." In Proceedings of Rice Production Seminar 1976. Esso Pakistan Fertilizer Company, Ltd. Karachi, Pakistan: Esso Pakistan, 1976.

Khan, Riaz Ahmad. "Marginal Rates of Substitution between Fertilizer and Land in Production of Wheat and Paddy Rice." Ph.D. dissertation, Iowa State University, 1965.

Laird, R. J.; Ruiz, A.; Rodriguez, H. J.; and Cady, F. B. "Combining Data from Fertilizer Experiments into a Function Useful for Estimating Specific Fertilizer Recommendations." CIMMYT Research Bulletin No. 12, 1969.

Lee, Jeung-Han. "A Study on the Relationships of Resource Use in Crop Production." Research Bulletin of Chinju Agricultural College (Korea) 3 (1964): 89-103.

Lee, Jeung-Han. "Factor Demand and Product Supply Functions and Optimal Allocation Patterns Derived from Experimental Fertilizer Production Functions." Journal of the Institute for Agricultural Resources Utilization, Chinju National Agricultural College (Korea) 6 (1967): 1-68. (a)

Lee, Jeung-Han. "The Least Cost Combination of Nutrients among Regions in Rice Production." Research Bulletin of Chinju Agricultural College (Korea) 6 (1967): 29-36. (b)

Mandac, Abraham M.; and Herdt, Robert W. Economic Inefficiency as a Constraint to High Rice Yields in the Philippines. International Rice Research Institute, Paper No. 78-04, 1978.

Montero, B. Emilio; and Pérez V., Santos, eds. Investigación Económica y Experimentación Agricola. Montevideo: Instituto Interamericano de Ciencias Agricolas, 1967.

Moss, Robert. Chile's Marxist Experiment. Newton Abbot, England: David and Charles, 1973.

Mujica-Ateaga, Rodrigo. "Analisis de Eficiencia Fisica y Económica de Fertilizantes Nitrogendados y Fosfatados en Ensayos de Papa y Trigo en Base a la Función de Respuesta Incorporando los Niveles de Fertilidad Natural." Thesis, Universidad Católica de Chile, 1965.

Ostle, Bernard; and Mensing, Richard W. Statistics in Research. Ames: Iowa State University Press, 1954, 1975.

Paddock, William; and Paddock, Paul. Famine-1975. Boston: Little, Brown, and Company, 1967.

Perrin, Richard K. "The Value of Information and the Value of Theoretical Models in Crop Response Research." American Journal of Agricultural Economics 58 (February 1976): 54-61.

Ping, Ho Kwon. "The Fourth Factor." Far Eastern Economic Review 106 (July 1979): 33-38.

Ramirez, Isabel San Cristobal de. "Influencia de la Población y Niveles Nitrogenados en los Rendimientos de Maices Híbridos." Agricultura Técnica 25 (December 1965): 155-162.

Rosegrant, Mark W. "The Impact of Irrigation on the Yield of Modern Rice Varieties." Unpublished paper, International Rice Research Institute, December 1976.

Reutlinger, Shlomo; and Selowsky, Marcelo. Malnutrition and Poverty: Magnitude and Policy Options. Baltimore: The Johns Hopkins University Press, 1976.

Saxena, P. N.; and Sirohi, A. S. "Response of Mexican Dwarf and Indian Tall Varieties of Wheat to Nitrogen Application." Journal of the Post Graduate School (India) 5 (June 1967): 123-173.

Slack, A. V. Defense against Famine. Garden City: Doubleday and Company, 1970.

Smith, T. Lynn. The Race between Population and Food Supply in Latin America. Albuquerque: University of New Mexico Press, 1976.

Stamp, Sir Dudley. Asia: A Regional and Economic Geography. London: Methuen and Company, Ltd., 1967.

Steele, F.; and Bourne, A., eds. The Man/Food Equation: Proceedings of a Symposium Held at the Royal Institution, London, September 1973. London: Academic Press, 1975.

Suggate, L. S. Africa. London: George G. Harrap and Co., 1971.

Tejeda-Sanhueza, Hernan R. "Statistical Analysis and Model Building for a Wheat Production System in Chile." Ph.D. dissertation, Iowa State University, 1973.

Tisdale, Samuel L.; and Nelson, Werner L. Soil Fertility and Fertilizers. New York: Macmillan Publishing Co., 1975.

Turrent, Antonio Fernandez. "Empirical Relationships between Yield of Experimentally Grown Corn and some Environmental Factors in Iowa." Ph.D. dissertation, Iowa State University, 1968.

Voss, R. D.; and Pesek, J. T. "Geometrical Determination of Uncontrolled-Controlled Factor Relationships Affecting Crop Yield." Agronomy Journal 57 (September-October 1965): 460-463.

Weil, Thomas; et al. Area Handbook for Brazil. Washington, D.C.: Government Printing Office, 1975.

White, William C.; and Collins, Donald N., eds. The Fertilizer Handbook. Washington: Fertilizer Institute, 1972.

Yudelman, Montague; with Howard, Frederic. Agricultural Development and Economic Integration in Latin America. London: George Allen and Unwin, 1970.

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APPENDIX A: YIELD AS A FUNCTION OF FERTILIZER USE: TIME SERIES AND CROSS-SECTIONAL ANALYSIS

In an effort to test the significance of fertilizer use in increasing grain yields, a time-series regression analysis was conducted using data from the countries included in the present study, plus some additional ones. The time period covered was 1953-1972. In addition to the time-series analysis, a cross-sectional examination of average yields versus fertilizer consumption was made for the years 1975 and 1976. All data were from the FAO (1978a,c).

Time Series Analysis

Data for the time-series regressions of rice yields were obtained for Japan, Taiwan, Korea, India, Pakistan, the Philippines, Thailand, and Peru. For wheat, the countries were Argentina, Chile, India, and Pakistan. Because of a lack of sufficient and reliable data on fertilization by specific crop or per hectare of cultivated land, yields were simply regressed over time against total fertilizer use.

Since fertilizer use tended to increase together with yields over time, we wished to test which variable better explained the yield increases; fertilizer use itself, or a "time" variable presumably embracing technological change. Models were run with yield as a function of each of these variables separately.

A summary of the model results for rice and wheat is given below. Y refers to average yield in kg/ha, T to time in years from 1953, and F to total fertilizer use in metric tons. The numbers in parentheses below the regression coefficients are t-values. The asterisks denote the same significance levels as have been used in the rest of this paper: * for .10 significance; ** for .05 significance; and *** for .01 significance.

India:

Time only: $Y^{1} = 1221.17^{***} + 22.679757T^{***2}$ $R^2=.60$ (93)
(24.01885) (5.08200)

Fertilizer use only: $Y = 1314.54^{***} + .000159F^{***3}$ $R^2=.53$ (94)
(32.41899) (4.38419)

Japan:

Time only: $Y = 3922.47^{***} + 96.208271T^{***}$ $R^2=.78$ (95)
(29.25400) (7.97391)

Fertilizer use only: $Y = 2539.01^{***} + .001365F^{***}$ $R^2=.78$ (96)
(9.44741) (8.80426)

Korea:

Time only: $Y = 2461.42^{***} + 118.904170T^{***}$ $R^2=.73$ (97)
(12.44189) (6.84727)

Fertilizer use only: $Y = 2090.11^{***} + .004607F^{***}$ $R^2=.68$ (98)
(7.47440) (5.99772)

Pakistan:

Time only: $Y = 1212.49^{***} + 40.353973T^{***}$ $R^2=.52$ (99)
(12.47364) (4.13413)

Fertilizer use only: $Y = 1269.99^{***} + .002309F^{***}$ $R^2=.71$ (100)
(21.30794) (6.32557)

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[1] Average yield in kg/ha.

[2] Time in years from 1953.

[3] Total fertilizer use in metric tons.

Peru:

Time only: $Y = 4024.25^{***} + 1.509904T$ $R^2=.0013$ (101)
(25.94414) $(.12401)$

Fertilizer use only: $Y = 3593.57^{***} + .005685F$ $R^2=.17$ (102)
(12.35200) (1.58255)

Philippines:

Time only: $Y = 1071.36^{***} + 23.678804T^{***}$ $R^2=.58$ (103)
(18.46011) (4.73076)

Fertilizer use only: $Y = 1050.83^{***} + .002572F^{***}$ $R^2=.77$ (104)
(25.40749) (7.30998)

Taiwan (data cover only eight-year period):

Time only: $Y = 2517.72^{***} + 74.235589T^{***}$ $R^2=.94$ (105)

Fertilizer use only: $Y = 1788.79^{***} + .007156F^{***}$ $R^2=.82$ (106)
(8.72768) (5.20986)

Thailand:

Time only: $Y = 1201.37^{***} + 45.031869T^{***}$ $R^2=.88$ (107)
(20.62210) (9.72869)

Fertilizer use only: $Y = 1469.67^{***} + .004892F^{***}$ $R^2=.63$ (108)
(21.70761) (4.68270)

Wheat

Argentina:

Time only: $Y = 1332.00^{***} - 1.000000T$ $R^2=.0012$ (109)
(17.80057) $(-.14851)$

Fertilizer use only: $Y = 1361.01^{***} - .001125F$ $R^2=.0312$ (110)
(21.46108) $(-.76117)$

Chile:

Time only: $Y = 1205.57^{***} + 28.255639T^{***}$ $R^2=.74$ (111)
(27.46431) (7.15343)

Fertilizer use only: $Y = 1048.67^{***} + .004515F^{***}$ $R^2=.69$ (112)
(14.71038) (6.36287)

India:

Time only: $Y = 589.58^{***} + 27.967854T^{***}$ $R^2 = .71$ (113)
$(11.96710)\quad(6.46732)$

Fertilizer use only: $Y = 674.83^{***} + .000233F^{***}$ $R^2 = .88$ (114)
$(28.80896)\quad(11.09008)$

Pakistan:

Time only: $Y = 713.45^{***} + 18.286894T^{***}$ $R^2 = .55$ (115)
$(17.23482)\quad(4.39912)$

Fertilizer use only: $Y = 741.53^{***} + .001030F^{***}$ $R^2 = .73$ (116)
$(29.27217)\quad(6.63910)$

An examination of the results shows that time and fertilizer use were each significant by themselves in explaining increases in rice yields. The exception was Peru, where neither variable did a satisfactory job of explaining the changes. Increases in total fertilizer use did a better job of explaining yield increases in Japan, Korea, and the Philippines, while time (technological change) was a better explanatory variable for India, Taiwan, and Thailand.

The regressions of wheat yields gave significant results for both time and fertilizer use variables, with the exception of Argentina, where neither model gave statistically significant results. This is not surprising in light of the fact that the highly fertile soils of the country are not very responsive to fertilization, and yields are greatly affected by year-to-year fluctuations in precipitation. Of the remaining three countries for which wheat yield data were examined, only in Chile did time do the best job of explanation. Total fertilizer use explained yield increases better than time in India and Pakistan.

Cross-Sectional Analysis

For the cross-sectional view of yields versus fertilizer use, data from 1975 and 1976 were averaged together. A linear model was estimated for the response of rice to fertilization in the United States, India, Pakistan, Japan, Korea, Thailand, the Philippines, and Peru. It took the following form:

$$Y^{1} = \underset{(4.60)}{2352^{***}} + \underset{(3.70)}{1.0443F^{***\,2}} \qquad R^2 = .69 \quad (117)$$

A log-linear transformation gave results inferior to those above. A quadratic model, however, gave a significant improvement in fit:

$$Y = \underset{(2.51)}{1491^{*}} + \underset{(2.75)}{3.8248F^{**}} - \underset{(-2.02)}{.000736F^{2*}} \qquad R^2 = .83 \quad (118)$$

A linear model was estimated for the response of wheat to fertilization in the United States, Argentina, Chile, India, and Pakistan. Its form was as follows:

$$Y = \underset{(10.81)}{1372^{***}} + \underset{(2.26)}{.5073F^{*}} \qquad R^2 = .63 \quad (119)$$

An alternative linear model with yield and fertilizer values transformed in natural logarithm form gave less satisfactory results than the above equation. A quadratic model was not estimated because of the small number of error degrees of freedom.

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[1]Average yield in kg/ha.

[2]Average fertilizer use in kg per ha of arable land and permanent crops.

The implication of the equations presented above is that levels of fertilizer use do explain a significant portion of yield differences across countries. The results for rice indicate the existence of diminishing and eventually negative marginal yields from increased fertilizer application. Maximum yield for the quadratic function in (118) is 6460 kg/ha, obtained with fertilizer application of 2598 kg/ha.

APPENDIX B: PHYSIOLOGY OF PLANT RESPONSE TO FERTILIZER

Slack (1970) has listed three criteria which together indicate that a nutrient is essential for plant growth. They are:

1) The plant cannot mature without a sufficient quantity of the element.
2) There is no completely acceptable substitute for that particular mineral.
3) The element is needed for the nutrition of the plant and not to correct the condition of the soil.

Plants are composed primarily of carbon, hydrogen, and oxygen. These essential elements are found in abundance in the atmosphere, however, and plants can absorb them from this source. There are thirteen other elements which have been found to be essential to plant growth using the criteria mentioned above. They are nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), boron (B), molybdenum (Mo), and chlorine (Cl).

Nitrogen, phosphorus, and potassium play such an important role in plant nutrition that they are referred to as macronutrients. Since the present study focuses on yield response to these three elements, they will be the only ones discussed in this section.

At first glance, the need for adding nutrients to the soil may not seem apparent. Depending on the crop, macronutrient uptake by plants ranges from 11 to 168 kg/ha, while the upper three centimeters of the soil typically contain between 1120 and 6720 kilograms of nitrogen, 896 and

2240 kilograms of phosphorus, and up to 54,880 kilograms of potassium per hectare. The problem, of course, is that most of what is in the soil is in insoluble form.

Plants obtain nitrogen from the soil. In addition, legumes absorb nitrogen from the atmosphere and transfer it to the roots, where by bacterial action it is converted into usable form. The value of alternating legumes with other crops in order to increase soil nitrogen is well-known, but for the high yield, extensive, commercialized grain production typical of exporting countries, nitrogen fertilizers are a necessity (Slack, 1970).

Nitrogen is normally taken up in the form of ammonium or nitrate ions. These ions combine with carbon compounds in the plant to form amino acids. The amino acids undergo further reactions to give either proteins or enzymes which act as catalysts to bring about reactions in the plant. Nitrogen is usually applied as ammonium nitrate, ammonium sulfate, or urea.

Nitrogen deficiency manifests itself in stunted growth and yellow appearance of the leaves. If the deficiency is serious, the leaves will turn brown and die (Tisdale and Nelson, 1975).

There is wide variation in the usability of different phosphate fertilizers. The usability depends primarily on the dissolving rate, the rate at which the phosphate solution is replenished as the plant takes it up. Phosphorus has various roles in plant nutrition. It aids in the conversion of starches into sugars, in the process of cell division, and in the development of certain types of plant tissue. However, the most important function of phosphorus is in forming certain chemical bonds which are necessary for photosynthesis.

Potassium is taken up from the soil, and does not present solubility problems. Acceptable potash compounds may be mixed directly from abundant deposits in diverse places on the globe.

The physiological functions of potassium are not entirely clear. It is a necessary element for healthy plant growth and disease resistance. Potassium is believed to be important also in the conversion of amino acids into protein and in the formation of carbohydrates. Potassium deficiency is not always readily visible, but may result in significant yield reductions (Tisdale and Nelson, 1975).

Fertilizer Response and Water

Water can be just as much of a yield-limiting factor as mineral nutrients (Steward, in White and Collins, 1972). Thus, results of the study can be expected to have depended at least somewhat on the amounts of rainfall and/or water applied through irrigation during the periods in which the fertilizer trials were conducted.

Insufficient water availability to the plant results in a condition known as water stress. The result is a wilting of the plant, and if the condition persists, its death.

Water is necessary not only for the plant to carry out physiological processes, but also for the transport of nutrients. As Tisdale and Nelson (1975) explain:

> Nutrient absorption is affected directly by level of soil moisture as well as indirectly by the effect of water on the metabolic activity of the plant, soil aeration, and the salt concentration of the soil solution. (p. 624)

Fertilizer use has been found to improve the water-use efficiency, defined as the amount of dry matter produced divided by the amount of water used. In a Nebraska study, application of nitrogen to maize increased water use by an average of 3.3 cm, but increased water use efficiency by 44 percent. Similarly, application of nitrogen to wheat increased water use by 2.3 cm, but raised water use efficiency twelve percent (Tisdale and Nelson, 1975).

Improvement of soil fertility gives more organic residues, greater root volumes, and deeper root penetration. These characteristics both provide protection against drought and help the soil to dry out more quickly when it is over-saturated.