# INDUCED INNOVATION IN AGRICULTURAL DEVELOPMENT

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## I. Introduction

There has been a sharp transition in economic doctrine with respect to the relative contribution of agricultural and industrial development to national economic growth during recent decades. There has been a shift away from an earlier "industrial fundamentalism" to an emphasis on the significance of growth in agricultural production and productivity for the total development process.

Nevertheless, the process of agricultural development itself has, with few exceptions, remained outside the concern of most development economists. Both technical change and institutional change have been treated as exogenous to their systems.

In our view technical change represents an essential element in the growth of agricultural production and productivity from the very beginning of the development process. The process of technical change in agriculture can best be understood as a dynamic response to the resource endowments and economic environment in which a country finds itself at the beginning of the modernization process. The design of a successful agricultural development strategy in each country or region involves a unique pattern of technical change and productivity growth in response to the particular set of factor prices which reflect the economic implications of resource endowments and resource accumulation in each society. It also involves a complex pattern of institutional evolution in order to create an economic and social environment conducive to the effective response by individuals, private firms and public agencies to the new technical opportunities.

Any attempt to develop a model of agricultural development in which technical change is treated as endogenous to the development process rather than as an exogenous factor that operates independently of other development processes must start with the recognition that there are multiple paths of technological development. Technology can be developed to facilitate the substitution of relatively abundant (hence cheap) factors for relatively scare (hence expensive) factors in the economy.

A second consideration in any attempt to develop an adequate model of agricultural development is explicit recognition of the role of the public sector in the agricultural development process. Advances in agricultural science and technology represent a necessary condition for releasing the constraints on agricultural production imposed by inelastic factor supplies. Yet technical innovations are among the more difficult products to produce in a country in the early stages of economic development. Institutionization of the process by which a continuous stream of new agricultural technology is made available to a nation's farmers is particularly difficult to achieve. In most countries which have been successful in achieving rapid rates of technical progress "socialization" of agricultural research has been deliberately employed as an instrument of modernization in agriculture. The modernization process has involved the development of both experiment station and industrial capacity capable of producing the biological (or biological and chemical) and mechanical (or engineering and mechanical) innovations adapted to factor supply conditions.

In this paper we extend the theory of "induced innovation" to include the process by which public sector investment in agricultural research, in the adaptation and diffusion of agricultural technology, and in the institutional infrastructure that is supportive of agricultural development, is directed toward releasing the constraints on agricultural production imposed by the factors characterized by a relatively inelastic supply. We then elaborate an operational model, suitable for testing the "induced innovation" hypothesis. Finally the model is tested against the long term agricultural development experience of Japan and the United States.

## II. Induced Innovation in the Private and Public Sectors

There is a substantial body of literature on the "theory of induced" innovation. A major controversy has centered around the existence of a mechanism by which differences or changes in factor prices affect inventive or innovative activity. This discussion has been conducted entirely within the framework of the theory of the firm. The discussions of induced innovation available in the literature offer little insight into the mechanism through which differences in resource endowments affect resource allocation in public sector research.

### A. Induced Innovation in the Private Sector

It had generally been accepted, at least since the publication of The Theory of Wages by John R. Hicks, that changes or differences in the relative prices of factors of production could influence the direction of invention or innovation [Hicks, 1932, pp. 124-125]. There have also been arguments raised by W. E. G. Salter and others against Hicks' theory of induced innovation. [1/] The argument runs somewhat as follows: Firms are motivated to save total cost for a given output; at competitive equilibrium, each factor is being paid its marginal value product; therefore, all factors are equally expensive to firms; hence, there is no incentive for competitive firms to search for techniques to save a particular factor.

The difference between our perspective and Salter's is partly due to a difference in the definition of the production function. Salter defined the production function to embrace all possible designs conceivable by existing scientific knowledge, and called the choice among these designs "factor substitution" instead of "technical change," (pp. 14-16). Salter admits, however, that "relative factor prices are the nature of signal posts representing broad influences that determine the way technological knowledge is applied to production." (p. 16)

Although we do not deny the case for Salter's definition, it is clearly not very useful in attempting to understand the process by which new technical alternatives become available. We regard technical change as any change in production coefficients resulting from the purposeful resource using activity directed to the development of new knowledge embodied in designs, materials, or organizations. In terms of this definition, it is entirely rational for competitive firms to allocate funds to develop a technology which facilitates the substitution of increasingly less expensive factors for more expensive factors. Using the above definition, Ahmad (1966) has shown that the Hicksian theory of market induced innovation can be defended with a rather reasonable assumption on the possibility of alternative innovations.

We illustrate the Ahmad argument with the aid of Figure 1. Suppose at a point of time a firm is operating at a competitive equilibrium, A or B, depending on the prevailing factor price ratio, p or m, for an isoquant, $u_o$, producing a given output; and this firm perceives multiple alternative innovations represented by isoquants, $u_1$, $u_1'$, ..., producing the same output in such a way as to be enveloped by a concave curve, U (Ahmad called it an innovation possibility curve), which can be developed by the same amount of research expenditure. 2/

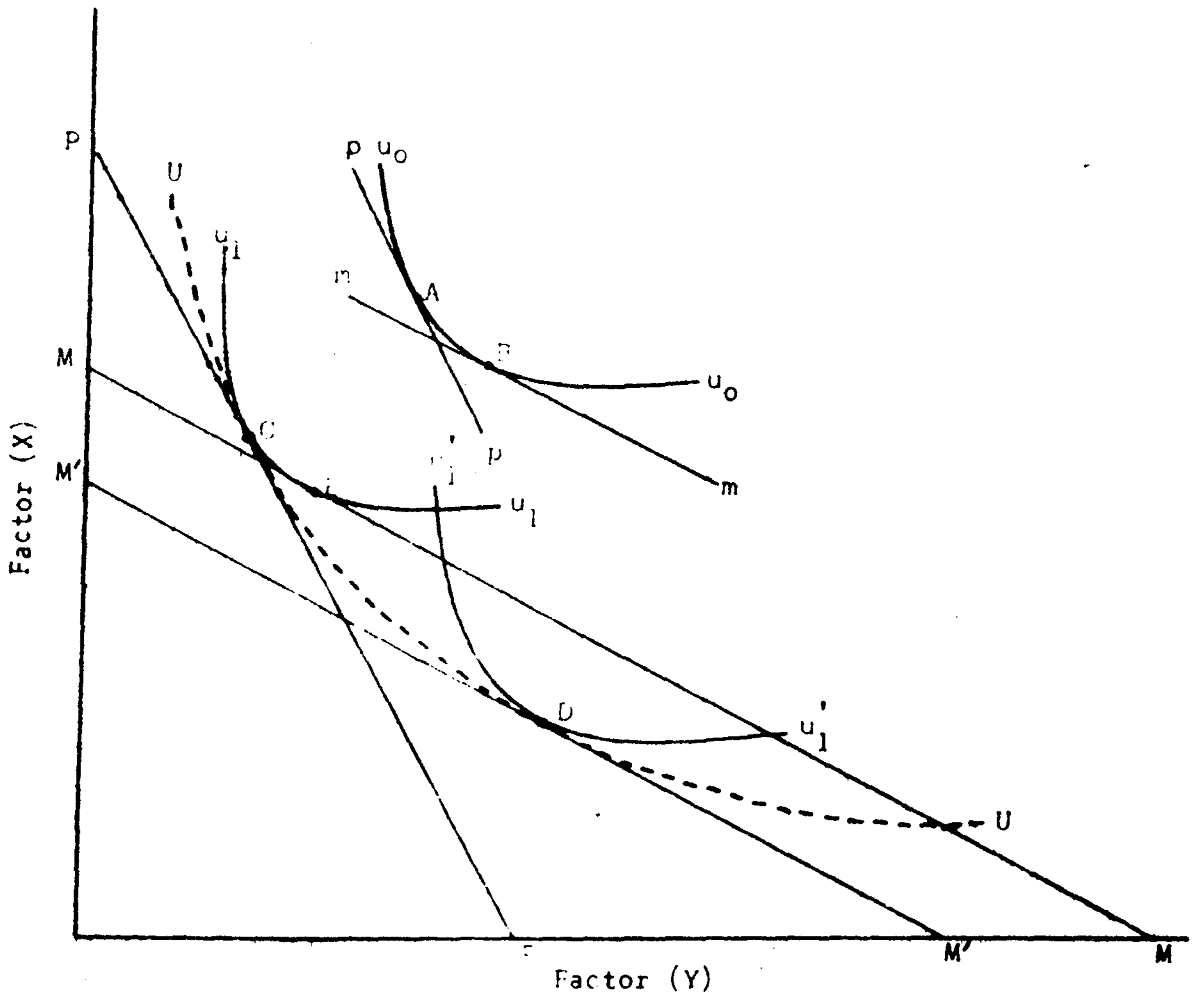



Figure 1

In order to minimize total cost for given output and given research expenditure, innovative efforts of this firm will be directed towards developing Y-saving technology ($u_1$) or X-saving technology ($u_1'$) depending on the prevailing factor price ratio, p (parallel to PP) or m (parallel to MM and MM'). If a firm facing a price ratio, m, developed a X-saving technology ($u_1'$) it can obtain an additional gain represented by the distance between M and M' compared with the case that developed a Y-saving technology ($u_1$). In this framework it is clear that, if X becomes more expensive relative to Y over time in an economy the innovative efforts of entrepreneurs will be directed towards developing a more X-saving and Y-using technology compared to the contrary case. Also in a country in which X is more expensive relative to Y than in another country innovative efforts in the country will be more directed towards X-saving and Y-using than in the other country. In this formulation the expectation of relative price change, which is central to Fellner's theory of induced innovation, is not necessary, although we do not deny that expectations may work as a powerful reinforcing agent in the actual economy.

The above theory is based on the restrictive assumption that there exists a concave innovation possibility curve (U) which can be perceived by entrepreneurs. This is not as strong a restrictive assumption as it may first appear. The innovation possibility curve need not be of a smooth well-behaved shape as drawn in Figure 1. The whole argument holds equally well for the case of two distinct alternatives. It seems reasonable to hypothesize that entrepreneurs can perceive, though vaguely, a few alternative innovation possibilities for a given research and development expenditure through consultation with staff scientists and engineers or through the suggestions of inventors. 3/

B. Induced Innovation in the Public Sector

Innovative behavior in the public sector has largely been ignored in the literature on induced innovation. There is no theory of induced innovation in the public sector. 4/ This defect is particularly critical in attempting to understand the role of technical change in agricultural development because public sector research has represented a major source of technical innovation in agriculture.

Our view of the mechanism of "induced innovation" in public sector agricultural research is similar to the Hicksian theory of induced innovation in the private sector. We extend the traditional argument by basing the innovation inducement mechanism not only on the response to changes in market prices by profit maximizing firms but also on the response by research scientists and administrators in public institutions to resource endowments and economic change.

We hypothesize that technical change is guided along an efficient path by price signals in the market, provided that (a) the prices efficiently reflect changes in the demand and supply of products and factors and (b) there exists effective interaction among farmers, public research institutions, and private agricultural supply firms. If the demand for agricultural products increases, due to the growth in population and income, prices of the inputs for which the supply is inelastic will rise relative to the prices of inputs for which the supply is elastic. Likewise, if the supply of particular inputs shifts to the right faster than others, the prices of these inputs will decline relative to the prices of other factors of production.

In consequence, technical innovations that save the factors characterized by an inelastic supply, or by slower shifts in supply, become relatively more profitable for agricultural producers. Farmers are induced, by shifts in relative prices, to search for technical alternatives which save the increasingly scarce factors of production. They press the public research institutions to develop the new technology and, also, demand that agricultural supply firms supply modern technical inputs which substitute for the more scarce factors. Perceptive scientists and science administrators respond by making available new technical possibilities and new inputs that enable farmers to profitably substitute the increasingly abundant factors for increasingly scarce factors, thereby guiding the demand of farmers for unit cost reduction in a socially optimum direction. [5/]

The dialectic interaction among farmers and research scientists and administrators is likely to be more effective when farmers are organized into politically effective local and regional farm "bureaus" or farmers associations. The response of the public sector research and extension programs to farmers' demand is likely to be greatest when the agricultural research system is highly decentralized, as in the United States. In the United States, for example, each of the state agricultural experiment stations has tended to view its function at least in part, as to maintain the competitive position of agriculture in its state relative to agriculture in other states. /‾Tichenor and Ruttan, p. 7_/ Similarly, national policy makers may regard investment in agricultural research as an investment designed to maintain the country's competitive position in world markets or to improve the economic viability of the agricultural sector producing import-substitutes. Given effective farmer organizations and a mission or client oriented experiment station system, the competitive model of firm behavior can be usefully extended to explain the response of experiment station administrators and research scientists to economic opportunities.

In this public sector induced innovation model, the response of research scientists and administrators represents the critical link in the inducement mechanism. The model does not imply that it is necessary for individual scientists or research administrators in public institutions to consciously respond to market prices or, directly to farmers' demands for research results, in the selection of research objectives. They may, in fact, be motivated primarily by a drive for professional achievement and recognition. /‾Niskanen, 1968_/ They may, in the Rosenberg terminology, view themselves as responding to an "obvious and compelling need" to remove the constraints on growth of production or on factor supplies. It is only necessary that there exists an effective incentive mechanism to reward the scientists or administrators, materially or by prestige, for their contribution to the solution of significant problems. [6/] Under these conditions, it seems reasonable to hypothesize that the scientists and administrators of public sector research programs, do respond to the need of society in an attempt to direct the results of their activity to public purpose. Furthermore, we hypothesize that secular changes in relative factor and product prices convey much of the information regarding the relative priorities which society places on the goals of research.

The response in the public research sector is not limited to the field of applied science. It is not uncommon for major breakthroughs in basic science to occur as a result of efforts to solve the problems raised by research workers in the more applied fields. [7/] It appears reasonable, therefore, to hypothesize, as a result of the interactions among the basic and applied sciences and the process by which public funds are allocated to research, that basic research tends to also be directed toward easing the limitations on agricultural production imposed by relatively scarce factors.

We do not argue, however, that technical change in agriculture is wholly of an induced character. There is a supply (an exogenous) dimension to the process as well as a demand (an endogenous) dimension. Technical change in agriculture reflects in addition to the effects of resource endowments and growth in demand, the progress of general science and technology. Progress in general science (or scientific innovation) which lowers the "cost" of technical and entrepeneurial innovations may have influences on technical change in agriculture unrelated to changes in factor proportions and in product demand. (Nelson, 1959) Even in these cases, the rate of adoption and the impact on productivity of autonomous or exogenous changes in technology will be strongly influenced by the conditions of resource supply and product demand as these forces are reflected through factor and product markets. /‾Schmookler, 1966_7

C. Institutional Innovation

Extension of the theory of "induced innovation" to explain the behavior of public research institutions represents an essential link in the construction of a theory of induced development. In the induced development model advances in mechanical and biological technology respond to changing relative prices of factors, and to changes in the prices of factors relative to products, to ease the constraints on growth imposed by inelastic supplies of land or labor. Neither this process, nor its impact, is confined to the agricultural sector. Changes in relative prices in any sector of the economy act to induce innovative activity, not only by private producers but also by scientists in public institutions, in order to reduce the constraints imposed by those factors of production which are relatively scarce.

We further hypothesize that the institutions that govern the use of technology or the "mode" of production can also be induced to change to enable both individuals and society to take fuller advantage of new technical opportunities under favorable market conditions. [8/] The Second Enclosure Movement in England represents a classical illustration. The issuance of the Enclosure Bill facilitated the conversion of communal pasture and farmland into single private farm units, thus encouraging the introduction of an integrated crop-livestock "new husbandry" system. The Enclosure Acts can be viewed as an institutional innovation designed to exploit the new technical opportunities opened up by innovations in crop rotation utilizing the new fodder crops (turnip and clover), in response to the rising food prices. /̅C. Peter Timmer, 1969_7

A major source of institutional change has been an effort by society to internalize the benefits of innovative activity to provide economic incentives for productivity raising activity. In some cases, institutional innovations have involved the reorganization of property rights, in order to internalize the higher income streams resulting from the innovations. The modernization of land tenure relationships, involving a shift from share tenure to lease tenure and owner-operator systems of cultivation in much of western agriculture, can be explained, in part, as a shift in property rights designed to internalize the gains of innovative activity by individual farmers.

We view institutional change as resulting from the efforts of economic units (firms and households) to internalize the gains and externalize the costs of innovative activity; and by society to force economic units to internalize the costs and externalize the gains. Where internalization of the gains of innovative activity are difficult to achieve, institutional innovations involving public sector activity become essential. The socialization of much of agricultural research, particularly the research leading to advances in biological technology, represents an example of a public sector institutional innovation designed to realize for society, the potential gains from advances in agricultural technology.

Profitable opportunities, however, do not necessarily lead to immediate institutional innovations. Usually the gains and losses from technical and institutional change are not distributed neutrally. There are limits on the extent to which group behavior can be mobilized to achieve common or group interests. /‾Olson, 1968_/ The process of transforming institutions in response to technical and economic opportunities generally involves time lags, social and political stress, and, in some cases, disruption of social and political order. Economic growth ultimately depends on the flexibility and efficiency of society to transform itself in response to technical and economic opportunities.

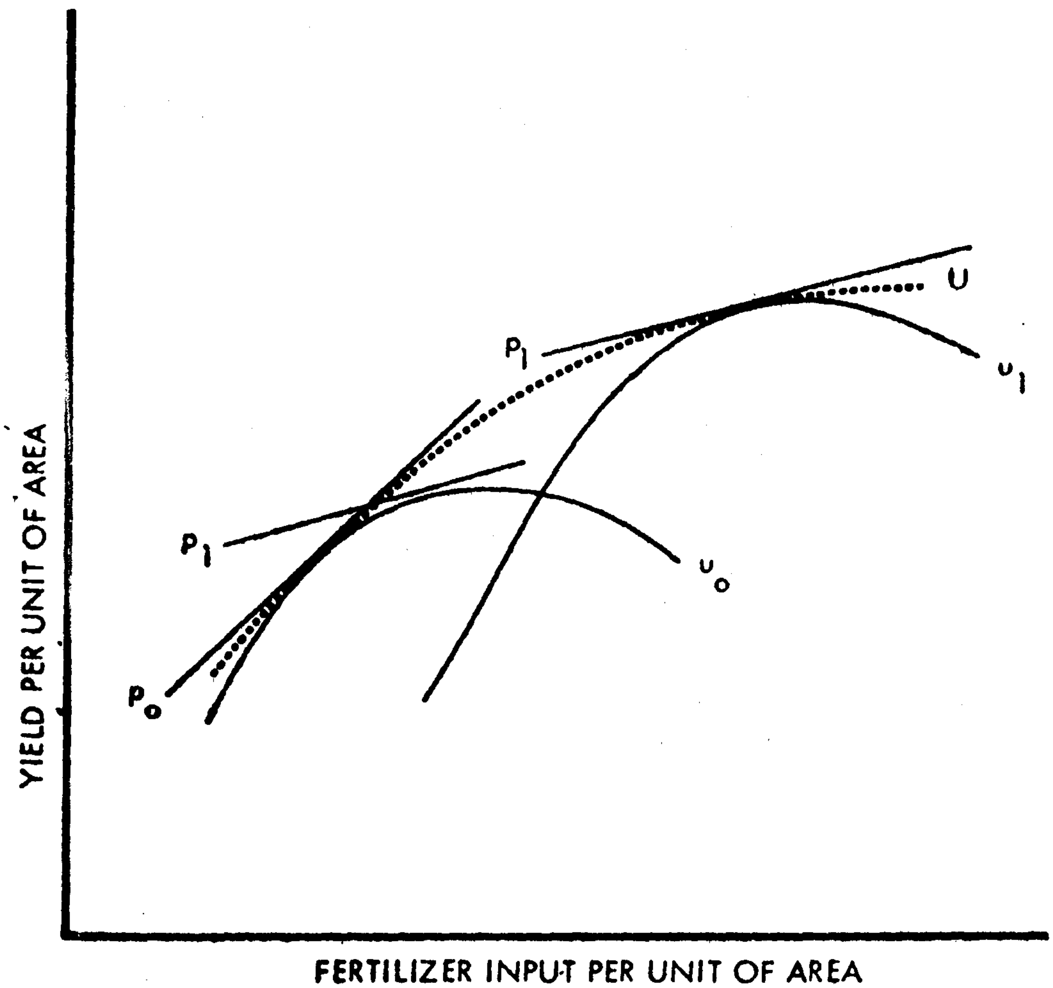
## III. An Operational Model of Induced Innovation in Agriculture

A clear requisite for agricultural productivity growth is the capacity of the agricultural sector to adapt to a new set of factor and product prices. These changes may arise as a result of the growth of demand pressing against factor supplies or as a result of changes in factor prices resulting from shifts in the supply functions for factor inputs. Adaptation by the agricultural sector to changes in factor-factor and factor-product price ratios involves, in the perspective outlined in the previous section, not only the movement along a fixed production surface but also innovations leading to a new production surface.

For example, even if fertilizer prices decline relative to the prices of land and farm products, increases in the use of fertilizer may be limited unless new crop varieties are developed which are more responsive to high levels of biological and chemical inputs than traditional varieties. For illustrative purposes, the relationship between fertilizer use and yield may be drawn, as in Figure 2, letting $u_o$ and $u_1$ represent the curve of "indigenous" and "improved" varieties respectively. For farmers facing $u_o$ a decline in the fertilizer prices relative to the product price from $p_o$ to $p_1$ would not be expected to result in much increase in the level of fertilizer use or in yield per unit area. The full impact of a decline in the fertilizer price on fertilizer use and output can be fully realized only if $u_1$ is made available to farmers as a result of innovations leading to more responsive crop varieties.

Conceptually it is possible to draw a curve such as U in Figure 2 which is the envelope of individual response curves, each representing a different variety of the same crop characterized by a different degree of response to fertilizer. We identify this curve as a "meta-production function" or a "potential production function." [9] We do not insist that the meta-production function is inherent in nature or that it remains completely stable over time. It may shift with the general accumulation of scientific knowledge. We do consider, however, that it is operationally feasible to assume a reasonable degree of stability for the time range that is relevant for many empirical analyses, because shifts in the meta-production function are much slower than adjustments along the surface, or to the surface from below the meta-production function.

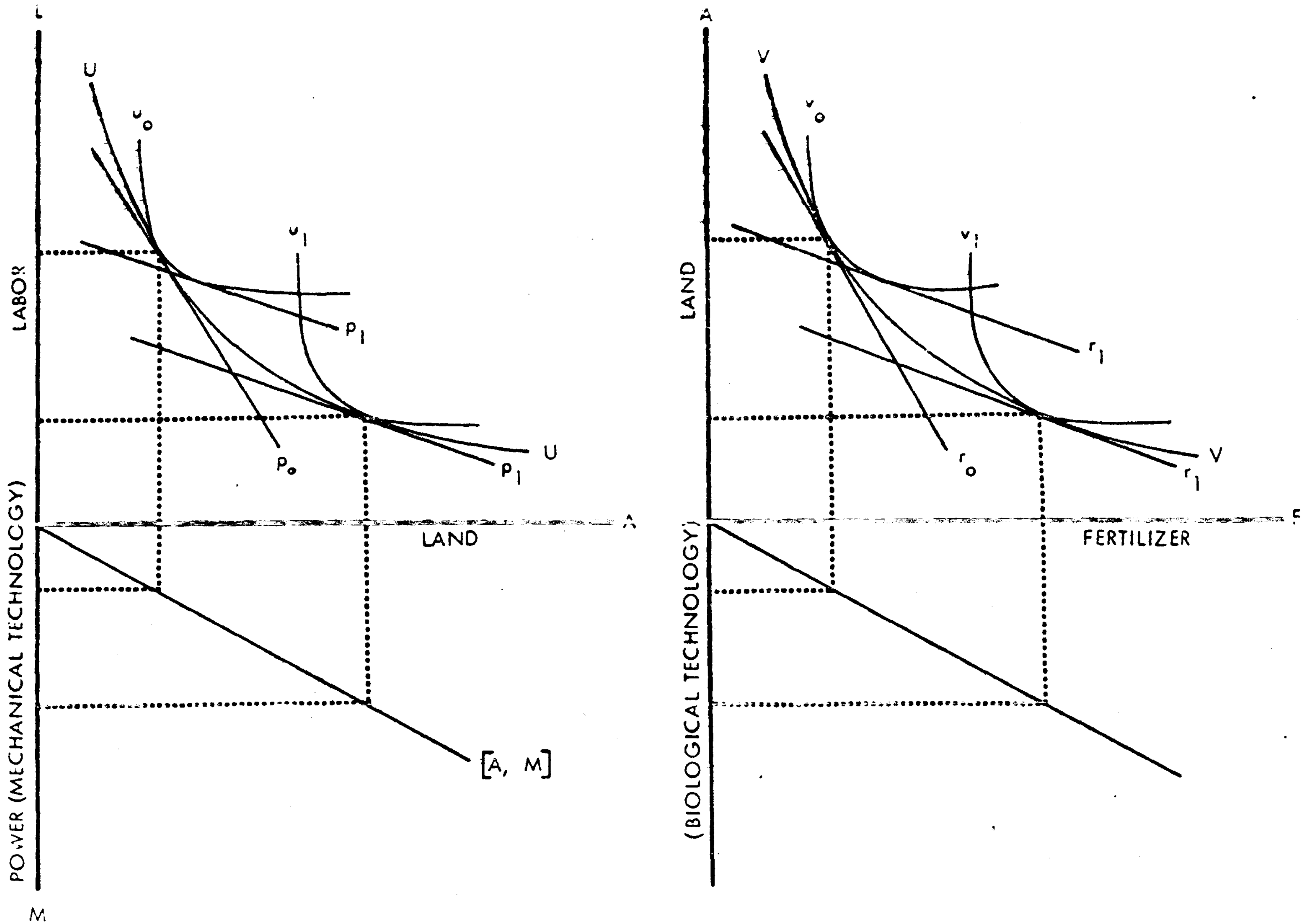
Our basic hypothesis that adjustments in factor proportions, in response to changes in relative prices, represent "non-neutral" movements along the iso-product surface of a meta-production function is further illustrated in Figure 3.



YIELD PER UNIT OF AREA
FERTILIZER INPUT PER UNIT OF AREA
U
$p_1$
$u_1$
$p_1$
$u_o$
$p_o$


Figure 2

Figure 3


L
U
$u_o$
$u_1$
LABOR
$p_1$
$p_o$
U
$p_1$
LAND
A
POWER (MECHANICAL TECHNOLOGY)
M
[A, M]
A
V
$v_o$
$v_1$
LAND
$r_1$
$r_o$
V
$r_1$
FERTILIZER
F
(BIOLOGICAL TECHNOLOGY)

U in Figure 3 represents the land-labor isoquant of the meta-production function which is the envelope of less elastic isoquants such as $u_o$ and $u_1$ corresponding to different types of machinery or technology. A certain technology represented by $u_o$ (e.g., reaper) is created when a price ratio, $p_o$, prevails a certain length of time. When the price ratio changes from $p_o$ to $p_1$, another technology represented by $u_1$ (e.g., combine) is induced in the long-run, which gives the minimum cost of production for $p_o$.

The new technology represented by $u_1$, which enables enlargement of the area operated per worker, generally corresponds to higher intensity of power per worker. This implies the complementary relationship between land and power, which may be drawn as a line representing a certain combination of land and power [A , M]. In this simplified presentation, mechanical innovation is conceived as the substitution of a combination of land and power [A , M] for labor (L) in response to a change in wage relative to an index of labor and machinery prices, though, of course, in actual practice land and power are substitutable to some extent.

In the same context, the relation between the fertilizer-land price ratio and bio-chemical innovations represented by the development of crop varieties which are more responsive to application of fertilizers is illustrated in Figure 3. V represents the land-fertilizer isoquant of the meta-production function, which is the envelope of less elastic isoquants such as $v_o$ and $v_1$ corresponding to varieties of different fertilizer responsiveness. A decline in the price of fertilizer relative to the price of land from $r_o$ to $r_1$ makes it more profitable for farmers to search for crop varieties which are described by isoquants to the right of $v_0$. They also press public research institutions to develop new varieties. Through a kind of dialectic process of interaction among farmers and experiment station workers a new variety such as that represented by $v_1$ will be developed.

All mechanical innovations are not necessarily motivated by labor saving incentives nor are all biological innovations necessarily motivated incentives to save land. For example, in Japan horse plowing was initially introduced as a device to permit deeper cultivation so as to increase yield per hectare. In the United States in recent years, attempts have been made to develop crop varieties suitable for mechanical harvesting. At the most sophisticated level, technological progress may depend on a series of simultaneous advances in both biological and mechanical technology. In the case of the mechanization of tomato harvesting, the plant breeding research and the engineering research was conducted cooperatively, in order to invent new machines capable of harvesting the tomatoes specifically bred to facilitate mechanical harvesting. /_Rasmussen, 1968_7 In our judgement, however, the dominant factor leading to the growth of labor productivity has been progress in mechanization, and the dominant factor leading to growth in land productivity has been progress in biological technology.

## IV. Testing the Induced Innovation Hypothesis

The plausibility of the induced innovation hypothesis is reinforced by the data on the relationship between fertilizer-rice price ratios and yields per hectare in Japan and other Asian countries shown in Table 1. It shows that (a) the higher rice yield per hectare in Japan than in Southeast Asian countries is associated with a considerably lower price of fertilizer relative to the price of rice, (b) a high inverse correlation between the rice yield per hectare and the fertilizer-rice price ratio in the Japanese time series data, (c) a substantial decline in the fertilizer-rice price ratio from 1955-57 to 1963-65 in other Asian countries, associated with only small gains in rice yield per hectare, and (d) fertilizer-rice price ratios in the Southeast Asian countries today that are much more favorable than those that prevailed in Japan at the beginning of this century and earlier.

It seems reasonable to infer that the considerable differeces in the rice yield between Japan and the Southeast Asian countries represent different positions on the meta-production functions. The consistent rise in rice yield per hectare accompanied by the consistent decline in fertilizer-rice price ratio in the historical experience of Japan can be interpreted as reflecting movement along the meta-production function.

Why, then did, the rice yields per hectare of the Southeast Asian countries not increase significantly from 1955-57 to 1963-65 despite the substantial decline in the fertilizer-rice price ratio? Also, why did rice yields in these countries remain low in spite of a price ratio more favorable than in Japan at the beginning of this century? This

Table 1. Fertilizer-rice price ratios and rice yields per hectare in selected Asian countries and in Japan 1883-1962.

| Country | Currency unit | Price of Fertilizer: per m. ton of nitrogen (1) | Price of Rice: per m. ton of milled rice (2) | Fertilizer-rice price ratio (1) / (2) | Rice yield per hectare m. ton of paddy (3) |
|---|---|---|---|---|---|
| Cross-country comparison | | | | | |
| 1963-65 | | | | | |
| India | rupee | 1750 | 595[a] | 2.9 | 1.5 |
| | | | 723[b] | 2.4 | |
| Pakistan (East) | rupee | 1632 | 780 | 2.1 | 1.7 |
| Philippines | peso | 1048 | 530 | 2.0 | 1.3 |
| Thailand | U. S. dollar | 229 | 70 | 3.3 | 1.6 |
| Japan | 1000 yen | 97 | 99 | 1.0 | 5.0 |
| 1955-57 | | | | | |
| India | rupee | 1650 | 417[a] | 4.0 | 1.3 |
| | | | 505[b] | 3.3 | |
| Pakistan (East) | rupee | 1322 | 511 | 2.6 | 1.4 |
| Philippines | peso | 962 | 352 | 2.7 | 1.1 |
| Thailand | U. S. dollar | 393 | 79 | 5.0 | 1.4 |
| Japan | 1000 yen | 119 | 77 | 1.5 | 4.8 |
| Japan's time series | | | | | |
| 1958-62 | 1000 yen | 100 | 85 | 1.2 | 4.9 |
| 1953-57 | 1000 yen | 113 | 75 | 1.5 | 4.2 |
| 1933-37 | yen | 566 | 208 | 2.7 | 3.8 |
| 1923-27 | yen | 1021 | 277 | 3.7 | 3.6 |
| 1913-17 | yen | 803 | 125 | 6.4 | 3.5 |
| 1903-07 | yen | 815 | 106 | 7.7 | 3.1 |
| 1893-97 | yen | 670 | 69 | 9.7 | 2.6 |
| 1883-87 | yen | 450 | 42 | 10.7 | |

Notes to Table 1.

a. Price at Sambalpur (Orissa)

b. Price at Bombay

(1) Price paid by farmers. Cross country data: average unit price of nitrogen contained in ammonium sulphate; 1963-65 data are the averages for 1962/63 - 1964/65; 1955/57 data are the data of 1956/57; government subsidies of 50 percent for 1963-65 and of 40 percent for 1955-57 are added to Pakistan's original data. Japan data: average unit price of nitrogen contained in commercial fertilizers.

(2) This is the wholesale price at milled rice basis. Japan data are converted from brown rice basis to a milled rice basis assuming 10 percent for processing cost.

(3) Japan data are converted from a brown rice basis to a milled rice basis assuming 0.8 for a conversion factor. 

Source:

Cross-country data: FAO, Production Yearbook, various issues.

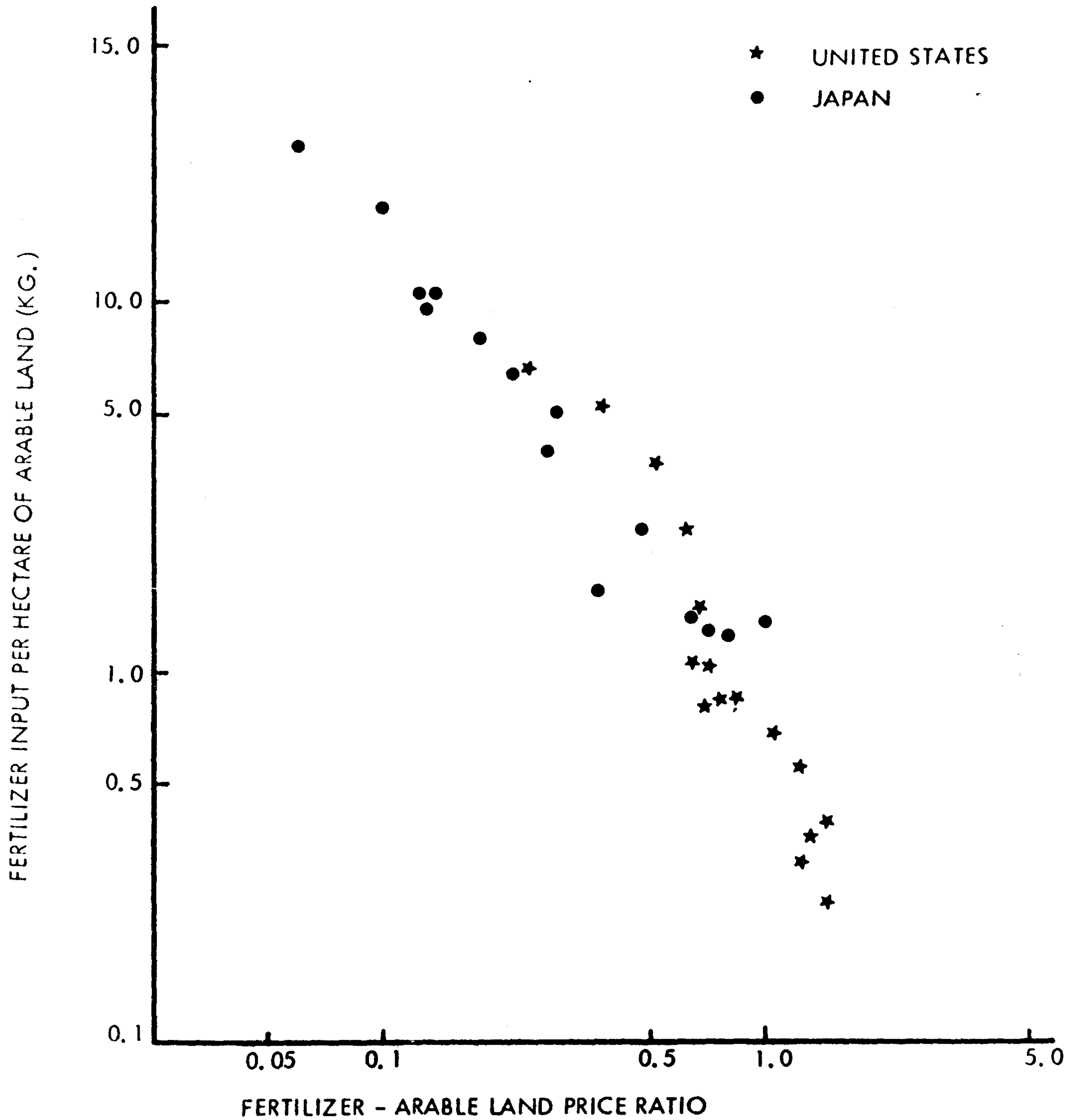
Japan data: Kazushi Ohkawa, et. al. (ed.), Long-term Economic Statistics of Japan, Vol. 9, (Tokyo: Toyokeizaishimposha, 1966), pp. 202-203; Nobufumi Kayo (ed.) Nihon Nogyo Kisotokei, (Tokyo: Norin Suisangyo Seisankojokaigi, 1958), p. 514; Toyokeizaishimposha, Bukku Yoran, (Tokyo, 1967), p. 80; Institue of Developing Economies, One Hundred Years of Agricultural Statistics in Japan, (Tokyo: 1969), p. 136.

must be attributable to the time lag required to move along the meta-production function, which tends to be extremely long in the absence of adequate institutions and human capital to generate the flow of new techniques. In terms of Figure 2 the countries in the Southeast Asia seem to have been trapped at the point of tangency of $p_1$ and $u_0$.

The development of fertilizer responsive rice varieties requires substantial investment in research before more responsive varieties become available to farmers. By the late 1960's more responsive varieties were becomming available throughout South and Southeast Asia. /̄ Dana C. Dalrymple, 1969_7 We would expect the effect to be reflected in the new data that will become available in the early 1970's.

The plausibility of the induced innovation hypothesis is further strengthened by the data plotted in Figure 4. The data shows the relation between fertilizer input per hectare of arable land and the fertilizer arable land price ratio. In spite of the enormous differences in climate and other environmental conditions, and in spite of the enormous differences in social organization, the relationship between these two variables is essentially identical in both countries. Given our knowledge of the fertilizer response curve for individual crop varieties it is not plausible to assume that these observations could have been generated by movement along a common long run production function that has been available to farmers in both countries over the 1880-1969 period. [10/] The only explanation that seems plausible, is that the downward drift in the fertilizer-land price ratio has induced the development of more fertilizer responses crop varieties. In terms of Figure 2.0 it seems plausible that the data presented in Figure 4 were generated by shifts in individual fertilizer response curves along a

Figure 4. Relation between fertilizer input per hectare of arable land and fertilizer - arable land price ratio ( = hectares of arable land which can be purchased by one ton of N + $P_2O_5$+ $K_2O$ contained in commercial fertilizers), the United States and Japan: quinquennial observations for 1880-1960.



common "meta-production function" in response to a decline in the fertilizer land price ratio.

As an additional test of the induced innovation hypothesis, we have tried to determine the extent to which the variations in factor proportions, as measured by the land-labor, power-labor, and fertilizer-land ratios, can be explained by changes in factor price ratios in Japanese and United States agriculture for 1880-1960. In a situation characterized by a fixed technology, however, it seems reasonable to presume that the elasticities of substitution among factors are small, and this permits us to infer that innovations were induced, if the variations in these factor proportions are consistently explained by the changes in price ratios. [11/] The historically observed changes in those factor proportions in the United States and Japan are so large that it is hardly conceivable that these changes represent substitution along a given production surface describing a constant technology (Table 2).

In order to have an adequate specification of the regression form, we have to be able to infer the shape of the underlying meta-production function and the functional form of the relationship between changes in the production function and in factor price ratios. Because of a lack of adequate a priori information, we have simply specified the regression in log-linear form with little claim for theoretical justification. [12/] If we can assume that production function is linear homogeneous, the factor proportions can be expressed in terms of factor price ratios alone and are independent of product prices.

Table 2. Changes in output, productivity, and factor-factor ratios in agriculture: The United States and Japan, 1880-1960[a]

| | 1880 | 1900 | 1920 | 1940 | 1960 | Annual compound rate of growth 1880-1960 |
|---|---|---|---|---|---|---|
| | | | | | | percent |
| United States | | | | | | |
| Output index (1880=100)[b] | 100 | 155 | 180 | 232 | 340 | 1.5 |
| Productivity index (1880=100) | | | | | | |
| Total productivity[c] | 100 | 112 | 105 | 128 | 179 | 0.7 |
| Output per male worker | 100 | 125 | 141 | 217 | 680 | 2.4 |
| Output per hectare of arable land | 100 | 91 | 72 | 94 | 143 | 0.4 |
| Factor-factor ratios | | | | | | |
| Arable land area per male worker (hectare) | 10 | 13 | 18 | 22 | 46 | 2.0 |
| Power per male worker (horsepower)[d] | 1.8 | 2.2 | 3.0 | 6.7 | 40.9 | 3.9 |
| Fertilizer per hectare (kg. in $N+K_2O_5+P_2O$) | 1.5 | 3.3 | 5.0 | 9.5 | 41.6 | 4.1 |
| Japan | | | | | | |
| Output index (1880=100)[b] | 100 | 149 | 232 | 264 | 358 | 1.6 |
| Productivity index | | | | | | |
| Total productivity[c] | 100 | 142 | 195 | 208 | 229 | 1.0 |
| Output per male worker | 100 | 152 | 238 | 326 | 453 | 1.9 |
| Output per hectare or arable land | 100 | 135 | 184 | 205 | 280 | 1.3 |
| Factor-factor ratios (1880=100) | | | | | | |
| Arable land area per male worker (hectares) | 0.61 | 0.68 | 0.79 | 0.96 | 0.97 | 0.6 |
| Power per male worker (horsepower)[d] | 0.15 | 0.16 | 0.17 | 0.29 | 1.01 | 2.4 |
| Fertilizer per hectare (kg. in $N+K_2O_5+P_2O$) | 13 | 17 | 63 | 115 | 260 | 3.8 |

[a]Flow variables such as output and fertilizer are five year averages centering on years shown. Stock variables such as land and labor are measured in years shown.
[b]Gross output net of seeds and feed.
[c]Output divided by total input.
[d]Sum of draft animal power and tractor power.

Source: Yujiro Hayami, "Resource Endowments and Technological Change in Agriculture: U.S. and Japanese Experiences in International Perspective," American Journal of Agricultural Economics, Vol. 51, No. 5, December 1969, p. 1294.

Considering the crudeness of data and the purpose of this analysis, we used quinquennial observations (stock variables measured at every five years' interval and flow variables averaged for five years) instead of annual observations for the regression analysis. A crude form of adjustment is built into our model, since our data are quinquennial observations and prices are generally measured as the averages of the past five years preceeding the year when the quantities are measured (e.g., the number of workers in 1910 is associated with the 1906-1910 average wage).

The results of regression analyses are summarized in Tables 3 and 4. Table 3a presents the regressions for land-labor and power-labor proportions for the United States. In those regressions we originally included the fertilizer-labor price ratio as well. But, probably due to high intercorrelation between machinery and fertilizer prices, either the coefficients for the fertilizer-labor price ratio were insignificant or resulted in implausible results for the other coefficients. 13/ This variable was dropped in the subsequent analysis.

In Table 3a more than 80 percent of the variation in the land-labor ratio and in the power-labor ratio is explained by the variation in their price ratios. The coefficients are all negative and are significantly different from zero at the standard level of significance except the land price coefficients in Regressions (2) and (4). Such results indicate that in U.S. agriculture the marked increases in land and power per worker over the past 80 years have been closely associated with declines in the prices of land and of power and machinery relative

Table 3a. Regressions of Land-Labor Ratio and Power-Labor Ratio on Relative Factor Prices: United States, 1880-1960 Quinquennial Observations.

| Regression Number | Dependent Variables | Coefficients of Price of: Land Relative to Farm Wage | Coefficients of Price of: Machinery Relative to Farm Wage | $\bar{R}^2$ | $\bar{S}$ | d |
|---|---|---|---|---|---|---|
| | Land-labor ratio: | | | | | |
| (1) | Agricultural land per male worker | -0.451<br>(0.215) | -0.486<br>(0.120) | .828 | .0844 | 1.29 |
| (2) | Arable land per male worker | -0.035<br>(0.180) | -0.708<br>(0.101) | .882 | .0706 | 1.37 |
| (3) | Agricultural land per worker | -0.492<br>(0.215) | -0.463<br>(0.120) | .828 | .0789 | 1.34 |
| (4) | Arable land per worker | -0.077<br>(0.182) | -0.686<br>(0.102) | .879 | .0713 | 1.41 |
| | Power-labor ratio: | | | | | |
| (5) | Horsepower per male worker | -1.279<br>(0.475) | -0.920<br>(0.266) | .827 | .1865 | 1.33 |
| (6) | Horsepower per worker | -1.321<br>(0.474) | -0.898<br>(0.265) | .828 | .1863 | 1.36 |

Equations are linear in logarithm. Inside of the parentheses are the standard errors of the estimated coefficients.

Table 3b. Regressions of Land-Labor Ratio and Power-Labor Ratio on Relative Factor Prices: Japan, 1880-1960 Quinquennial Observations.

| Regression Number | Dependent Variables | Coefficients of Price of: Land Relative to Farm Wage | Coefficients of Price of: Machinery Relative to Farm Wage | $\bar{R}^2$ | $\bar{S}$ | d |
|---|---|---|---|---|---|---|
| | Land-labor Ratio: | | | | | |
| (7) | Arable land per male worker | 0.159<br>(0.110) | -0.219<br>(0.041) | .751 | .0347 | 1.17 |
| (8) | Arable land per worker | 0.230<br>(0.049) | -0.155<br>(0.019) | .914 | .0156 | 1.71 |
| | Power-Labor Ratio: | | | | | |
| (9) | Horsepower per male worker | -0.665<br>(0.261) | -0.299<br>(0.685) | .262 | .2191 | 0.60 |
| (10) | Horsepower per worker | -0.601<br>(0.236) | -0.228<br>(0.620) | .266 | .1982 | 0.61 |

Equations are linear in logarithms. Inside of the parentheses are the standard errors of the estimated coefficients.

to the farm wage rate. The hypothesis that land and power should be treated as complementary factors is confirmed by the negative coefficients. This seems to indicate that in addition to the complementarity along a fixed production surface, mechanical innovations which raise the marginal rate of substitution of power for labor tend to also raise the marginal rate of substitution of land for labor.

The results of the same regressions for Japan (Table 3b) are much inferior in terms of statistical criteria. This is probably because the ranges of observed variation in the land-labor and in the power-labor ratios are too small in Japan to detect any significant relationship between the factor proportions and price ratios. It may also reflect the fact that the mechanical innovations developed in Japan were motivated by a desire to increase yield rather than as a substitute for labor.

The results of the regression analyses of the determinants of fertilizer input per hectare of arable land for the United States are presented in Table 4a. The results indicate that variations in the fertilizer-land price ratio alone explains almost 90 per cent of the variation in fertilizer use. It is also shown that the wage-land price ratio is a significant variable, indicating a substitution relationship between fertilizer and labor. Over a certain range, fertilizer input can be substituted for human care for plants (e.g., weeding). A more important factor in Japanese history would be the effects of substitution of commercial fertilizer for labor allocated to self-supplied fertilizers.

A comparison of Table 4b with Table 4a indicates a striking similarity in the structure of demand for fertilizer in the United States and Japan. The results in these two tables seem to suggest that, despite enormous differences in climate and initial factor endowments, the agricultural production function, the inducement mechanism of innovations, and the response of farmers to economic opportunities have been essentially the same in the United States and Japan. [14/]

Overall, the results of the data from Japan and the United States examined in this section are consistent with the induced innovation hypothesis. Agricultural growth in the United States and Japan during the period 1880-1960 can best be understood when viewed as a dynamic factor substitution process. Factors have been substituted for each other along a meta-production function in response to long-run trends in relative factor prices. Each point on the meta-production surface is characterized by a technology which can be described in terms of specific sources of power, types of machinery, crop varieties and animal breeds. Movements along this meta-production surface involve innovations. These innovations have been induced, to a significant extent, by the long-term trends in relative factor prices.

Table 4a. Regressions of Fertilizer Input Per Hectare of Arable Land on Relative Factor Prices: United States, 1880-1960 Quinquennial Observations.

| Regression Number | Coefficients of Prices of: Fertilizer Relative to Land | Labor Relative to Land | Machinery Relative to Land | $\bar{R}^2$ | $\bar{S}$ | d |
|---|---|---|---|---|---|---|
| (11) | -1.622<br>(0.200) | 1.142<br>(0.275) | 0.014<br>(0.286) | .950 | .1042 | 2.08 |
| (12) | -1.615<br>(0.134) | 1.138<br>(0.255) | -- | .954 | .0968 | 2.09 |
| (13) | -1.951<br>(0.166) | -- | -- | .895 | .1406 | .77 |
| (14) | -1.101<br>(0.184) | 1.134<br>(0.173) | -0.350<br>(0.214) | .969 | .0816 | 1.38 |
| (15) | -1.357<br>(0.102) | 1.019<br>(0.168) | -- | .970 | .0832 | 1.15 |
| (16) | -1.707<br>(0.154) | -- | -- | .884 | .1481 | .84 |

Equations are linear in logarithms. Inside of the parentheses are the standard errors of the estimated coefficients.

Table 4b. Regressions of Fertilizer Input Per Hectare of Arable Land on Relative Factor Prices: Japan 1880-1960 Quinquennial Observations.

| Regression Number | Coefficients of Price of: Fertilizer Relative to Land | Labor Relative to Land | Machinery Relative to Land | $\bar{R}^2$ | $\bar{S}$ | d |
|---|---|---|---|---|---|---|
| (17) | -1.437<br>(0.238) | 0.662<br>(0.244) | 0.236<br>(0.334) | .973 | .0865 | 2.45 |
| (18) | -1.274<br>(0.057) | 0.729<br>(0.220) | -- | .974 | .0810 | 2.45 |
| (19) | -1.211<br>(0.071) | -- | -- | .953 | .1036 | 1.52 |
| (20) | -1.248<br>(0.468) | 1.217<br>(0.762) | -0.103<br>(0.708) | .878 | .1820 | 1.76 |
| (21) | -1.313<br>(0.131) | 1.145<br>(0.556) | -- | .888 | .1670 | 1.79 |
| (22) | -1.173<br>(0.126) | -- | -- | .860 | .1794 | 1.52 |

Equations are linear in logarithms. Inside of parentheses are the standard errors of the estimated coefficients.

## VI. Conclusion

The results of this study indicate that the enormous changes in factor proportions which have occurred in the process of agricultural growth in the United States and Japan are explainable in terms of changes in factor price ratios. In spite of strong reservations regarding the data and the methodology, when we relate the results of the statistical analysis to historical knowledge of the progress in agricultural technology, we conclude that the observed changes in factor input ratios represent a process of dynamic factor substitution accompanying changes in the production surface induced by the changes in relative factor prices.

This conclusion, if warranted, represents a key to the understanding of the success of agricultural growth in Japan and the United States. In both countries agricultural growth was associated with contrasting changes in land-labor price ratios. Prices of agricultural inputs such as fertilizer and machinery supplied by the nonfarm sector tended to decline relative to the prices of land and labor. Such trends induced farmers, public research institutions and private agricultural supply firms to search for new production possibilities that would offset the effects of the relative price changes. Mechanical innovations of a labor-saving type were, thus, induced in the United States and biological innovations of a yield-increasing type were induced in Japan. After the 1930's the decline in fertilizer price was so dramatic that innovation in U.S. agriculture shifted from a predominant emphasis on mechanical technology to the development of new biological innovations, in the form of crop varieties that were highly responsive to the lower cost fertilizer.

Rapid growth in agriculture in both countries could not have occurred without such dynamic factor substitution. If factor substitution had been limited to substitution along a fixed production surface, agricultural growth would have been severely limited by the inelastic supply. Development of a continuous stream of new technology which altered the production surface to conform to long term trends in factor prices was the key to the success in agricultural growth in the United States and Japan.

Such inducement of technological change was not attained without cost. The United States and Japan are among the few countries which have made a substantial national effort in agricultural research and extension for the past 100 years. The history of agricultural research and extension in the United States is relatively well known. Japan's efforts to develop agricultural techniques were no less significant than in the United States.[15] The important point in the context of this paper is that in both countries such efforts were directed appropriately in terms of relative factor prices.

For both the United States and Japan vigorous growth in the industries which supplied machinery and fertilizers at continuously declining relative prices has been an indispensable element in the process of agricultural growth. The development of effective research and extension systems to exploit the opportunities created by industrial development has also been of critical importance. In the absence of fertilizer responsive crop varieties only limited economic gains could have been realized from lower fertilizer prices. The success in agricultural growth in both the United

States and Japan seems to lie in the capacity of their farmers, research institutions and farm supply industries to exploit new opportunities according to the information transmitted through relative price changes.

The significance of our findings in terms of this conference is that they reinforce the emerging perspective that major advances in the understanding of economic development processes and in the design of development policies must be more solidly based on an understanding of micro-economic process and behavior. The pervasive impact of economic forces on the direction of innovative activity on the part of farmers, the firms that supply the industrial inputs to agriculture, and the public sector research and extension institutions that produce and disseminate the new knowledge leading to technical change is of particular significance. The theory of induced innovation in the public sector remains somewhat uncertain. The model presented here does not possess formal elegance. Yet it has added significantly to our power to interpret the process of agricultural development in Japan and the United States. In both the United States and Japan the public sector research and education institutions designed to serve agriculture have responded effectively to economic forces in directing their activities to releasing the constraints on agricultural growth imposed by inelastic factor supplies.

## FOOTNOTES

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1/ See W. E. G. Salter [1960, pp. 43-44]. For the major land marks in the discussion generated by Salter see Syed Ahmad [1966, Sept. 1967, Dec. 1967]; John S. Chipman [1970]; William Fellner [1961, 1967]; Charles Kennedy [1964, 1966, 1967]; Paul A. Samuelson [1965, 1966].

2/ Whether the innovation possibility curve is exogenously determined or is dependent of a past innovation does not affect the present discussion, although it is a crucial problem in developing a theory of distributed shares. See discussions by Kennedy [1967] and Ahmad [1967].

3/ Nathan Rosenberg /‾1969_/ has suggested a theory of induced technical change based on "obvious and compelling need" instead of relative factor scarcity and relative factor prices. In the Rosenberg model research is directed toward removing constraints that limit growth. C. Peter Timmer has pointed out to us in a letter that the Rosenberg model is consistent with the model outlined here since, in a linear programming sense, the constraints represent the "dual" of the factor prices.

4/ There is a growing literature on public research policy. Much of this literature tends to be normative rather than analytical. For a recent survey see Richard R. Nelson, Merton J. Peck and Edward D. Kalachek /‾1967, pp. 151-211._/ They view public sector research activities as having arisen from three considerations: (a) fields where the public interest is believed to transcend private incentive (such as health and aviation); (b) industries where the individual firm is too small to capture the benefits from research (agriculture and housing); (c) broad scale support for basic research and science education.

5/ The literature on research resource allocation in agriculture is relatively limited. See however, Walter L. Fishel (1971) and Willis L. Peterson (1969).

6/ The issue of incentive is a major issue in many developing economies. In spite of limited scientific and technical manpower many countries have not succeeded in developing a system of economic and professional reward that permits them to have access to, or make effective use of, the resources of scientific and technical manpower that are potentially available to them.

7/ The symbiotic relationship between basic and applied research can be illustrated by the relation between work in (a) genetics and plant physiology and (b) plant breeding at the International Rice Research Institute. The geneticist and the physiologist are involved in research designed to advance understanding of the physiological processes by which plant nutrients are transformed into grain yield and of the genetic mechanisms or processes involved in the transmission from parents to progenies of the physiological characteristics of the rice plant which affect grain yield. The rice breeders utilize this knowledge from genetics and plant physiology in the design of crosses and the selection of plants with the desired growth characteristics, agronomic traits, and nutritional value. The work in plant physiology and genetics is responsive to the need of the plant breeder for advances in knowledge related to the mission of breeding more productive varieties of rice.

8/ At this point we share the Marxian perspective on the relationship between technological change and institutional development. /_Karl Marx, p. 406n; Mandel Morton Bober_/ We do not accept the Marxian perspective regarding the monolithic sequences of evolution based on clear-cut class conflicts. For two recent attempts to develop broad historical generalizations regarding the relation between institutions and economic forces, see John Hicks, /_1969_/ and Douglass C. North and Robert Paul Thomas. /_1970_/

9/ The "metaproduction function" can be regarded as the envelope of commonly conceived neo-classical production functions. In the short run, in which substitution among inputs is circumscribed by the rigidity of capital and equipment, production relationship can be described by an activity with relatively fixed factor-factor and factor-product ratios. In the long run, in which the constraints exercised by existing capital disappear and are replaced by the fund of available technical knowledge, including all alternative feasible factor-factor and factor-product combinations, production relationships can be adequately described by the neoclassical production function. In the secular period, in which the constraint given by the available fund of technical knowledge is further relaxed to admit all potentially discoverable possibilities, production relationships can best be described by a metaproduction function which describes all conceivable technical alternatives that might be discovered. For further discussion of short-run, long-run and secular production processes are Murray Brown [1966, pp. 95-109]. The relationship between U and $u_i$'s of Figure 2 is somewhat similar to the interfirm envelope of a series of intra-firm production functions as discussed by Martin Bronfenbrenner [1944, pp. 35-44].

10/ See for example Randolph Barker [1970]

11/ A discussion of this test and the data used in the test are reported in greater detail in a forthcoming article by Yujiro Hayami and V. W. Ruttan /‾1970_7

12/ A direct test of the induced innovation hypothesis would involve a test for non-neutral change in the production surface. A possible approach is suggested by David and Klundert /‾2_7.

13/ Derivation of factor demand functions from a multi-factor production function with different elasticities of substitution, as attempted by Zvi Griliches /‾1964(a) and 1969 (b)_7, seems to suggest a possibility for improving the present specification. Our regressions are similar to Griliches' but our factor prices do not measure the costs of factor services other than fertilizer.

14/ The possibility of structural changes in the metaproduction function over time, as suggested by some of low Durbin-Watson statistics in Tables 2 and 3, was tested by running regressions separately for 1880-1915 and 1920-1960. The results, in Hayami and Ruttan /‾1970_7, do not suggest any significant structural change occurred between those two periods. The inference from this test is relatively weak, however, because of the small number of observations involved.

15/ The role of agricultural research in the economic development of Japan and the United States is reviewed in Hayami and Ruttan /‾1971_7.

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