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INDUCED INNOVATION: A CES-TYPE META-PRODUCTION FUNCTION

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I. INTRODUCTION

The Hicksian version of the induced innovation hypothesis [5] focuses the cause of technological change on changes in relative input scarcities. Recent developments of the induced innovation hypothesis include the introduction of the concept of a "meta-production function" (see Hayami and Ruttan [3]). It is the purpose of this study to develop a meta-production function by adapting the currently popular CES production function, and to present a more direct empirical test of the validity of the Hicksian induced innovation hypothesis.

A brief review of the development of the Hicksian hypothesis is given in Section II. The CES-type meta-production function and its properties will be developed in Section III. Using historical aggregate statistical data for agricultural production in Japan, 1880 through 1940, the empirical analysis is presented in Section IV.

II. HICKSIAN INDUCED INNOVATION: A BRIEF REVIEW

The induced innovation hypothesis was initially postulated by Sir John Hicks in 1932 [5]. Since then, the hypothesis has developed along various lines (see, for instance, W. Fellner [2] and C. Kennedy [6].

In what follows, we shall stick to the spirit of Hicks' original version of the hypothesis.

According to the htpothesis, technological changes frequently occur in response to the inelastic supply of certain productive inputs. This situation can be depicted in the manner of Syed Ahmad's graphical elaboration [1] (Figure 1).

Suppose the initial input price situation for a two-factor case is represented by the relative price line p_0p_0, and the efficient production of Q_1 of the output is shown by the tangency point b. (An autonomous neutral technological improvement would be shown by a shift of the isoquant Q_0 to Q_1, with the new tangency point b still lying along the same factor-intensity ray OR as point a.) Let Factor 2 become relatively more expensive, so that the relative prices are now represented by p_1p_1. The traditional substitution effect would shift the point of tangency along Q_1 from b to c.

Suppose induced innovation is now introduced into the analysis. When the relative factor price change forces a departure of the equilibrium point from the initial point b, then a concommitant shift of the isoquant Q_1 to Q_1' occurs, so that the new tangency point becomes d instead of c. This concommitant adjustment of the isoquant reflects a non-neutral technological change which is biased against Factor 2 (Factor 2 saving) and biased towards Factor 1 (Factor 1 using). In this situation, costs have decreased from p_1p_1 to $p_1'p_1'$. The locus of efficient points such as b and d gives rise to an envelope curve uu which Ahmad called an "innovation possibility curve." The entire set of uu curves describes a dynamic production function.

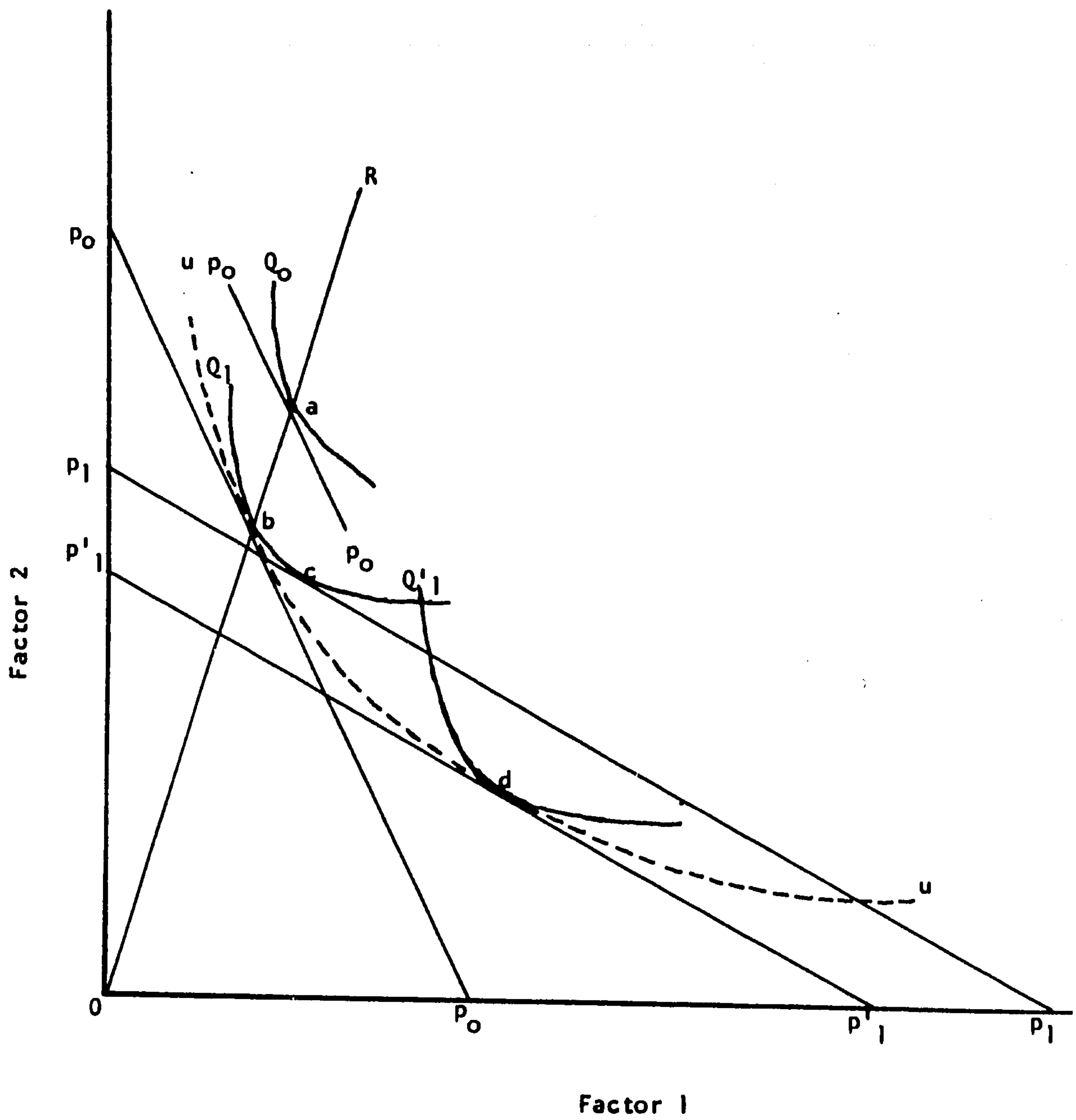

Figure 1: Depiction of Biased Technological Change Induced by the Inelastic Supply of Factor 2.

A similar kind of dynamic production function was given the name of "meta-production function" by Y. Hayami and V. W. Ruttan [3]. Studying the cases of agricultural production in the United States and Japan, Hayami and Ruttan concluded that changes in input mixes represent a process of a dynamic factor substitution which accompanies changes in the production surface induced by changes in relative factor prices. In the course of economic development, with demand for farm product increasing, the price of a less elastic factor tends to rise relative to the prices of more elastic ones. Prices of machinery and fertilizer tend to decline relative to the prices of land or labor, as the case may be. Under such conditions, technological innovation has been directed toward relaxing the constraints imposed by the relatively inelastic supplies of primary factors of production. Mechanical innovations are seen to be induced toward labor-saving, and biochemical innovations as induced toward land-augmentation.

An explicit form of meta-production function was postulated by Hayami and Ruttan in [4]. There, they presented a rather general model of agricultural development for thirty-eight developed and under-developed countries involving such explanatory variables as land and livestock to serve as proxies for internal resource accumulation, machinery and fertilizer to reflect technical inputs, and general and technical education in agriculture as an approximate measure for human capital. A critical assumption in their approach is that technical possibilities available to agricultural producers in different countries are subsumed under the same potential or meta-production function.

Though the meta-production function specified by Hayami and Ruttan may be used to test the induced innovation hypothesis, a more direct test of the hypothesis may be devised within Ahmad's simpler framework. This will be the task of sections III and IV.

III. A CES-TYPE META-PRODUCTION FUNCTION

A dynamic two-factor production of the general form

$$Y = F(K, L; t)$$

can be explicitly specified to be of the CES form:

$$(1) \qquad Y_t = [\alpha(K_t e^{\delta t})^{-\rho} + \beta(L_t e^{\lambda t})^{-\rho}]^{-1/\rho}$$

where Y, K, L and t represent output, capital, labor and time respectively; α and β are traditionally referred to as the distribution parameters, δ and λ the rates of factor augmentation over time, and ρ the substitution parameter (see, for example, Y. Kotowitz [7]. A specific feature of this approach is that the factors are expressed in efficiency units.

There are, however, certain weaknesses implicit in this approach. First, the rates of factor augmentation are assumed to be fixed over time. There is no a priori reason why this should be true. Second, the question of whether the technological change indicated is induced or autonomous is ignored, the source of innovation being left unspecified.

To reduce these weaknesses, Equation (1) can be improved upon by postulating that the innovation is induced by relative input price changes, such as in Ahmad's framework. Specifically, in dealing with agricultural output (Q), stipulating the primary factors to be land (A) and labor (L), a meta-production function may be written as

$$Q_t = [\alpha(A_t\, e^{\delta I_t})^{-\rho} + \beta(L_t\, e^{\lambda I_t})^{-\rho}]^{-1/\rho} \tag{2}$$

where I_t represents an index of relative factor prices of labor and land. Like Equation (1), it is homogeneous in the inputs. The essential difference between Equation (2) and Equation (1) lies in the replacement of time t with the labor-land index I_t. In this case, factor augmentation is assumed explicitly to be induced by changes in I_t. Even though constant factor-augmentation parameters, δ and λ, are still postulated, the rates of factor augmentation need not be constrained to be constant over time.[1/]

In both Equation (1) and Equation (2), it can be observed that if δ and λ are equal and different from zero, then technological change is neutral. When δ is different from λ, the innovation is non-neutral in character. Furthermore, in Equation (2) if δ exceeds λ, the case is land-saving (labor-using) and if λ exceeds δ, the case is labor-saving (land-using).

To make Equation (2) operational, let us define the relative factor price index to be

$$I_t = \left(\frac{w}{r}\right)_t \Big/ \left(\frac{w}{r}\right)_{t_0} \tag{3}$$

[1/] They would not be constant over time if and when I_t is not perfectly correlated with t.

where $\left(\frac{w}{r}\right)_t$ is the relative prices of labor and land in the t-th year and t represents the base year.

Assuming that factors are paid according to their marginal productivities,

$$r = \frac{\partial Q}{\partial A} = \alpha\left(\frac{Q}{A}\right)^{1+\rho} e^{-\delta\rho I} \tag{4}$$

and

$$w = \frac{\partial Q}{\partial L} = \beta\left(\frac{Q}{L}\right)^{1+\rho} e^{-\lambda\rho I} \tag{5}$$

Dividing Equation (5) by Equation (4) yields:

$$\frac{w}{r} = \frac{\beta}{\alpha}\left(\frac{A}{L}\right)^{1+\rho} e^{(\delta-\lambda)\rho I} \tag{6}$$

Taking lagarithms and re-arranging terms,

$$\ln\left(\frac{A}{L}\right) = -\frac{1}{1+\rho}\ln\frac{\beta}{\alpha} + \frac{1}{1+\rho}\ln\frac{w}{r} - \frac{(\lambda-\delta)\rho}{1+\rho} I \tag{6a}$$

from which we can obtain the elasticity of factor substitution σ,

$$\sigma = \frac{d\ \ln\left(\frac{A}{L}\right)}{d\ \ln\left(\frac{w}{r}\right)} = \frac{1}{1+\rho} + \frac{|(\lambda-\delta)|\rho}{1+\rho} I = \frac{1}{1+\rho}\left[1 + |(\lambda-\delta)|\rho I\right], \tag{7}$$

Since our CES-type production function is dynamic, this elasticity is not constant over time, but changes with I_t.[1/] Therefore, as the dynamic

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[1/] Note that as I approaches zero, the adjustment term $[1 + (\lambda-\delta)\rho I]$ approaches the constant elasticity value $\left(\frac{1}{1+\rho}\right)$ of static conditions. This occurs irrespective of whether $(\lambda-\delta)$ is expressed in absolute terms. However, from the description of Figure 1, it is evident that the adjustment factor is positive, regardless in which direction the innovation is biased. Therefore, the $(\lambda-\delta)$ term should be replaced by its absolute value.

(variable) elasticity is associated with the concept of meta-production function, it may be referred to as the "meta-elasticity of factor substitution."

IV. EMPIRICAL ANALYSIS

The specification of the functional form of the meta-production function developed in the preceding section offers a direct test of the Hicks-Ahmad version of the induced innovation hypothesis. Specifically, it is shown that positive verification of this hypothesis is obtained by rejecting the null hypothesis that δ is different from λ at the traditional levels of significance.

Statistical Model

The estimation of the unknown parameters of (2) is obtained by converting equations (4) and (5) to ln form as follows:

(4a) $$\ln\left(\frac{Q}{A}\right) = -\frac{1}{1+\rho}\ln\alpha + \frac{1}{1+\rho}\ln r + \frac{\delta\rho}{1+\rho} I$$

and

(5a) $$\ln\left(\frac{Q}{L}\right) = -\frac{1}{1+\rho}\ln\beta + \frac{1}{1+\rho}\ln w + \frac{\lambda\rho}{1+\rho} I.$$

Since the coefficient $1/(1+\rho)$ is common to both variables r and w these equations were combined to yield the following estimating equation

(8) $$Q' = X\beta + u$$

where

$$Q' = \begin{bmatrix} \ln (Q/A)_{t_o} \\ \vdots \\ \ln (Q/A)_{t_n} \\ \ln (Q/L)_{t_o} \\ \vdots \\ \ln (Q/L)_{t_n} \end{bmatrix} \qquad X = \begin{bmatrix} 1 & 0 & \ln r_{t_o} & I_{t_o} & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & \ln r_{t_n} & I_{t_n} & 0 \\ 0 & 1 & \ln w_{t_o} & 0 & I_{t_o} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 1 & \ln w_{t_n} & 0 & I_{t_n} \end{bmatrix}$$

$$B = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \\ b_5 \end{bmatrix} = \begin{bmatrix} -\frac{1}{1+\rho} \ln \alpha \\ -\frac{1}{1+\rho} \ln \beta \\ \frac{1}{1+\rho} \\ \frac{\delta\rho}{1+\rho} \\ \frac{\lambda\rho}{1+\rho} \end{bmatrix}$$

and u is a $2(n+1)$ component vector of disturbances which are assumed to be randomly, log normally and independently distributed with a zero mean and a constant variance. This formulation allows for the restricted estimation of $(1/1+\rho)$ by ordinary least squares and therefore the derivation of unique estimates of the parameters of (2).

In the case of Japan, it has been observed that for the period 1880 to 1940 Japanese agricultural production increased as wages secularly declined relative to land values. Under these circumstances, the induced innovation hypothesis suggests that technological progress was biased against (in favor of) land (labor). Therefore the null hypothesis is that δ is not different from λ and the alternative hypothesis is that δ is larger than λ.

This test is predicated on the prior test that only ρ is different from zero and of the appropriate sign since reliable estimates of α and β are generally difficult to obtain. In other words, testing the hypothesis that the model of form (2) is a "sufficient" explanation of the data.

Data

Time series observations on agricultural output, land and labor inputs, their prices and a discussion of its derivation are available from [4] for Japan for the period 1880 to 1960. However, only the data for the period 1880 to 1940 were used because of data and structural discontinuities during the war and postwar periods.

All observations are quin-quennial. Observations on land and labor are measured at every five years beginning with 1880. Prices (rents and wages) are measured as the average of five years ending the year specified. This is to take into account the effect of expectation and adjustment lag on technological adoption.

The apriori selection of the "best" measures of agricultural output, and the land and labor inputs, is difficult in the case of this model when various measures appear to contain a similar level of accuracy. Therefore, the two data series which are used as measures of agricultural output are gross agricultural output net of intermediate goods supplied within agriculture (all commodities) and gross output (all crops) Table 1. The

TABLE 1

JAPANESE AGRICULTURAL OUTPUT, LAND AND LABOR INPUTS AND THEIR PRICES FOR THE PERIOD 1880 TO 1940

Year	Agricultural Production (Q)		Land (A)		Labor (L)	
	All commodities (VAR.1) (1880=100)	All crops (VAR.2) (1880=100)	Paddy field (VAR.3) (1000's ha.)	Arable land (VAR.4) (1000's ha.)	All workers (VAR.5) (1000's)	Male workers (VAR.6) (1000's)
1880	100	100	2801	4748	14655	7842
1885	113	111	2824	4814	14481	7766
1890	126	120	2858	4922	14279	7677
1895	131	121	2877	5034	14185	7651
1900	149	134	2905	5200	14211	7680
1905	165	144	2936	5300	14069	7617
1910	188	159	3007	5579	14020	7606
1915	214	176	3072	5778	13942	7585
1920	232	182	3136	5997	13939	7593
1925	231	179	3199	5914	13941	7586
1930	249	185	3274	5961	13944	7579
1935	263	198	3290	6103	13750	6972
1940	264	202	3276	6121	13549	6365

Source: Y. Hayami and V.W. Ruttan, Agricultural Development - An International Perspective (Baltimore: John Hopkins, forthcoming, 1971) [4].

TABLE 1 (continued)

JAPANESE AGRICULTURAL OUTPUT, LAND AND LABOR INPUTS AND THEIR PRICES FOR THE PERIOD 1880 TO 1940

Land Price (r)		Farm Wage (w)		Rel.Fac.Price Index (I×10)	
Average value of arable land (VAR.7)	Arable land price index (VAR.8)	Daily wage rate (VAR.9)	Index (VAR.10)	(using variables 9 and 7) (VAR.11)	(using variables 10 and 8) (VAR.12)
(yen/ha.)	(1934-36=100)	(yen/day)	(1934-36=100)		
343	10.5	0.22	18.3	100.000	100.000
373	12.4	0.16	21.4	66.878	99.027
444	14.6	0.17	19.3	59.695	75.852
615	21.7	0.19	25.9	48.167	68.486
917	31.5	0.31	40.3	52.706	73.410
998	34.5	0.31	44.9	48.429	74.677
1586	46.9	0.41	49.5	40.304	60.561
1613	63.0	0.46	61.9	44.463	56.378
3882	109.7	1.39	127.3	55.825	66.586
3711	140.3	1.65	172.9	69.321	70.713
3388	132.4	1.12	156.5	51.540	67.825
2783	97.1	0.91	96.9	50.980	57.262
4709	131.1	1.90	154.2	62.907	67.490

two measures of land are hectars of paddy fields and hectars of arable land, while the two measures for labor are all workers and male works (Table 1).

Two different measures are also used to measure land price and farm wages (Table 1). The average value of arable land prices are the weighted average of the prices of paddy fields and upland fields where the areas of each are used as weights. The arable land price index is the simple average of paddy field price index and the upland field price index. The two measures of farm wages are the wage of daily contract workers and the index of male daily contract workers.

From the information in Table 1, eight estimations of Equation (8) can be obtained. The first four estimations are based on four dependent variable transformations each regressed on the independent variables 7, 9 and 11 (Table 1). The second four estimations are based on the same four dependent variable transformations each regressed on the independent variables 8, 10 and 12 (Table 2). The four dependent variable transformations are

$$Q_1' = \begin{bmatrix} \ln(\text{Var.1}/\text{Var.3}) \\ \ln(\text{Var.1}/\text{Var.5}) \end{bmatrix}, \quad Q_2' = \begin{bmatrix} \ln(\text{Var.2}/\text{Var.3}) \\ \ln(\text{Var.2}/\text{Var.5}) \end{bmatrix}, \quad Q_3' = \begin{bmatrix} \ln(\text{Var.1}/\text{Var.4}) \\ \ln(\text{Var.1}/\text{Var.6}) \end{bmatrix}, \quad Q_4' = \begin{bmatrix} \ln(\text{Var.2}/\text{Var.4}) \\ \ln(\text{Var.2}/\text{Var.6}) \end{bmatrix}$$

V. EMPIRICAL FINDINGS

The results from fitting the statistical model (8) to the data presented in Table 1 appears in Table 2. The statistical model seems to fit the data reasonably well and the coefficient estimates are generally consistent in sign. However, sign changes did occur in the estimates of b_1 based on the dependent variable Q_1' regressed on the independent variables 7, 9 and 11 and with the estimate of b_4 based on the dependent variable Q_4' regressed on the variables 8, 10 and 12. Variance estimates of the coefficients b_1, b_2, and b_3 are less than twice their corresponding coefficient magnitudes with four exceptions. These exceptions are the variance estimates of b_1 based on the dependent variables Q_1' and Q_4' regressed on variables 7, 9 and 11, the variance estimate of b_1 based on the dependent variable Q_3' regressed on variables 8, 10 and 12 and the variance of b_2 based on the dependent variable Q_1' regressed on variables 8, 10 and 13 of Table 1. In all cases, the variance estimates of b_4 are large while the variance estimates of b_5 are small.

The parameter estimates of the economic model (2) and their variance are derived from the estimated statistical model (Table 3). The derivation of the parameter estimates is straightforward. The estimated parameter variance is based on the large sample property relationships of the asymptotic distribution of a function of sample moments [8].

The estimated distribution parameters α and β are of the correct sign in all cases although the estimated variance of these parameters are

TABLE 2

ESTIMATED COEFFICIENTS OF THE STATISTICAL MODEL (8) BASED ON FOUR DEPENDENT VARIABLE TRANSFORMATIONS REGRESSED ON VARIABLES 7, 9 AND 11, AND VARIABLES 8, 10 AND 12 OF TABLE 1

Depend. Var.	Coefficient Estimates Based on Variables 7, 9 and 11							Coefficient Estimates Based on Variables 8, 10 and 12						
	b_1	b_2	b_3	b_4	b_5	R^2	d	b_1	b_2	b_3	b_4	b_5	R^2	d
Q_1'	-.162273	1.132597	.309482	-.023943	-.089195	.993	1.743	1.220919	.191278	.282035	-.024351	-.102839	.984	1.238
	(.267098)	(.135807)	(.016576)	(.014163)	(.913761)			(.302511)	(.289140)	(.019869)	(.017004)	(.015636)		
Q_2'	1.108703	1.489571	.205620	-.018028	-.067594	.994	1.420	2.105071	1.002605	.180309	-.018085	-.083460	.995	1.197
	(.225793)	(.114805)	(.014013)	(.011873)	(.011633)			(.264944)	(.253233)	(.017402)	(.014892)	(.014892)		
Q_3'	-.726265	1.789972	.302507	-.011691	-.086380	.921	1.082	.512234	.903483	.278167	-.002392	-.002392	.937	.872
	(.361160)	(.183633)	(.022414)	(.019151)	(.018607)			(.412978)	(.394724)	(.027125)	(.023213)	(.021345)		
Q_4'	.544715	2.146948	.198644	-.005775	-.064779	.888	.831	1.396393	1.714817	.176440	.003873	-.088926	.909	.842
	(.330194)	(.167889)	(.020492)	(.017509)	(.017012			(.377912)	(.361208)	(.024821)	(.021214)	(.019533)		

TABLE 3

PARAMETER ESTIMATES OF MODEL (2) BASED ON EIGHT ESTIMATIONS OF THE STATISTICAL MODEL a/

Depend. Var.	Parameter Estimates Based on Variables 7, 9 and 11					Parameter Estimates Based on Variables 8, 10 and 12				
	α	β	ρ	δ	λ	α	β	ρ	δ	λ
Q_1'	1.689336 (1.412877)	.025741 (.015611)	2.231205 (.173065)	-.034674 (.021217)	-.129172 (.020118)	.013181 (.017996)	.507527 (.543169)	2.545659 (.249789)	-.033916 (.023891)	-.143237 (.022634)
Q_2'	.004553 (.013672)	.000714 (.001588)	3.863343 (.331429)	-.022694 (.015340)	-.085091 (.015113)	.000009 (.000022)	.003847 (.007362)	4.546048 (.535252)	-.022063 (.018283)	-.101818 (.017202)
Q_3'	11.032250 (11.323627)	.002693 (.002676)	2.305714 (.244930)	-.016761 (.027506)	-.123843 (.026921)	.158586 (.262094)	.038852 (.065814)	2.594964 (.350552)	-.003314 (.032185)	-.150042 (.030775)
Q_4'	.064431 (.123549)	.000020 (.000038)	4.034128 (.519312)	-.007207 (.021852)	-.080837 (.021364)	.000365 (.001176)	.000060 (.000202)	4.667648 (.797321)	.004703 (.025725)	-.107978 (.024492)

a/ Variance estimates of these parameters are derived from the following equations:

$$\text{Var. } \alpha = \left[\frac{1}{b_3^2} e^{-2\frac{b2}{b3}}\right] \left[\text{Var. } b_1 + \left(\frac{b2}{b3}\right)^2 \text{Var. } b_3 - 2\frac{b_1}{b_3} \text{Cov.} b_1, b_3\right]; \text{Var. } \beta = \left[\frac{1}{b_3^2} e^{-2\frac{b2}{b3}}\right] \left[\text{Var. } b_2 + \left(\frac{b2}{b3}\right)^2 \text{Var. } b_3 - 2\frac{b2}{b3} \text{Cov.} b_2 b_3\right];$$

$$\text{Var. } \rho = \left(-\frac{1}{b_3^2}\right)^2 \text{Var. } b_3; \text{ Var. } \delta = \left[\frac{1}{1-b_3}\right]\left[\frac{1}{1-b_3} \text{Var. } b_4 + \frac{b_4^2}{1-b_3} \text{Var. } b_3 - 2\frac{b_4}{1-b_3} \text{Cov.} b_3, b_4\right]; \text{Var. } \lambda = \left[\frac{1}{1-b_3}\right] \left[\frac{1}{1-b_3} \text{Var. } b_5 + \frac{b_5^2}{1-b_3}\right.$$

$$\left.\text{Var. } b_3 - 2\frac{b_5}{1-b_3} \text{Cov.} b_5, b_4\right].$$

large. It follows from the relationship for estimating their variance that this estimate is sensitive to the magnitude and signs of the intercepts b_1 and b_2.[1/] Therefore, if the assumptions which guarantee consistent estimates of b_1 and b_2 are not strictly valid, the variance of α and β may be overestimated.

Of primary importance here, are the estimates of the parameters δ, λ and ρ. The estimates of the factor augmentation parameters δ and λ are of the same sign with one exception. In all cases, the value of δ exceeds the value of λ even though the estimated variance of δ is large.

The estimates of the substitution parameter ρ are of the correct sign and strongly different from zero in all cases. Thus, it seems reasonable to conclude that model (2) is a "sufficient" explanation of the data. We therefore proceed with testing the induced innovation hypothesis.

To test the hypothesis that δ is not different from λ, it is necessary to estimate their covariance since only the covariance of b_4, b_5 is given directly.[2/] The carrying out of this test suggests that this

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[1/] The relationship for estimating the variance of δ and λ appears in footnote a of Table 3. It should be noted that each of these equations contain a remainder term which approaches zero as sample size increases.

[2/] The estimate of the covariance of $\delta\lambda$ is based on Thiel [8] and is of the form:

$$\text{Cov.}\ (\delta\lambda) = \left(\frac{b_4}{(1-b_3)^2}\right)\left(\frac{b_5}{(1-b_3)^2}\right)\text{Var. } b_3 - \left(\frac{b_4}{(1-b_3)^2}\right)\left(\frac{1}{1-b_3}\right)\text{Cov.}\ (b_3b_5)$$

$$- \left(\frac{1}{1-b_3}\right)\left(\frac{b_4}{(1-b_3)^2}\right)\text{Cov.}\ (b_3b_4) - \left(\frac{1}{1-b_3}\right)\left(\frac{b_5}{(1-b_3)^2}\right)\text{Cov.}\ (b_4b_5)$$

hypothesis is strongly rejected in all cases. We therefore accept the hypothesis that δ is different from λ. This is consistent with the induced innovation hypothesis that for the circumstances observed in Japan from 1880 to 1940 technological progress was biased against (in favor of) land (labor) and therefore confirms the conclusions drawn by Hayami and Ruttan [3].

The mean meta-elasticity of factor substitution estimates were derived for the years 1880 to 1890, 1880 to 1940 and 1930 to 1940 (Table 4). With one exception, the elasticity estimates are less than unity and, in all cases, decline over the period 1880 to 1940. This implies that the estimated production function is bounded, i.e., the function reaches a finite maximum as one factor increases while the other is held constant. This also implies that the adoption of technology in Japanese agriculture over this period has decreased the marginal rate of substitution of labor for land.[1/] In other words, the development of biological innovations of a yield-increasing type in Japan have increased the difficulty of efficiently substituting a growing supply of labor for land.

It was pointed out earlier that the essential difference between the meta-production function in equation (2) and the traditional formulation of a comparable CES-type dynamic production function lies in replacing t with I_t. In so doing, the factor-augmentation parameters are not

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[1/] This result is substantiated by Wolkowitzs [9] findings in the estimation of alternative homothetic production functions that "Given that biased technical change enters ... so as to decrease the marginal rate of technical substitution, it will in turn decrease the elasticity of substitution."

TABLE 4

MEAN META-ELASTICITY OF FACTOR SUBSTITUTION ESTIMATES FOR PERIODS 1880-1890, 1880-1940 AND 1930-1940 BASED ON FOUR DEPENDENT VARIABLE TRANSFORMATIONS REGRESSED ON VARIABLES 7, 9 AND 11 AND VARIABLES 8, 10 AND 12

Dep. Var.	Elasticity Estimates Based on Variables 7, 9 and 11							Elasticity Estimates Based on Variables 8, 10 and 12						
	Static Elast. of Factor Sub.[a]	Augmentation to Static Elast. of Factor Substitution[b]			Meta-Elasticity of Factor Substitution[c]			Static Elast. of Substitution[a]	Augmentation to Static Elast. of Factor Substitution[b]			Meta-Elasticity of Factor Substitution[c]		
		1880-90	1880-1940	1930-40	1880-90	1880-1940	1930-40		1880-90	1880-1940	1930-40	1880-90	1880-1940	1930-40
Q'_1	.3095	.4928	.3771	.3597	.8023	.6865	.6692	.2820	.5926	.4534	.4326	.8746	.7354	.7146
Q'_2	.2056	.3743	.2863	.2732	.5799	.4919	.4788	.1803	.4937	.3777	.3604	.6740	.5580	.5407
Q'_3	.3025	.5641	.4315	.4117	.8666	.7341	.7142	.2782	.7998	.6118	.5838	1.0780	.8900	.8620
Q'_4	.1986	.4454	.3407	.3251	.6440	.5393	.5237	.1764	.7013	.5365	.5119	.8778	.7130	.6834

[a] Equal to $1/1+\rho$.

[b] Equal to $(1/1+\rho)\ |\lambda-\delta|\ \rho\ I_t$.

[c] See equation (7).

constrained to be constant over time when I_t is not perfectly correlated with t.

For purposes of comparison I_t was replaced in the estimating equation by t, $t=t_0, t_1, t_2, \ldots$, for the years 1880, 1885, 1890, ... The results of this analysis are briefly presented in the next section.

Relationships Between I_t and t

The results from fitting (8) to the data listed in Table 1 when t is substituted for I_t is presented in Table 5 and Table 6.

While a large portion of the variation in the dependent variable is explained, multi-collinearity between t and ln r, and between t and ln w exceeded 0.9 in all cases. Also, the likelihood of serial correlation appears to be higher in this model. In all but one case, the variance estimates of the b_3 coefficient is large. However, the estimates of the remaining coefficients are generally consistent in sign with small variances.

The problem of estimating the distribution parameters α and β appears to be more severe in this case than in the previous model. The estimates of the substitution parameter ρ vary considerably in magnitude and the corresponding variance estimates are large in all but one case. Therefore, it is concluded that model (1) is not a "sufficient" explanation of the data and we do not proceed with testing the hypothesis involving the difference $(\delta - \lambda)$. However, for the single case where ρ is significantly different from zero, the difference $(\delta - \lambda)$ is found not to be significantly different from zero.

TABLE 5

ESTIMATED COEFFICIENTS OF THE STATISTICAL MODEL (1) BASED ON FOUR DEPENDENT VARIABLE TRANSFORMATIONS REGRESSED ON VARIABLES 7, 9 AND t AND VARIABLES 8, 10 AND t WHERE $t = t_0, t_1, \ldots,$

Depend. Var.	Coefficient Estimates Based on Variables 7, 9 and 11							Coefficient Estimates Based on Variables 8, 10 and 12						
	b_1	b_2	b_3	b_4	b_5	R^2	d	b_1	b_2	b_3	b_4	b_5	R^2	d
Q_1'	3.013435	1.686306	.044978	.012020	.016251	.994	.681	2.663797	.941905	.100433	.009388	.014095	.995	.951
	(.537176)	(.204885)	(.042939)	(.002224)	(.002072)			(.423533)	(.444055)	(.046537)	(002366)	(.002087)		
Q_2'	3.372192	1.835397	.018059	.008019	.012144	.995	.727	3.179551	1.481703	.046087	.006690	.011043	.996	.877
	(.448940)	(.171231)	(.035886)	(.001859)	(.001731)			(.372632)	(.390688)	(.040944)	(.002081)	(.001837)		
Q_3'	2.830458	2.410375	.017059	.011606	.018516	.983	.932	2.698842	2.129084	.037982	.010613	.017703	.984	1.061
	(.380235)	(.145026)	(.030943)	(.001574)	(.001466)			(.316596)	(.331936)	(.034787)	(.001768)	(.001564)		
Q_4'	3.189218	2.559467	-.009860	.007605	.014409	.976	1.084	3.214598	2.668884	-.016364	.007916	.014651	.977	1.045
	(.343751)	(.131111)	(.027478)	(.001423)	(.001326)			(.291134)	(.305240)	(.031989)	(.001626)	(.001435)		

TABLE 6

PARAMETER ESTIMATES OF MODEL (1) BASED ON EIGHT ESTIMATIONS OF THE STATISTICAL MODEL (8)[a]

Depend. Var.	Parameter Estimates Based on Variables 7, 9 and 11					Parameter Estimates Based on Variables 8, 10 and 12				
	α	β	ρ	δ	λ	α	β	ρ	δ	λ
Q'_1	*	*	21.232919	.012586	.017017	*	*	8.956926	.010436	.015668
	**	**	(21.225105)	(.002627)	(.002582)	**	**	(4.613658)	(.002885)	(.002638)
Q'_2	*	*	54.372641	.008167	.012367	*	*	20.698323	.007014	.011577
	**	**	(110.032070)	(.002042)	(.001996)	**	**	(19.277042)	(.002331)	(.002130)
Q'_3	*	*	57.619293	.011808	.018837	*	*	25.328185	.011032	.018402
	**	**	(106.327345)	(.001783)	(.001825)	**	**	(24.113163)	(.002053)	(.001954)
Q'_4	***	***	-102.420485	.007531	.014268	***	***	-62.108894	.007788	.014416
	**	**	(282.641554)	(.001513)	(.001517)	**	**	(119.456126)	(.001711)	(.001622)

[a] See footnote a, Table 3.

* Denotes a value equal to or less than e^{-37}.

** Denotes an estimated standard error value that exceeds the value of the corresponding coefficient by multiple of at least 300.

*** Denotes a value equal to or greater than e^{166}.

This analysis suggests that the meta-production function postulated in (2) is superior to the function specified in (1) in explaining agricultural production in Japan for the years 1880 to 1940 as well as in providing for a direct test of the induced innovation hypothesis.

IV. CONCLUSION

A dynamic CES-type function and its properties is developed which incorporates the Hicksian induced innovation hypothesis into a meta-production function. Essentially, a relative input-price index is used as the shift variable of this function which is postulated within a two-dimensional input space. This study uses only a partial equilibrium approach in that changes in the relative price index are assumed to be exogenously determined.

Using historical data for Japanese agricultural production, it was found that the hypothesis that biased technological progress of a land-saving type was induced by the relative secular increase in land values was found to be statistically warranted.

A variable meta-elasticity of substitution is derived in Equation (7). Its estimated magnitudes are less than unity and generally decline over the years 1880 to 1940, suggesting that the development of biological innovations of a yield-increasing type in Japan have increased the difficulty of substituting a growing supply of labor for land.

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