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AGRARIAN STRUCTURE, TECHNOLOGICAL INNOVATIONS, AND THE STATE

by

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Following Solow's pioneering study on the role of technological change in explaining economic growth, a number of similar studies applied to agriculture revealed that technology could be at least as important a source of growth in that sector as it had been shown to be for the whole economy. Thus, Lave found that, in the United States between 1850 and 1958, technological change in agriculture had been twice as rapid as in manufacturing. Much lower rates of technological change were, however, observed in the less-developed countries (LDCs). Hayami and Ruttan estimated that half of the difference in labor productivity between more developed countries (MDCs) and LDCs was explained by the use of modern technical inputs from the industrial sector and by human capital.

Technological change generally substitutes for factors unequally. The bias of technological change thus describes which factor is being saved most by technology. According to the Hicksian definition of bias, for instance, technological change is laborsaving when, at constant factor prices, the labor-capital ratio falls. Alternatively, it is laborsaving when, at constant factor ratio, the marginal product of labor falls relative to that of capital.

While a number of measurements of both the rate and bias of technological change are available, attempts at identifying their economic and social determinants are recent and few. A major advance was made with the theory of induced technological innovations which uses price signals to explain rate and bias. We start by reviewing the achievements of this theory to conclude that price signals are indeed a necessary but far from sufficient explanation.

Using a transactions cost approach in a context of incomplete markets, we show

that the structure of asset ownership is also an important determinant of the rate and bias of technological change. Finally, when technology is a public good generated in public research institutions, collective action can be used to affect the allocation of resources to alternative technological innovations. The structure of political power can thus further distort the rate and bias of technological change. We use a formal model of optimum technological choice to show in what direction structural characteristics of agriculture and collective action affect the bias of technological change. We also use cross-country data to show that structural characteristics and the size of public research budgets do indeed affect the nature of technological change beyond the effect of price signals.)

## 1. Theoretical Framework and Unresolved Puzzles

### 1.1. The Theory of Induced Technological Innovations<sup>1</sup>

The objective of the pure neoclassical theory of induced technological innovations is to explain the rate and bias of technological change as an economic response to market forces by profit-maximizing entrepreneurs and by the state. This theory was cast in its modern form by introduction of the concept of a "metaproduction function" (Hayami and Ruttan) and of its isoquants, the "innovation possibility curves" (IPC) (Ahmad). The IPC is the envelope of all the isoquants (technologies) which an entrepreneur or the state can develop with a given research budget for a given state of scientific knowledge. When relative factor prices change, factor substitution can occur in the short run within a given production function and in the longer run within the IPC by switching to other attainable technologies. The role of technology is thus to allow to increase factor substitution away from the

factors that have become relatively more expensive and toward those which have become relatively cheaper.

Even without changes in relative factor price, technology can also change factor ratios if higher research budgets or advances in scientific knowledge shift the IPC toward the origin in a non-Hicks neutral fashion. In this case, the factor-saving bias of technological change is determined by the ability of a given research expenditure to improve the relative efficiencies of specific factors of production.

Over time, observed changes in factor ratios will result from the cumulative effects of these three changes: (1) factor substitution within the production function currently used, (2) factor saving due to technological change within  $IPC_t$ , and (3) factor saving due to higher research budgets and advances in scientific knowledge that shift  $IPC_t$  to an  $IPC_{t+1}$  closer to the origin. If the change in IPC is Hicks neutral, the factor ratio that results from these three changes is undoubtedly toward saving that factor which has become relatively more expensive. If, however, the change in IPC is not Hicks neutral, it is not impossible that a strong bias in IPC more than compensates the shift in factor ratios within a given IPC. This would, for instance, be the case if a strong bias in scientific advances toward laborsaving technology occurred at the same time as wages fell relative to the price of laborsaving capital goods.

With land and labor as the two primary factors of production in agriculture, it is useful to decompose capital goods between those that substitute for land and those that substitute for labor (Sen; Hayami and Ruttan). Land-saving capital is usually identified with biological, chemical, and water control investments, reflecting in particular the inputs of the Green Revolution

(improved seeds, fertilizers, insecticides, and irrigation). This capital is landsaving because it increases yields. Laborsaving capital is usually identified with machinery and equipment, tractors most particularly. This capital is laborsaving as it increases the land area per worker and the productivity of labor. Correspondingly, technological advances in capital goods can be classified as landsaving or laborsaving technological changes according to whether they increase the productivity of landsaving or laborsaving capital goods.

Based on this contrast, the production function in agriculture can be usefully represented as a separable, two-level production function such as:

$$Q = F[X_A(E_{AA}, E_{FF}), X_L(E_{LL}, E_{MM})]$$

where

$Q$  = agricultural output

$X_A(\cdot)$  = "land" input index

$X_L(\cdot)$  = "labor" input index

$A$  = land

$L$  = labor

$F$  = landsaving capital (fertilizer)

$M$  = laborsaving capital (machinery)

$E_i = E_i(a_i t + b_i \theta_i B)$ ,  $i = A, F, L, M$ , efficiency parameters

$t$  = exogenous technological change (scientific knowledge)

$B$  = research budget

$\theta_i$  = share of research budget allocated to factor  $i$

and

$a_i, b_i$  = exogenous parameters.

The usefulness of this classification is that it allows us to expect a high elasticity of substitution within subfunctions (i.e., between land and landsaving capital and between labor and laborsaving capital and technology) and a low or negative elasticity of substitution between the "land" and "labor" indexes which are largely complementary in production. In practice, the classification is not necessarily successful since many types of biological advances are also laborsaving (e.g., herbicides) and many mechanical advances are yield increasing (e.g., tractors that speed up tasks and allow for one additional crop in the year). Yet, when verified, it is a very convenient dichotomy for policy analysis.

Empirical evidence on the Allen partial elasticities of substitution between inputs in the same subfunction ( $\sigma_{AF}$  and  $\sigma_{LM}$ ) and between inputs in different subfunctions ( $\sigma_{AL}$ ,  $\sigma_{FL}$ ,  $\sigma_{FM}$ , and  $\sigma_{AM}$ ) generally supports the proposition that elasticities within subfunctions are higher than elasticities across subfunctions and that they are all systematically less than one.<sup>2</sup> We will use this result in the simulation exercises that follow in this paper.

Separability of the production function implies that the ratio of the marginal productivities of two inputs within the same subfunction (e.g., L and M) is not affected by the level of use of a factor in the other subfunction (Kaneda). Even if technological change created by shifts in IPC is Hicks neutral within subfunctions and relative factor prices do not change, technological change may be biased between land and labor if the rate of technological change in landsaving capital differs from that in laborsaving capital (Thirtle, 1985a).

Which area of the IPC is explored by technological innovators in response to changes in relative factor prices can be made endogenous by specifying a



research production function (a given state of scientific knowledge) and a given research budget B. Kamien and Schwartz thus specify a research production function of the type:

$$f \left( \frac{\partial E_i}{\partial t} \right) = B.$$

The optimal bias of technological change can then be derived by simultaneously allocating B and the other factors of production in order to maximize the present value of the future stream of net profits. The optimal technological bias is a function of the initial technology, relative factor prices, and the relative costs of acquiring the different types of technological changes.

The research budget, and thus the IPC, can in turn be endogenized by specifying decreasing returns to research expenditures and making resource allocation to research compete with resource allocation to production (Binswanger, 1974a, b). This allows determination of both the optimum bias and rate of technical change and brings out the role of not only factor price ratios but also product price levels and the relative value of output of different activities. In this case, the rate and bias of technical change are found to depend on the relative expected present value of the total cost of factors, the relative productivity of research in acquiring the different types of technology, and the value of output of the activity which depends on price level and quantity of output.

There exists a large number of studies that have measured the internal rate of return from investment in agricultural research. While there are many conceptual and empirical difficulties with these measurements, they tend to systematically indicate that there has been underinvestment in agricultural

research. The internal rates of return estimated tend to range between 20 and 100 percent which is quite evidently above the opportunity cost for most public goods programs (Hayami and Ruttan, pp. 63-66). If this is the case, the size of research budgets is not determined by equilibrium conditions in resource allocation but by noneconomic rules. In the following analysis, we consequently take the research budget as exogenous. The rate of technological change is thus determined by the size of this budget, the productivity of resources in the generation of technological advances, and the rate of diffusion of new technologies.

Empirical support for the theory of induced innovations has generally been positive, but it is fair to say that a rigorous and unambiguous test is still to be performed. Over the long pull of history, the qualitative implications of the theory tend to be verified. Thus, in Japan, with rising land scarcity associated with population pressure, the course of technological change was directed at raising land productivity more than labor productivity. In the United States, by contrast, labor scarcity and abundance of land led to technological advances aimed at raising labor productivity.

More precise empirical tests using econometric analysis to relate the bias of technological change to changes in relative factor prices start by observing that, over the long run, there have been enormous changes in factor proportions that could hardly have occurred as a result of substitution among factors in the absence of technological change. The observed factor substitutions are thus postulated to have occurred along the IPC or across changing IPCs as the levels of research budgets and of scientific knowledge have changed over time. Factor substitution within a given production function, technological change within an IPC, and technological change across IPCs are thus confounded in the observed change in factor ratios. Regression results

for the United States over the period from 1880 to 1980 (Hayami and Ruttan) tend to show the following results:

$$\frac{F}{A} = f \left( -\frac{f}{r}, +\frac{w}{r}, -\frac{m}{r} \right)$$

$$\frac{M}{L} = f \left( -\frac{m}{w}, -\frac{r}{w} \right)$$

$$\frac{A}{L} = f \left( +\frac{r}{w}, -\frac{m}{w} \right)$$

where  $r$ ,  $f$ ,  $w$ , and  $m$  are the prices of  $A$ ,  $F$ ,  $L$ , and  $M$ , respectively. The negative signs for the own-price ratios in the first two equations support the theory of induced innovations but not the positive sign in the third. This latter result is attributed to an "innate laborsaving bias" in technological change (Hayami and Ruttan, p. 186) or to a greater ability of research to improve the efficiency of laborsaving technological change relative to that of landsaving technological change, leading to rising land/labor ratios in spite of rising land rent/wage ratios. The same result was found by Thirtle (1985c) using U. S. data for four crops in 10 regions during the period 1939-1978. As we shall see, this observed puzzle could be explained by structural changes leading to the creation of larger farms and transactions costs in the access to labor that raise effective labor costs on the larger farms.

Another anomaly relative to the two-level specification of the production function is that, while machinery and fertilizers (first equation) and machinery and land (second and third equations) are expectedly shown to be complements by the negative signs observed for the corresponding price ratios, fertilizer and labor (first equation) are shown to be substitutes by the positive sign observed.

Beyond the crudeness of empirical support for the theory of induced innovations, there are at least two important aspects in which it is evidently lacking. One is the failure to take into account the existence of transactions costs that differentiate factor prices and, hence, optimum factor biases across farms. The other is the failure to incorporate in the model the practice of collective action that biases the performance of the state in delivering public goods such as technology. In the following two sections, we introduce a number of concepts from the theories of transactions costs and collective action that need to be incorporated in the theory of induced innovations in order to increase its explanatory power.

## 1.2. The Theory of Transactions Costs

In its pure neoclassical form, the theory of induced innovations postulates that perfect markets exist for all products and factors as well as for risk. Prices thus convey all the relevant information to decision-makers and all agents face equal prices. In this case, resources are efficiently allocated irrespective of the personal distribution of assets. If there are no economies of scale in production, there is only one optimum technological choice for a given research budget and state of scientific knowledge. If, as Hayami and Ruttan postulate, the state is equally responsive to market signals in the delivery of public goods as are private agents, the technology induced in public research institutions for one particular product will be uniquely determined by relative factor prices, the size of the research budget, and the state of scientific knowledge. There is, consequently, no room for collective action to influence the allocation of a research budget toward alternative technological innovations.

This is, of course, an idealized vision of the world that abstracts from the pervasiveness of transactions costs. As the recent contributions of Akerlof, Stiglitz, and Williamson, among others, have amply shown, introducing transactions costs into rational choice models eventually leads to patterns of resource allocation that are markedly different from those of an idealized first-best world. We show here that this is true for the inducements of technological innovations as well. When transactions costs are taken into account, optimum technology becomes conditional upon the distribution of assets and there, consequently, no longer exists a single optimum choice across farms. It is this multiplicity of private optima that, in turn, makes collective action to influence public choices in research so important.

Transactions costs refer to a number of costs not typically considered in the neoclassical concept of production costs with atomistic agents, market prices, and zero cost of market clearing (Nugent). They include the costs of information and of negotiating, monitoring, supervising, coordinating, and enforcing contracts. Existence of these costs is created by the possibility of opportunistic behavior in social relations. In labor contracts, in particular, there exists the possibility that hired labor paid on a time rate basis will shirk, thus requiring supervision by the owner-operator or family labor. Supervision costs thus represent a transactions costs in the access to hired labor. As the number of hired workers on a farm increases, the ratio of hired to family labor increases, and the price of a unit of effective labor thus increases as well. Another transactions cost is a fixed cost in land transactions which implies that the price of land tends to decline with farm size.

As opposed to the pure neoclassical theory of the first-best which is ahistorical, extending that theory by introducing transactions costs makes it

specific to a particular structural context. In the following analysis, we consider a situation where there are no economies of scale in production, where landownership is unequally distributed, where there is a rental market for land but no market for land in ownership, where there exists a credit constraint determined by the ownership of land which serves as collateral, where supervision costs on hired labor imply that the price of effective labor increases with employment, and where the price of land declines with farm size. Clearly, these conditions are not universal, and different farm models with transactions costs must be specified for different structural contexts.

While transactions costs have not been formally introduced in the theory of induced technological innovations, their importance in affecting the adoption of new technologies across farm sizes has been noted by Griffin for Latin America in particular. In this case the technology of the Green Revolution was observed to benefit more large than small farmers because of a decreasing cost of credit with farm size.

The farm-level model we use to introduce transactions costs into the theory of induced technological innovations is one where the production function is a two-level constant elasticity of substitution (CES):

$$Q = \left[ \gamma X_A^{-\rho} + (1 - \gamma) X_L^{-\rho} \right]^{-1/\rho}$$

$$X_A = \left[ \alpha A^{-\rho_A} + (1 - \alpha) (E_F F)^{-\rho_A} \right]^{-1/\rho_A}$$

$$X_L = \left[ \beta L^{-\rho_L} + (1 - \beta) (E_M M)^{-\rho_L} \right]^{-1/\rho_L}.$$

The efficiency parameters are exogenous at the farm level:

$$E_F = E(\lambda_F \theta B)$$

$$E_M = E[\lambda_M(1 - \theta) B]$$

where

$E(\cdot)$  = research function.

$\lambda_i$  = productivity parameter,  $i = F, M$ .

and

$\theta$  = allocation of budget  $B$  between  $E_F$  and  $E_M$ .

With transactions costs in access to labor and land, the farm-level prices of these inputs vary as follows:

$$w = w(L), w' > 0, w'' < 0$$

$$r = r(A), r' < 0, r'' > 0$$

while the prices of output ( $p$ ), fertilizer ( $f$ ), and machinery ( $m$ ), are constant.

The farm operator maximizes profit under a credit constraint,  $K(\bar{A})$ , determined by the size of ownership unit  $\bar{A}$ . Credit availability constrains total expenditure on inputs, including the rental of land. With constant returns to scale, the credit constraint determines the level of output. The farmer's problem is thus:

$$\text{Max}_{A,L,F,M} p Q(A, L, F, M; E_F, E_M) - (1 + \lambda) (rA + wL + fF + mM) + \lambda K$$

$$\text{subject to } w = w(L), r = r(A).$$

The optimum levels of factor use are

$$A, L, F, M = f(p, f, m, \bar{A}, E_i, i = F, M).$$

Optimum factor ratios change with farm size. As farm size increases, fertilizer per acre and labor per acre decrease while machinery per acre, machinery per worker, and the machinery/fertilizer ratio all increase.

### 1.3. The Theory of the State and Collective Action

It is well known that much agricultural technology has the character of public goods because the returns from research cannot easily be appropriated privately. This explains the importance of the public sector in the generation of agricultural research. A theory of induced innovations for agriculture, consequently, needs to incorporate a theory of the state.

In their theory of induced innovations, Hayami and Ruttan postulate that the state responds to changes in relative prices in a fashion that is optimal for farmers since the state responds to their organizations. As they explain,

"Farmers are induced by shifts in relative prices to search for technical alternatives that save the increasingly scarce factors of production. They press the public research institutions to develop the new technology and demand that agricultural supply firms supply modern technical inputs that substitute for the more scarce factors. Perceptive scientists and science administrators respond by making available new technical possibilities and new inputs that enable farmers profitably to substitute the increasingly abundant factors for increasingly scarce factors, thereby guiding the demand of farmers for unit cost reduction in a socially optimum direction.

"The dialectic interaction among farmers and research scientists and administrators is likely to be most 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" (page 88).

Because there are no differential transactions costs across farms and no economies of scale, farmers' demands are for a unique technological alternative, whatever their scale of operation in a given activity. Collective action can thus be reduced to its simplest form, the transfer of socially un-specific information (demands) to the public sector. There are two problems with this simplification.



One is that, once the existence of structure-specific transactions costs is recognized, the demand for public goods becomes social group-specific, and collective action takes on its true meaning of distributional struggles at the level of the state. If collective action by large farmers is more effective than that by small farmers, the dominance of large farmers' demands will distort the optimum technological bias toward the factor-price ratios that correspond to their particular types of farms.

The studies of Olson and Hardin have helped identify some of the determinants of success in collective action. The main condition for success is the ability of a group to suppress free riding, and this is largely a matter of the characteristics of the group. Success in collective action is thus expected to be greater the smaller the group, the more homogeneous its origin, the longer its members have been together or it has been in existence, the more complementary the goals of different members, the closer the social and physical proximity among its members, the greater the difficulty of "exit" as opposed to "voice" behavior, etc. (Hirschman; Nugent). These group characteristics have been used to explain why farmers in LDCs usually have less power over the state than industrialists and urban consumers, resulting in the well-known urban bias (Lipton). The same characteristics can be used to explain why large farmers tend to have more success in lobbying than small farmers.

Another excessive simplification in the Hayami and Ruttan theory of the state and public goods is that it fails to endow the state with any type of autonomy from demands by organized farmers. This is a subject on which there exists a considerable degree of controversy (Hamilton). Yet, it is, for instance, possible for the state to use technology as an instrument of an income policy and as a surrogate for asset redistribution.

The role of collective action and of autonomous state initiatives in influencing the allocation of public research budgets and the consequent technological biases in public sector research have been observed in several studies (de Janvry, Guttman). With its highly skewed distribution of landownership and its long tradition of strong state interventionism, no where is this more visible than in Latin America. In a recent extensive study of the pattern of technological change in that continent, Pineiro and Trigo observed that international availability of new technologies, expected profitability of the innovation, and changes in relative factor prices are not sufficient to explain technological change. They found, by contrast, that successful occurrences of technological innovations tend to result from either one of the following two conditions.

One is when the structural conditions for successful collective action are satisfied. This was observed to happen when the producers of a commodity are few, economically powerful, homogeneous, and regionally concentrated. Their lobbies may then be able to influence the allocation of public budgets to research in their favor. This was the case with large-scale sugar plantations in Colombia and with hacendado milk producers in Ecuador. The other is when a commodity is of national significance as either a wage good or a source of foreign exchange earnings. In this case, even though the ultimate beneficiaries of technological change are numerous and disorganized, the state may act on their behalf. This is how successful research programs were implemented in rice in Colombia and corn in Argentina. Situations where neither are producers powerfully organized nor is the commodity of national significance tend to result in technological stagnation. This explains the lack of research on peasant crops and peasant farming systems.

In the following model of induced technological innovations, we show that the bias of technological change can be significantly affected by the existence of both transactions costs and collective action.

## 2. Microfoundation of Induced Technological Change: Optimal Bias by Farm Size

The farm-level model introduced previously is used to define the demand for technological change that would emerge from a homogeneous group of farms. Keeping exogenous the decision on the size of the research budget  $B$ , there is an optimal allocation  $\tilde{\theta}$  of this budget between research on landsaving and on laborsaving technological changes which maximizes farm profit. It is determined by including  $\theta$  as a decision variable of the farm operator in the maximization problem. Since land and labor costs (and, consequently, factor use), depend on the size of ownership unit  $\bar{A}$ ,  $\tilde{\theta}$  will also be found to vary with  $\bar{A}$ . In the general case, the solution for  $\theta$  cannot be separated from the solution for the levels of factor use as they are jointly determined. Taking land and labor prices as explicit functions of  $\bar{A}$ , rather than as functions of the levels of factor use  $L$  and  $A$ , greatly simplifies the exposition of the problem since it allows decisions on factor use and on optimal technological change to be taken sequentially. The analysis which follows is based on this simplified model. In that case, the optimal levels of factor use and the corresponding unit cost function ( $c$ ) associated with the two-level CES production function can be explicitly written as functions of the exogenous factor prices ( $m$  and  $f$ ), landownership ( $\bar{A}$ ), and the efficiency parameters ( $E_i$ ):

$$c = c[r(\bar{A}), w(\bar{A}), f, m, E_i].$$

Total production and profit are direct functions of the unit cost:

$$Q = K/c,$$

$$\text{profits} = \left(\frac{p}{c} - 1\right) K,$$

where  $p$  is the product price and  $K$  the total credit available to the farm.

$\tilde{\theta}$  derives from minimizing the cost  $c$ ;

$$\min_{\theta} c[r(\bar{A}), w(\bar{A}), f, m, E_i(\theta, B), \quad i = F, L].$$

## 2.1 Optimal Budget Allocation

Returning to the farm model with efficiency parameters applying to the capital inputs only, the optimal  $\theta$  is solution of the cost minimization problem with

$$c = \left[ \gamma^{\sigma} R^{1-\sigma} + (1 - \gamma)^{\sigma} W^{1-\sigma} \right]^{1/(1-\sigma)},$$

where

$$R = \left[ \alpha^{\sigma_A} r^{1-\sigma_A} + (1 - \alpha)^{\sigma_A} \left( \frac{1}{E_F} f \right)^{1-\sigma_A} \right]^{1/(1-\sigma_A)}$$

$$W = \left[ \beta^{\sigma_L} w^{1-\sigma_L} + (1 - \beta)^{\sigma_L} \left( \frac{1}{E_M} m \right)^{1-\sigma_L} \right]^{1/(1-\sigma_L)}$$

are the unit costs of the land and labor aggregates.

The first-order condition implicitly defines  $\tilde{\theta}$  as the solution of the equation:

$$\frac{dc}{d\theta} = \left( \frac{\gamma c}{R} \right)^{\sigma} \left[ \frac{(1 - \alpha) R}{E_F^* f} \right]^{\sigma_A} f \frac{dE_F^*}{d\theta} + \left[ \frac{(1 - \gamma) c}{W} \right]^{\sigma} \left[ \frac{(1 - \beta) W}{E_M^* m} \right]^{\sigma_L} m \frac{dE_M^*}{d\theta} = 0 \quad [2.1]$$

where  $E_i^* = 1/E_i$  gives the equivalent price decrease of an efficiency gain on factor use. The second-order condition which ensures that the cost reaches a minimum is written

$$\frac{d^2c}{d\theta^2} = \frac{\partial^2 c}{\partial E_F^{*2}} \left( \frac{dE_F^*}{d\theta} \right)^2 + \frac{\partial c}{\partial E_F^*} \cdot \frac{d^2 E_F^*}{d\theta^2} + \frac{\partial^2 c}{\partial E_M^{*2}} \left( \frac{dE_M^*}{d\theta} \right)^2 + \frac{\partial c}{\partial E_M^*} \cdot \frac{d^2 E_M^*}{d\theta^2}.$$

The sign of this expression cannot be unambiguously assessed. The second derivatives of  $E_F^*$  and  $E_M^*$  with respect to  $\theta$  are positive if the research has decreasing return to scale in  $E_i^*$ , and the second and fourth terms are then positive. But, with positive elasticities of substitution  $\sigma$ ,  $\sigma_A$ , and  $\sigma_L$ , the second derivatives of the cost  $c$  with respect to  $E_F^*$  and  $E_M^*$  are both negative. However, if these elasticities of substitution are small and/or the research function has decreasing return to scale with a sufficient curvature, the whole expression is positive, and  $\tilde{\theta}$  corresponds to a minimum cost. The intuitive reason is that, in this case, for values of  $\theta$  beyond the optimal  $\tilde{\theta}$ , the reduction in the cost of "efficient fertilizer" has little impact on the overall cost and does not compensate for the corresponding increase in "efficient machinery" cost. The importance of the curvature of the research functions on  $\tilde{\theta}$  will be confirmed numerically later in this section.

Assuming that the second-order condition is satisfied, it is quite clear that  $\tilde{\theta}$  depends on the structure of input prices. The signs of these relationships are established by total differentiation of equation [2.1] at  $\theta = \tilde{\theta}$ . In particular,  $d\tilde{\theta}/dw$  has the sign of

$$-c^\sigma \frac{\partial^2 c}{\partial \theta \partial w} = -(\sigma_L - \sigma)(1 - \gamma)^\sigma (1 - \beta)^{\sigma_L} w^{\sigma_L - \sigma - 1} m^{1 - \sigma} \frac{\partial w}{\partial w} E_M^{\sigma_L - 2} \frac{dE_M^*}{d\theta}$$

which is negative for  $\sigma_L > \sigma$ . Similarly,  $d\tilde{\theta}/dr$  can be shown to be positive for  $\sigma_A > \sigma$ .

The demand for technological change originating in large farms which face higher transactions costs on labor and lower transactions cost on land will thus be biased toward improvement of mechanization which can substitute for labor while the demand by small farmers will be biased toward factor-augmenting technological change in fertilizers.

The impact of changing the prices of the capital inputs on the demand for research can similarly be assessed. The optimal share of the research budget to be allocated to fertilizer is an increasing function of its price  $f$  if

$$\frac{\sigma_A - \sigma}{1 - \sigma_A} \frac{(1 - \alpha)^{\sigma_A} (E_F^* f)^{1 - \sigma_A}}{R^{1 - \sigma_A}} + 1 > 0,$$

which is true for  $\sigma < \sigma_A < 1$ . Similarly, the budget share allocated to research on machinery is an increasing function of the machinery price  $m$  if  $\sigma < \sigma_L < 1$ . This is logical since the course of technological innovations is directed at saving on the factor that becomes relatively more expensive.

A convenient way of summarizing this information on signs is the following:

$$\tilde{\theta} = \theta(+f, +r, -w, -m, B)$$

in which the sign in front of each variable indicates the sign of the partial derivative of the function with respect to that variable.

For use in the empirical analysis that follows, the expression which defines  $\tilde{\theta}$  can also be written in terms of relative factor prices as follows:

$$\begin{aligned} & \left(\frac{r}{w}\right)^{1-\sigma} \gamma^\sigma (1-\alpha)^{\sigma_A} \left(\frac{R}{r}\right)^{\sigma_A-\sigma} \left(\frac{f}{r}\right)^{1-\sigma_A} E_F^{\sigma_A-2} \frac{dE_F}{d\theta} \\ & + (1-\gamma)^\sigma (1-\beta)^{\sigma_L} \left(\frac{W}{w}\right)^{\sigma_L-\sigma} \left(\frac{m}{w}\right)^{1-\sigma_L} E_M^{\sigma_L-2} \frac{dE_M}{d\theta} = 0 \end{aligned}$$

which shows that  $\tilde{\theta}$  can be expressed as a function of the three relative prices  $f/r$ ,  $m/w$ , and  $r/w$  and the budget  $B$  with signs that are:

$$\theta = \theta(+f/r, -m/w, ++r/w, B),$$

where ++ indicates that the impact of an increasing  $r/w$  dominates that of a decreasing  $f/r$  if coming from a change in  $r$  only.

Allocation of the research budget, therefore, responds to increasing prices of land and fertilizers by increasing the share devoted to fertilizer research, if the elasticities of substitution are all lower than one and the elasticities of substitution within each of the two aggregates are higher than that between these aggregates.

The relationship between factor prices and the optimal allocation of the research budget can be further analyzed by numerical simulations in the farm model. To do this, specific values are given to the parameters and variables of the cost and research functions, and transactions costs functions are analytically defined. The initial set up is a symmetrical case between labor and land inputs with

$$\alpha = \beta = \gamma = 0.5$$

$$m = f = 1$$

$$w = r = 1$$

$$\sigma_A = \sigma_L = .7$$

$$\sigma = .2.$$

The research functions are specified as the following relations between  $\theta$  and the inverse of the efficiency parameters:

$$\frac{1}{E_F} = \frac{1}{2} + [(1 - \theta)B]^e$$

$$\frac{1}{E_M} = \frac{1}{2} + (\theta B)^e,$$

with the same  $e$  parameters to eliminate any possible innate bias due to different efficiencies of the two research activities and  $B$  set to 1.

Simulation results confirm that the curvature of the research function,  $e$ , has a paramount impact on the shape of the relationship between total output and  $\theta$ . For linear research functions (i.e., for  $e = 1$ ), the relation between output and  $\theta$  is convex, and the optimal  $\theta$  is then either 0 or 1, implying complete specialization in research. In the following simulations, sufficiently large values of  $e$  were consequently chosen to avoid this occurrence.

Table 1 gives the optimal  $\theta$  for different values of the parameters  $\sigma_A$ ,  $\sigma_L$ ,  $\sigma$ , and  $e$  and of the variables  $w$  and  $r$ .

In the perfectly symmetrical case chosen above,  $\tilde{\theta}$  is 0.5 (experiment a in Table 1). Keeping  $w = r$  but setting  $\sigma_A$  different from  $\sigma_L$  (experiment b in Table 1),  $\tilde{\theta}$  is no longer 0.5. If  $\sigma_A > \sigma_L$ ,  $\tilde{\theta} > 0.5$  and vice versa. This rather intuitive result simply says that, when substitution possibilities are better for, say, land, the optimum research strategy will emphasize land-displacing innovations. Also, the departure of  $\tilde{\theta}$  from 0.5 gets larger as  $\sigma$  and/or  $e$  get smaller. This means, that when the substitution possibilities between land and labor are narrower or when marginal returns to research



TABLE 1

Simulation Results: Variation of the Optimal  $\theta$  with Factor Substitutability, Research Efficiency, and Factor Prices

			$\sigma = .2$	$\sigma = .4$	$\sigma = .5$
a	$w = r = 1$	$\sigma_A = \sigma_L = .7$	.50	.50	.50
b	$w = r = 1$	$\sigma_A = .8 \quad \sigma_L = .6$			
		$e = 2$	.86	.82	.79
		$e = 4$	.63	.60	.59
c	$w = 10 \quad r = 1$	$\sigma_A = \sigma_L = .7$			
		$e = 2$	.27	.34	.39
		$e = 4$	.43	.46	.47
d	$w = 10 \quad r = 1$	$\sigma_A = .8 \quad \sigma_L = .6$			
		$e = 2$	.76	.76	.76
		$e = 4$	.58	.57	.57

are decreasing, an optimum research strategy will emphasize even more innovation on the factor that is easier to substitute for land or labor, as the case may be.

Going back to the case where  $\sigma_A = \sigma_L$ ,  $\tilde{\theta}$  is affected by the relative values of  $w$  and  $r$  (experiment c in Table 1). When  $w > r$ , i.e., on a large farm where the cost of supervision increases the cost of labor,  $\tilde{\theta}$  is now less than 0.5. The optimum research strategy is to promote laborsaving technology. As before, the relation between output and  $\tilde{\theta}$  is more "centered" toward 0.5 when  $\sigma$  and  $e$  are large. The bias of technological change away from  $\tilde{\theta} = 0.5$  is thus reduced when research specialization is less likely (large  $e$ ) and when substitution between land and labor aggregates is easier (large  $\sigma$ ).

Differences between  $\sigma_A$  and  $\sigma_L$  can lead to interesting results. For instance, when  $\sigma_A > \sigma_L$ , it is possible that the optimal research strategy puts more emphasis on landsaving technology even when  $w > r$  (experiment d in Table 1). This means that the substitution advantage of land over labor may be sufficient to counterbalance higher labor costs. The result is understandably somewhat mitigated when  $\sigma$  is very large. Moreover,  $\tilde{\theta}$  increases when  $e$  and/or  $\sigma$  decrease.

From the above, it is clear that relative factor prices do not determine unambiguously the sign of the optimum technological bias. Simulation results show that the magnitude of partial elasticities of substitution of the IPC is important. How well new technology can substitute itself to land or labor will also have a very important impact on optimal research strategies.

Introducing into the farm model transactions costs that make effective prices change with farm size  $\bar{A}$  leads to  $\tilde{\theta}$  that also vary across farm sizes. Labor and land cost functions are specified as:

$$w(\bar{A}) = \frac{1}{2} + \left( \frac{\bar{A} - 1}{7} \right)^3$$

$$r(\bar{A}) = \frac{1}{2} + 50 \left( \frac{10}{10 + \bar{A}} \right)^3.$$

For land varying from 0.25 to 45 acres, these functions induce a relative effective price of labor to land that increases from .01 to 310. The variation in optimal research allocation, which corresponds to this range of variation in prices, is represented in Figure 1. It clearly shows the differences in demands for technological biases that originate in small versus large farms. With  $\theta$  specific to farm size, the different classes of farm sizes will have conflicting demands for technological innovations.

## 2.2 Factor Use and Technological Bias

How do factors substitute for each other in this model of induced technological change, and how does the mere introduction of technological change bring about a bias in factor use even at constant factor prices? These questions can partially be answered analytically and will be further explored with numerical simulations.

The structural model which determines the optimum levels of factor use is

$$\frac{F}{A} = \left( \frac{1}{E_F} \right)^{1-\sigma_A} \left( \frac{1-\alpha}{\alpha} \right)^{\sigma_A} \left( \frac{r}{f} \right)^{\sigma_A}$$

$$\frac{M}{L} = \left( \frac{1}{E_M} \right)^{1-\sigma_L} \left( \frac{1-\beta}{\beta} \right)^{\sigma_L} \left( \frac{w}{m} \right)^{\sigma_L}$$

$$\frac{A}{L} = \left( \frac{\gamma}{1-\gamma} \right)^{\sigma} \frac{\alpha^{\sigma_A}}{\beta^{\sigma_L}} \left( \frac{w}{r} \right)^{\sigma} \frac{\left[ \alpha^{\sigma_A} + (1-\alpha)^{\sigma_A} \left( \frac{1}{E_F} \cdot \frac{f}{r} \right)^{1-\sigma_A} \right]^{(\sigma_A-\sigma)/(1-\sigma_A)}}{\left[ \beta^{\sigma_L} + (1-\beta)^{\sigma_L} \left( \frac{1}{E_M} \cdot \frac{m}{w} \right)^{1-\sigma_L} \right]^{(\sigma_L-\sigma)/(1-\sigma_L)}},$$

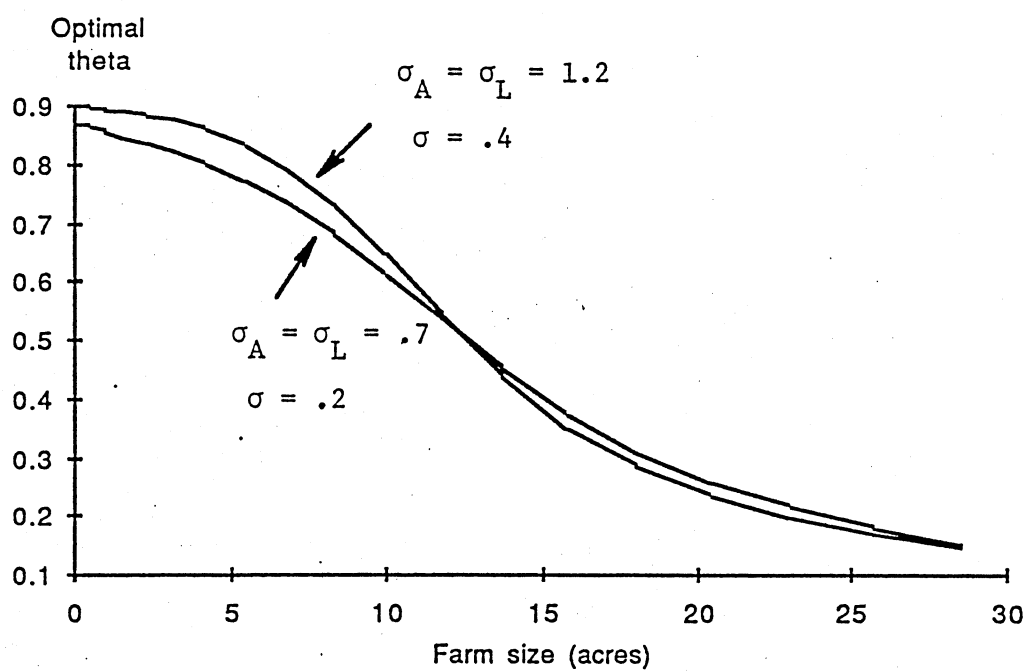


Figure 1  
Variation in Optimal Research Bias with Farm Size

together with the research functions

$$E_F = E(\lambda_F \tilde{\theta} B) \quad \text{and} \quad E_M = E[\lambda_M (1 - \tilde{\theta}) B]$$

and equation [2.1] which defines  $\tilde{\theta}$ .

The explicit dependence on factor prices represents the direct substitution among factors implemented in response to price changes. Within each aggregate, the elasticities of substitution are  $\sigma_A$  and  $\sigma_L$ , respectively. Across groups the elasticity of substitution between land and labor, for example, is not constant but can be seen to be greater than  $\sigma$ , with the substitutability between both factors in each aggregate contributing to increase the impact of the change of one price  $w$  or  $r$  on the land-labor ratio.

Introduction of a positive research budget increases the change in the factor ratios. Except for a budget completely specialized in one type of research ( $\tilde{\theta} = 0$  or  $1$ ), the research activities will raise the efficiency of both fertilizer and machinery and correspondingly lower their use relative to land and labor. However, the impact of technological change can either increase or decrease the land-labor ratio depending on whether or not the effect of increasing fertilizer efficiency, which reduces the share of the land aggregate, dominates the effect of increasing machinery efficiency.

The following relationships summarize the overall dependency of factor ratios on relative factor prices:

$$F/A = f(-f/r, -\tilde{\theta}, -B),$$

$$M/L = f(-m/w, +\tilde{\theta}, -B),$$

$$A/L = f(-r/w, +f/r, -m/w, -\tilde{\theta}, B),$$

$$\text{and } \tilde{\theta} = \theta(+f/r, -m/w, ++r/w, B).$$

Identification of the role of induced technological change on factor ratios derives from these expressions:

- (i) While direct substitution between fertilizer and land responds only to the relative price of these two inputs, technological change introduces an increase in relative fertilizer use when the price of machinery or the level of wages increase since less research is then devoted to increase fertilizer efficiency.
- (ii) In the land-labor ratio, direct substitution and the impact of technological change counteract each other. From simple substitutability, an increase in the fertilizer price generates direct substitution of land for fertilizer and thus a higher land use per worker. Technological change response, by contrast, increases research in fertilizer efficiency leading to lower use of both factors, land and fertilizer, and of the land aggregate.

The impact of the size of the research budget on the optimum factor bias is analytically ambiguous. Numerical simulations reported in Table 2 permit us to see, however, that a rising research budget always makes  $\tilde{\theta}$  converge toward .5 if there is no "innate bias" in research, i.e., if the efficiency of research is equal in generating landsaving or laborsaving innovations. The greater the research budget, the more neutrality there is in technological change whatever the elasticities of substitution and relative factor prices. This is due to the fact that there are decreasing marginal productivities in research and that, while the path toward capturing the gains from research is affected by the elasticities of substitution and relative factor prices, at the limit all potential gains from research become exhausted and there is convergence toward neutrality. Permanence of technological bias with infinitely high research budgets would only result from innate biases in research.

TABLE 2

Simulation Results: Variation of Optimal  $\theta$  with Factor Substitutability  
Factor Prices, and Size of the Research Budget

	B = .8	B = 1	B = 3	B = 10
w = r = 1 $\sigma_A = \sigma_L = .7$	.5	.5	.5	.5
w = r = 1 $\sigma_A = .8, \sigma_L = .6$	.96	.86	.58	.53
w = 10   r = 1 $\sigma_A = \sigma_L = .7$	.14	.27	.46	.48
w = 10   r = 1 $\sigma_A = .8, \sigma_L = .6$	.89	.76	.54	.52

Note: In these runs,  $e = 2$  and  $\sigma = .2$ .

### 3. Macroeconomic Determination of Induced Technological Change

So far, we have derived analytically and numerically the optimum bias of technical change in a farm model with a given farm size. We will now explore the impact that land distribution has on the choice by the state of an optimal research budget allocation for the farm sector as a whole.

With constant returns to scale in production and no transactions costs, relative factor use is the same for all farms, even if the credit constraint induces some differentiation in the size of operations. In such circumstances, the optimal research strategy would also be the same irrespective of farm size.

Differences in relative factor use are brought about if relative factor costs vary from farm to farm due to transactions costs. In this case, the size of operation determined by the credit constraint will also affect the relative factor costs and, therefore, the research budget allocation preferred by individual farmers. Global output response to various levels of  $\theta$  will now be the aggregation over all farms of differentiated impacts. In that sense, the way access to credit is distributed across farms will matter for choice by the state of an optimal  $\theta$ .

#### 3.1 The State's Problem

While each farm's demand for a specific bias of technological change is dictated by its own profit motive, the state, which provides technological change as a public good, has its own objective in the choice of bias. Minimizing food cost through a maximum sectoral output, insuring a minimum level of profit for small farmers, and underwriting the technological demands of the large farmers are alternative possible objectives for the state. To each corresponds a different optimal allocation  $\tilde{\theta}$  of the research budget.



We consider first the case where the state maximizes sectoral output. With credit a function of landownership  $K(\bar{A})$  and labor and land costs also a function of  $\bar{A}$ , the sectoral output is

$$Q(\theta) = \int_{\bar{A}} \frac{K(\bar{A})}{c[\theta, w(\bar{A}), r(\bar{A})]} \cdot f(\bar{A}) d\bar{A},$$

where  $f(\bar{A})$  is the frequency distribution of farms by size of ownership unit. Assuming that the second-order condition is satisfied, the optimal  $\theta$  is determined by:

$$\frac{dQ(\theta)}{d\theta} = \int_{\bar{A}} \frac{-K(\bar{A})}{c^2[\theta, w(\bar{A}), r(\bar{A})]} \cdot \frac{dc[\theta, w(\bar{A}), r(\bar{A})]}{d\theta} \cdot f(\bar{A}) d\bar{A} = 0.$$

To separate the role of transactions costs, which vary with farm size, from that of market factor prices ( $w_0$  and  $r_0$ ), which are observed, farm level labor and land costs can be written as:

$$w(\bar{A}) = w_0 + w^*(\bar{A}) \quad \text{and} \quad r(\bar{A}) = r_0 - r^*(\bar{A}).$$

In a first approximation in taking account of transactions costs, the sector can be treated as homogeneous in the sense that all farms are of equal size. The analysis of a homogeneous sector is a direct application of the farm level model in which the average farm size  $\bar{A}$  influences both the direct substitution among factors and the research decisions which combine in defining the factor use ratios.

With increasing transactions costs on labor and decreasing transactions costs on land, there will be an increasing bias in research toward raising the efficiency of labor relative to that of land as average farm size increases (negative sign of the coefficient of  $\bar{A}$  in the  $\tilde{\theta}$  function in Table 3). At the same time, direct substitution of fertilizer for land decreases while direct substitution of machinery for workers and of land for workers increases (sign of  $\bar{A}$  in the factor ratio equations of the structural model). Integration of these effects in the reduced model shows that technological change counteracts the direct factor substitution effect due to varying transactions costs in the determination of fertilizer use per acre and machinery use per worker. Observation of decreasing fertilizer use and increasing machinery use would, however, suggest that the direct substitution effects dominate over the technological change effects. On the land-labor ratio, substitution induced by differential transactions costs and technological change reinforce each other.

A model of induced technological innovations with transactions costs thus suggests that, across regions or countries, technological change will be sensibly different from what would have been expected on the basis of direct factor prices alone,  $w_0$  and  $r_0$ , with a greater bias toward mechanical innovations where average farm size is larger. It also indicates the need for a change in the orientation of research if any transformation of the pattern of landownership is happening or envisaged.

While the effect of average farm size on the technological bias can be derived analytically, the effect of inequality in the distribution of farm sizes requires numerical simulation. This is what we do in the following section.

TABLE 3

---

Structural model:

$$\tilde{\theta} = \tilde{\theta}(+f/r_o, -m/w_o, ++r_o/w_o, -\bar{\bar{A}}, B)$$

$$F/A = f(-f/r_o, -\tilde{\theta}, -\bar{\bar{A}}, -B)$$

$$M/L = (-m/w_o, +\tilde{\theta}, +\bar{\bar{A}}, -B)$$

$$A/L = (+f/r_o, -m/w_o, -r_o/w_o, -\tilde{\theta}, +\bar{\bar{A}}, B)$$

Reduced model of factor use<sup>a</sup>:

$$F/A = (-f/r_o, +m/w_o, -r_o/w_o, +\bar{\bar{A}}, B)$$

$$M/L = (+f/r_o, -m/w_o, +r_o/w_o, \pm\bar{\bar{A}}, B)$$

$$A/L = (\pm f/r_o, \pm m/w_o, -r_o/w_o, +\bar{\bar{A}}, B)$$


---

<sup>a</sup>When two signs are given, the top one is that which holds if the factor substitution effect for a given technology dominates while the lower one is that which holds if the induced innovations effect for a given budget size dominates.

### 3.2 The Simulation Setup

The distribution of access to credit (K) across farms was parameterized using a simple functional form of the Lorenz curve,  $y = x^\beta$ , where x is the cumulative share of the farming population and y is the cumulative share of K.  $\beta$  is a distribution parameter equal to or greater than one:  $\beta = 1$  means perfect equality while  $\beta = \text{infinity}$  means perfect inequality. The Gini coefficient can easily be computed on the basis of  $\beta$ :  $\text{Gini} = (\beta - 1)/(\beta + 1)$ . For comparative purposes, note that the Gini coefficient for land-ownership or usufruct is typically between 0.3 and 0.6 in Africa and between 0.5 and 0.8 in Latin America.  $\text{Gini} = 0$  for  $\beta = 1$  and  $\text{Gini} = 1$  for  $\beta = \text{infinity}$ . For  $\beta = 3$ ,  $\text{Gini} = 0.5$ .

From the Lorenz curve, the share of total K by quantile can be derived. Let v be the number of quantiles; then, the average K within the nth quantile is given by the product of  $(1/v)^{\beta-1}[n^\beta - (n-1)^\beta]$  by the average access to credit  $K/N$ , where N is the total number of farms in the sector.

The average K for each quantile is used to derive, first, the wage rate and the land rental rate and, consequently, the average output per farm for each quantile using the previously derived result that  $Q = K/c$ . Note that in so doing we have again assumed that access to credit is the parameterized variable that differentiates farmers.

Once average output per quantile is obtained from the above, aggregate output is directly derived by summing over the n quantiles. Total output is a function of  $\theta$ , and it is possible to derive numerically the optimal  $\theta$  that maximizes total output by iteration or, more quickly, by second-order Taylor

approximation around the optimum. For the subsequent analysis, the population was divided into 20 quantiles.

### 3.3 Some Results

Simulation results show that taking into account distribution effects does not contradict the hypothesis that a larger average farm size is associated with the choice of a more laborsaving technology.

The Lorenz curve specification we used allows us to dissociate the impact on  $\tilde{\theta}$  of the distribution of farm sizes from the effect of the average farm size. Figure 2 shows that, keeping the average farm size constant, an increase in inequality reflected by a higher Gini coefficient leads to a  $\tilde{\theta}$  that is smaller than the  $\tilde{\theta}_0$  computed on the basis of the average farm--that is for Gini = 0.

In other words, the results tell us that trying to estimate the optimum research budget allocation on the basis of the average farm size without paying attention to land distribution leads to a bias. This bias always goes in the same direction: the true  $\tilde{\theta}$  is geared toward a more laborsaving or less landsaving technology, that is, closer to the interests of large farmers. In fact, the bias can never be in favor of small farmers. This means that inequality in assets distribution combined with failures in factor markets can account for at least part of the unexplained bias in favor of mechanization observed by Hayami and Ruttan and Thirtle. This calls for adding asset distribution as an explanatory variable when testing for induced technological change.

Furthermore, Figure 2 shows that the discrepancy between the optimal  $\theta$  predicted by the simple average farm model and the optimal  $\theta$  controlling for

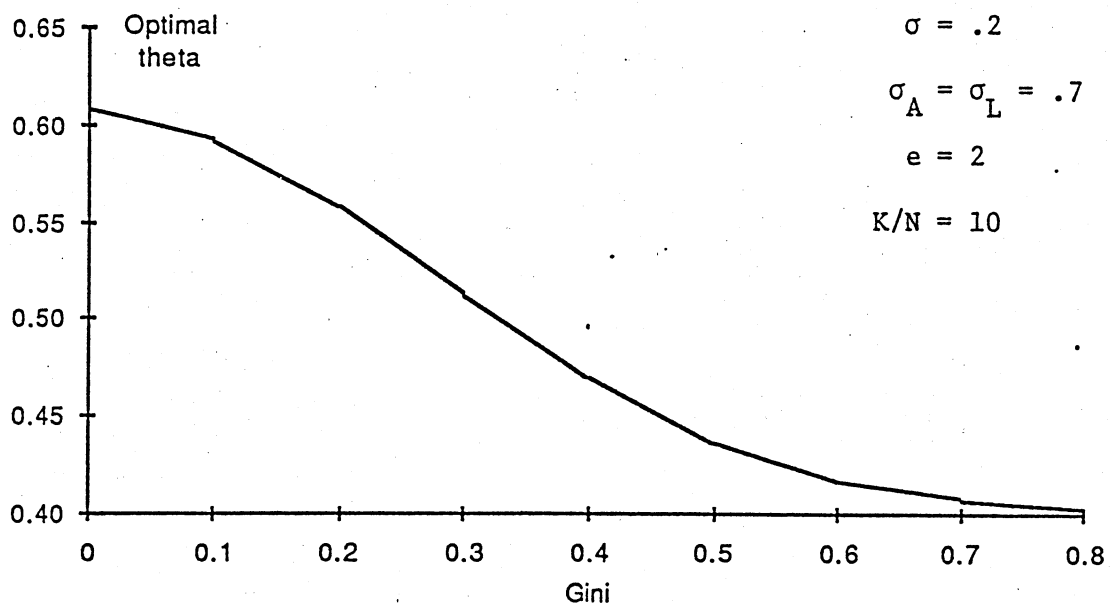


Figure 2  
Technology and Inequality

inequality in the distribution of assets is larger the larger inequality is. For low levels of inequality, the gap remains relatively small, but it grows progressively wider as inequality becomes marked.

Simulation results also show that, as is intuitively expected, less flexibility in production ( $\sigma$  smaller) and less decreasing returns of scale in research ( $e$  smaller) lead to a larger impact of asset distribution on the choice of the optimal  $\theta$ . Indeed, we have seen that quickly decreasing returns to research increases the curvature of the relationship between output and  $\theta$  and tend to concentrate  $\tilde{\theta}$  around 0.5. This is because, in that case, excessive specialization of research in one type of technology is not favored. Similarly, less flexibility in production increases differences between farms with different factor costs and, therefore, reinforces the effects of inequality.

Finally, we can also use the simulation model to establish numerically the signs of the relation between inequality and factor ratios. These signs could not be derived analytically in Section 3.1. The results in Table 4 show that, for given  $\theta$ , as inequality increases,  $F/A$  decreases while  $M/L$ ,  $A/L$ , and  $F/M$  increase when  $\sigma_A = \sigma_L < 1$ . If, however,  $\sigma_A = \sigma_L > 1$ ,  $F/M$  decreases with inequality.

#### 4. Lobbying for Technological Change

The farm model has shown that, with transactions costs, different groups of farmers have diverging interests concerning technological change. They will likely, therefore, try to affect the research effort in favor of their own optimal technological bias.

Without developing a full model of lobbying behavior with costs to farmers and impact functions of lobbying on the state's utility function (Zusman), the

TABLE 4

Simulation Results: Variation of the Optimal Factor Ratios  
with Inequality and Substitutability

Gini	F/A	M/L	A/L	F/M
$\sigma_A = \sigma_L = .9$				
.3	5.0	3.2	0.6	1.0
.5	2.7	4.8	1.9	1.1
.7	1.3	12.5	12.5	1.3
$\sigma_A = \sigma_L = 1.2$				
.3	8.3	5.0	0.6	1.0
.7	1.6	16.7	6.9	0.7

Note: In these runs,  $\sigma = .1$  and  $\theta = .5$ .



direction of the bias of technological change created by lobbying activities can be assessed with a few assumptions.

The motivation for and intensity of bargaining by a group of farmers with landownership  $\bar{A}$  is the loss in profit that they would incur with any allocation  $\theta$  of the research budget chosen by the state that deviates from  $\tilde{\theta}(\bar{A})$ , their own optimal  $\theta$ . As seen in the farm model, profit per unit of credit is directly related to output:

$$\pi(\theta, \bar{A}) = \frac{1}{K(\bar{A})} \left[ p - c(\theta, \bar{A}) \right] Q(\theta, \bar{A}) = p \frac{Q(\theta, \bar{A})}{K(\bar{A})} - 1$$

and potential loss in profit per unit of credit due to suboptimal research budget allocation is:

$$\pi^*(\theta, \bar{A}) = \frac{p}{K(\bar{A})} \left\{ Q(\theta, \bar{A}) - Q[\tilde{\theta}(\bar{A}), \bar{A}] \right\}.$$

The impact of lobbying activities on the state's objective function depends on this potential loss. It is approximated here by a linear function

$$g(\bar{A}) \cdot \pi^*(\theta, \bar{A})$$

in which  $g(\bar{A})$  represents the efficiency of lobbying.

The state then maximizes its utility which is a weighted average of its own objective goal of sectoral output and the utility derived from making concessions to the lobbies of the different classes of farmers. This is equivalent to

$$\text{Max}_{\theta} \int_{\bar{A}} \frac{1}{c(\theta, \bar{A})} [aK(\bar{A}) f(\bar{A}) + bg(\bar{A})] d\bar{A}.$$

In this model, the structure of the negotiating process and the efficiency of lobbying are completely summarized by the bargaining intensity function  $g(\bar{A})$  and by the weights  $a$  and  $b$  in the state's objective function.

A negotiating structure in which the power of a class of farmers is proportional to the size of their operational units or credit is characterized by

$$g(\bar{A}) = K(\bar{A}) f(\bar{A}).$$

The lobbying model then reduces to the state optimal policy of maximizing sectoral output.

A more "democratic" decision process which gives equal power to all farmers regardless of their farm sizes is represented by

$$g(\bar{A}) = f(\bar{A}).$$

Relative to the state's optimum for sectoral output maximization, the outcome will clearly be a bias toward the demand of small farmers for technological change.

By contrast, if lobbying power is determined by the cohesion of a group and its ability to control free riding, power will be inversely related to the number of farmers in the group (Olson). In this case,

$$g(\bar{A}) = K(\bar{A}) \cdot f(\bar{A})/f(\bar{A}) = K(\bar{A}).$$

This lobbying model will induce a strong bias in the state's decision toward the requests of the large farmers.

Using numerical analysis, we can simulate the impact that various specifications of the bargaining process have on the optimum  $\theta$ . Using as a functional form

$$g(\bar{A}) = K^{\alpha}(\bar{A}) f(\bar{A})$$

with  $\sigma = .2$ ,  $\sigma_L = \sigma_A = .7$ ,  $e = 2$ ,  $\text{Gini} = 0.5$ ,  $K(\bar{A}) = 10$ , for the bargaining function and leaving aside the state's own objective ( $a = 0$ ,  $b = 1$ ), we obtain:

$\alpha$	$\tilde{\theta}$	Type of bargaining
0	.63	Democracy
0.5	.52	
1	.44	State optimum
1.5	.38	
2	.33	
$\alpha = 1$ and $f(\bar{A}) = 1$	.27	Lobbying

While the state's optimum biases technology away from  $\tilde{\theta} = .5$  toward the technological interests of the large farmers ( $\tilde{\theta} = .44$ ), a democratic bargaining structure can lead to optimal research budget allocations that are favorable to small farmers ( $\tilde{\theta} = .63$ ). By contrast, collective action when the effectiveness of lobbies is inversely proportional to the size of class membership will further distort technological biases toward the interests of the large farmers ( $\tilde{\theta} = .27$ ).

We thus conclude that, once transactions costs are taken into account to make technological demands farm-class specific, the mechanisms of decision making at the level of the state become important determinants of the bias of technological change. The efficacy of collective action and the degree of autonomy of the state are thus essential components of a theory of induced technological innovations.

### 5. Empirical Tests of Induced Innovations

The induced innovations model which we have developed in this paper provides us with a set of testable propositions concerning the determinants of change in factor ratios. The expected signs in the relationship between factor ratios, relative factor prices, and structural variables (average farm size, inequality in the distribution of farm sizes, and size of the research budget) are summarized in the top third of Table 5.

To estimate these relationships, we use international data for the year 1970 starting from a sample of 45 more- and less-developed countries for which data on factor use are given by Hayami and Ruttan. This data set is complemented by data on wages (International Labor Organization), tractor prices (Kravis, Heston, and Summers), and fertilizer prices (United Nations, FAO). Land rents are calculated as a residual from

$$r = \frac{1}{A}(pQ - wL - fF - mM).$$

Data on public sector research budgets are taken from Boyce and Evenson. To eliminate the country size effect, the research budget is measured per acre of arable land. Data on average farm size and land distribution are obtained from the World Census of Agriculture (United Nations, FAO, 1981). Inequality ( $\bar{dA}$ ) in the distribution of farm sizes is measured as the negative of the percentage number of the largest farms controlling 50 percent of the land. Two alternative regressions are run where A is either total farmland or arable land. The most limiting data source is that for tractor prices which reduces

Table 5. Determinants of Factor Ratios: International Comparison

	$\log \frac{F}{r}$	$\log \frac{m}{w}$	$\log \frac{r}{w}$	$\bar{A}$	$\alpha \bar{A}$	$\frac{B}{A}$	$R^2$	
<u>Signs expected from theory</u>								
$\log F/A$	Substitution only <sup>a</sup>	-	0	0	-	-		
	Induced innovation <sup>b</sup>	-	+	-	$\frac{-}{+}$ <sup>c</sup>	$\frac{-}{+}$	? <sup>d</sup>	
$\log M/L$	Substitution only <sup>a</sup>	0	-	0	+	+	-	
	Induced innovation <sup>b</sup>	+	-	+	$\pm$	$\pm$	?	
$\log A/L$	Substitution only <sup>a</sup>	+	-	-	+	+	?	
	Induced innovation <sup>b</sup>	$\pm$	$\pm$	-	+	+	?	
$\log F/M$	Substitution only <sup>a</sup>	-	-	-	-	?	?	
	Induced innovation <sup>b</sup>	$\pm$	$\pm$	-	-	?	?	
<u>Observed prices, n = 18</u>								
$\log F/A$	Farmland	-2.84 (2.93) <sup>e</sup>	.59 (.62)	-.99 (1.02)	$\bar{F}$	-.06 (1.97)	140 (2.48)	.79
	Arable land	-1.35 (2.36)	-.38 (.67)	-.39 (.67)	-.02 (1.94)		69 (2.26)	.89
$\log M/L$	Farmland	-1.11 (1.24)	-1.13 (1.29)	-.57 (.66)				.88
	Arable land	-1.10 (1.31)	-1.12 (1.34)	-.60 (.73)				.89
$\log A/L$	Farmland	.41 (.87)	-.32 (.74)	-.23 (.50)	.02 (5.49)		-.80 (-2.55)	.92
	Arable land	-.21 (.63)	-.10 (.32)	-.28 (.82)	.04 (5.88)		-.35 (2.00)	.91
$\log F/M$	Farmland	-.78 (1.53)	1.47 (2.71)	-.97 (1.87)		-.05 (2.33)		.71
	Arable land	-.79 (1.59)	1.44 (2.75)	-.94 (1.87)		-.05 (2.33)		.71
<u>Price machinery = 1, n = 27</u>								
$\log F/A$	Farmland	-.30 (.85)	.55 (.21)	-.83 (2.96)	-.01 (1.74)			.86
	Arable land	-1.05 (2.81)	.48 (1.49)	-1.25 (4.23)		-.03 (1.58)	20 (1.64)	.89
$\log M/L$	Farmland	-.20 (.52)	-1.58 (5.45)	-.12 (.58)	.01 (2.35)			.90
	Arable land	0.37 (.94)	-1.45 (4.70)	-.27 (.85)	.01 (1.56)			.89
$\log A/L$	Farmland	-.32 (1.40)	-.19 (1.08)	-.33 (1.79)	.01 (6.74)		-.54 (4.15)	.88
	Arable land	.14 (.81)	-.54 (3.76)	-.05 (.36)	.02 (6.09)		-.45 (6.36)	.90
$\log F/M$	Farmland	.58 (1.91)	.45 (1.81)	-.14 (.06)		-.02 (1.72)		.81
	Arable land	.48 (1.50)	.54 (2.08)	-.09 (.35)		-.03 (1.89)		.78

<sup>a</sup>Substitution effects are measured as  $X_i/X_j = F(F/r, m/w, r/w; \theta; \bar{A}, \alpha \bar{A}, B)$ .

<sup>b</sup>Induced innovation effects are measured as  $X_i/X_j = F(F/r, m/w, r/w; \bar{A}, \alpha \bar{A}, B)$ .

<sup>c</sup>When two signs are given, the top one is that which holds if the factor substitution effect for a given technology dominates while the lower one is that which holds if the induced innovations effect for a given budget size dominates.

<sup>d</sup>Question mark indicates that the sign is analytically ambiguous.

<sup>e</sup>Figures in parentheses are t-ratios.

<sup>f</sup>Blanks indicate that the coefficient of the corresponding structural variable ( $\bar{A}$ ,  $\alpha \bar{A}$ ,  $B/A$ ) is not significantly different from zero at a 95 percent confidence level.

the sample of countries to 18. Since there is relatively little international variation tractor prices, we run an alternative set of regressions where we set the price of tractors equal to 1 to gain degrees of freedom, thus extending the sample of countries to 27.

The results obtained are strikingly consistent with theory, both in the price and structural determinants of differences in factor ratios across countries. They show that structural variables are indeed important in explaining factor biases in induced technological innovations. In particular, larger farms and/or more inequality in the distribution of farm sizes decrease the bias toward landsaving technological change ( $F/A$  and  $F/M$ ) while enhancing the bias toward laborsaving technological change ( $M/L$ ) and the land/labor ratio. The direction of the impact of the size of the research budget on the bias of induced innovations could not be predicted by theory.

A surprising result is that the size of the research budget per acre of arable land tends to increase the technological bias toward landsaving technological change and away from laborsaving technological change. This has three possible explanations. One is that, as the simulation results of Table 2 have shown, allocation of the research budget is biased toward labor-saving technological change ( $\tilde{\theta} < 0.5$ ). Both the state's optimum choice and successful lobbying by large farmers have, indeed, shown to be biased toward laborsaving. A rising research budget may, however, relax this bias as it allows to accommodate the demands of all farmers without exclusion. Another explanation is that there exists an innate bias in research toward laborsaving technological change which also implies a laborsaving bias that only decreases with rising research budgets. Finally, it may well be that research on mechanical innovations is principally funded by the private sector, since it

is easily patentable, while research on biological innovations, which is more of a public good, is funded by the public sector. Since the research budget measured by Boyce and Evenson is for public sector research, the observed association between budget size and landsaving bias is not surprising.

## 6. Conclusion

We have shown in this paper that introducing transactions costs and collective action into a formal model of induced technological innovations significantly alters the predictions of the pure neoclassical model. It explains, in particular, why different classes of farmers and the state all have different definitions of an optimum technological bias. If the state allocates resources to research so as to maximize sectoral output or value added, technology will be biased toward more laborsaving technological change than the optimum technology for the average farm. This bias will be reinforced by effective collective action by large farmers. Empirically, average farm size, inequality in the distribution of landownership, and the size of the research budget are seen to be important determinants of the observed technological bias. While a larger average farm size and a more unequal land tenure system increase the bias toward laborsaving technology, larger research budgets favor instead allocating a greater share of research expenditures toward landsaving technological innovations. A larger public sector research budget is thus less regressive on the distribution of welfare gains from technological change across farm sizes than a smaller budget. Progressive effects of technological change will, however, not come about without effective lobbying by small farmers to affect the definition of public sector research priorities.

Footnotes

<sup>1</sup>For an excellent recent review, see Thirtle and Ruttan.

<sup>2</sup>The main sources of empirical information on these elasticities are Kako, Hayami and Ruttan, Thirtle (1985a, b, c), and Lopez. Average values derived from these studies are: within group elasticities ( $\sigma_{AF} = .45$ ,  $\sigma_{LM} = .38$ ) and between group elasticities ( $\sigma_{AL} = .27$ ,  $\sigma_{FL} = .03$ ,  $\sigma_{FM} = .13$ ,  $\sigma_{AM} = .13$ ).



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