Modeling Directions of Technical Change in Agricultural Sector[*]

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ABSTRACT

This paper reviews the economic models explaining the directions of technical change. The application to agricultural sector is also explored. The induced innovation model extensively used in agricultural development studies has left unexplained stylized facts in several empirical evidences. This leads to the motivation of this paper to find an alternative model. While the induced innovation relies heavily on the change of relative factor price on biased technical change, the directed technical change model developed by Acemoglu (2002, 2007, 2009) endogenizes investment on research and explains the incentives of technology monopolists. The directed technical change model is developed and applied to agricultural sector. Given a hypothetical situation of increasing relative scarce agricultural labor, the model provides insights of which the policy direction for technical change in agricultural sector can be expected.

Keywords: directed technical change, induced innovation

JEL Classification: O31, O33

1. Introduction

Understanding the process of technical change has several important implications for economic growth and performance. While the process of technical change is complex, the economic theories and models of technical change were often oversimplified and may fail to capture the true essence of the inspiration. There has been a long history of development in economic theories and modeling to provide a better understanding of the process of technical change and relate it to market structure and economic policy. On the one hand, endogenous technical change models identify the determinants of technical change by embedding research efforts such as research expenditures and human capital into the model. The aggregate endogenous technical change models identify potential innovations and provide a better understanding of the sources and rates of innovation; however, the question of the direction or bias of technical change could not be explained by aggregate endogenous technical change models. Because stakeholders in different input industries receive different benefits depending on the direction of technical change, understanding the directed or bias technical change models, on the other hand, is essential in determining choices of technology, appropriate distribution of income, and allocation of resources to interested stakeholders.

Numerous developments in economic theories of technical change have focused on industrial sectors, but little has been applied to agricultural sectors. Because of its complexity, rationalizing the process of technical change in industrial sectors is not necessarily appropriate for the agricultural sector. The studies of technical change in agriculture have concentrated on empirical modeling and estimation of the aggregate intensities and impacts of technical change; whereas much less work has been done on the study of the direction of technical change. The most prominent theory of the direction of technical change, particularly applied to agricultural sector, is the "Induced Innovation" hypothesis. Although the induced innovation hypothesis simplifies the complexity of agricultural development, it left several unexplained stylized facts that require more appropriate economic theory. The motivation of this paper is to propose an alternative economic theory that could better explain the direction of technical change in agriculture. This paper will be divided into three sections. First, an overview of the previous development of induced innovation models is briefly discussed with the emphasis on agricultural sector evidences, and the reason why there is a need to find more appropriate models for the direction of technical change in agricultural development. Second, Acemoglu's "Directed Technical Change" model is explained as an alternative to explain the direction of technical change. And last, a hypothetical illustration of directed technical change model is illustrated for the agricultural sector.

2. The Induced Innovation Theory

The concept of induced innovation model derived from Hick's Theory of Wages. […a change in the relative price of the factors of production is itself a spur to invention, and to invention of a particular kind—directed to economize the use of the factor which has become relatively expensive…invention which are the result of a change in the relative prices of the factors; let us call these "induced" inventions…] (Hicks 1932, p. 124-125). […If we concentrate on two groups of factors, "labor" and "capital", and suppose them to exhaust the list, then we can classify inventions according as their initial effects are to increase, leave unchanged, or diminish the ratio of the marginal product of capital to that of labor. We may call these inventions "labor-saving," "neutral," and "capital-saving" respectively. "Labor-saving" intentions increase the marginal product of capital more than they increase the marginal product of labor; “capital-saving” inventions increase the marginal product of labor more than that of capital; “neutral” inventions increase both in the same proportion…] (Hicks 1932, p. 121-122)

Kennedy (1964) introduced the induced technical change model to the literature by suggesting the Innovation Possibility Function (IPF). What drives the innovation is not the change in relative factor prices, but the relative factor shares. Labor-saving innovations are competitive with capital-saving reduction in a typical two-factor production model. The greater the reduction in the labor required to produce a unit of output, the smaller will be the possible reduction in capital required (Kennedy, 1964). The IPF between capital and labor specifies the set of potential instantaneous rates of factor augmentation at a given state of knowledge. The greater the share of labor costs in total costs, the more labor-saving innovations are chosen by the entrepreneurs. The concave shape and the concept of IPF are similar to the Production Possibility Function (PPF), except that it has two advantages. First, the IPF has a dynamic sense of the possibilities to innovate rather than a static technology of the production function. Secondly, the characteristics of IPF determine the biased innovations reflected from the distributive shares of factors or the weights of cost-saving shares. However, the IPF did not explain how much a fall in labor requirements has been brought about by a labor-saving innovation rather than a substitution of cheaper capital for labor, and unable to take increasing returns and monopolistic production. The macro perspective of IPF, as criticized by Binswanger (1974b), was difficult for empirical analysis due to measurement of factor augmentation rates.

Samuelson (1965) adopted the factor augmenting model in neoclassical production and expanded the Kennedy IPF model. In a long-run equilibrium model, as long as labor and capital are not perfectly substitutable (elasticity of substitution less than 1), an increase in labor share from capital accumulation, will make it profitable to introduce relatively more labor-augmenting innovations. A long-run equilibrium is led by induced relatively labor-augmenting or labor-saving inventions to keep a constant capital/labor ratio. However, if the elasticity of substitution is greater than one, which will cause an unstable long-run equilibrium, the model shows that a research effort is simply to reduce the cost of production, with no implied bias of innovation.

Ahmad (1966) interpreted Kennedy's IPF by characterizing each innovation by a set of isoquants (corresponding to a particular production function), where labor and capital are represented on the two axes. Innovation possibility curve (IPC), in his analysis, is an envelope of all the alternative isoquants developed with the use of given innovating skills and time. An increase in a relative wage to price of capital will first encourage a substitution of capital for labor (a switch of isoquants representing particular production functions along IPC), and will further induce an innovation of labor-saving technology (a shift of IPC). The IPC in his analysis is purely technological or laboratory question, and the economic consideration would come from choosing a particular isoquant out of various isoquants belonging to a particular IPC. The IPC did not add further explanation of reasons of the movement from old IPC to new IPC, except for the relative change in factor prices.

The Induced Innovation theory has been widely used as a model to analyze a biased technical change in agriculture. Hayami and Ruttan (1970) were first to analyze the induced innovation hypothesis by a comparative study of technical progress between Japan and the U.S. during 1980-1960. A decrease in a relative price of land and machinery to wages in U.S. agriculture promoted a substitution of land and power for labor and also encouraged mechanical innovations. It was observed by a substantial increase in land and power to labor ratio which would have been a limited substitution with a fixed technology. While an inelastic supply of land in Japan and a decrease in relative price of fertilizer to price of land led to a significant increase in fertilizer input per crop area, it was not only because of a substitution of fertilizer for land, but also biological innovations such as improved seed varieties that are more responsive to fertilizer. A change in factor ratio in response to changes in relative factor prices represented a movement along the 'metaproduction function' or 'potential production function' similar to the IPC proposed by Ahmad. In their framework, the innovation of a new technology is represented by a movement alone the IPC instead of a shift of IPC itself, presumably because the elasticities of substitution between factors were small given fixed technology. The observed substantial changes in factor ratios in response to long-term relative factor prices would not have occurred with a fixed technology.

Simple regressions of factor ratios on relative factor prices, emphasized that it was not an attempt to test induced innovation hypothesis, show a strong negative correlation between factor ratios and relative factor prices consistent with the induced innovation hypothesis in US and Japan agricultural development. Their results found a strong evidence of the induced innovation hypothesis that countries developed a technology in response to market price signals to relax constraints on growth imposed by factor scarcities. One important observation was that not all mechanical (biological) innovations were motivated by labor (land) -saving incentives. For example, the improved varieties more suitable for mechanical harvesting were a biological innovation to save labor. Their framework later developed into a broader study of agricultural development in Western and Asian countries (Hayami and Ruttan, 1985).

Although the induced innovation hypothesis provided a simple framework of the direction of technological change, it failed to explain several empirical evidences. As pointed out by Olmstead and Rhode (1993), the evidences of what appeared to be consistent with the induced innovation hypothesis by Hayami and Ruttan (1970, 1985) in U.S. agriculture were in fact contradict to it. More updated and more accurate relative factor prices and factor ratios data when the technologies were developed in various U.S. regions explained different observations than what the induced innovation hypothesis would suggest.

Binswanger (1974a) criticized the induced innovation hypothesis for two main reasons: the difficulty to empirically test the hypothesis and the lack of microeconomic foundation. He provided a microeconomic model of innovation possibilities on the basis of research process, which has expected pay-off functions in terms of efficiency improvements, and introduces research costs. In this model, the bias of innovation was determined by 1) relative productivities of alternative researches e.g. possibility of success invention, 2) relative prices of researches e.g. price of capital-saving research to price of labor-saving research, 3) anything that changes the present value of factor cost e.g. an increase in a factor price or a factor/output ratio tends to increase relative bias in that factor-saving technology.

Binswanger (1974b) further developed an econometric model of a cost minimization approach to measure a bias technical change, allowing for many factors of production. His definition of bias was slightly different from Hick's definition. Hick's bias definition could be expressed in terms of a change in the elasticity of substitution (a ratio of marginal products) for a given factor ratio; whereas, Binswanger's definition of bias technical change was given in terms of a change in factor shares (of total cost). Based on U.S. agricultural data during 1912-1968, a five-input model of cost minimization was used to estimate a bias technical change. The bias calculated from an estimated change of factor shares over time showed that technical changes in U.S. agricultural production was biased towards machinery- and fertilizer-using, and labor-saving. The result of fertilizer-using was consistent with the induced innovation hypothesis as it was accompanied by a dramatic decrease in fertilizer price relative to price of agricultural outputs. Similarly, labor-saving technical change followed an increase in farm wages. However, a machinery-using direction contradicted to the induced innovation hypothesis as the machinery price was increasing over that time period. He explained that the direction of technical change responded only to a massive change in relative prices.

The most recent attempt to provide a microeconomic foundation to induced innovation hypothesis was done by Funk (2002). He assumed that for given factor prices, firms maximize a profit subject to the innovation possibilities. For a two-factor, capital and labor, model, the innovation possibility frontier is the set of possible pairs of the rates of factor augmentation from which firms can choose given the state of knowledge. The higher the chosen rate of labor augmentation, the smaller is the rate of capital augmentation, and vice versa. He provided both discrete and continuous time models. In the dynamic behavior of macro variables, it follows from the induced innovation hypothesis that the higher labor share in total income, the higher is the chosen rate of labor augmentation and the smaller is the chosen rate of capital augmentation. In a microeconomic model, the optimal rate of labor and capital augmentation depends on relative factor prices although it can also be expressed in terms of aggregate factor shares (as factor prices depend on aggregate quantities).

So what is wrong with the induced innovation hypothesis? The main challenges of the induced innovation hypothesis center on two main criticisms. First, there is a lack of microeconomic foundation. Binswanger (1974a, 1974b), Binswanger and Ruttan (1978) and Funk (2002) attempted to response to this criticism. These microeconomic models were developed on the basis of cost minimizing (Binswanger, 1974a, 1974b; Binswanger and Ruttan, 1978) or profit maximizing (Funk, 2002) behaviors of firms that the bias of technical change depends principally on relative factor prices. The models have been used for several empirical analyses which lead to the second criticism that sometimes empirical evidences do not support the induced innovation hypothesis. Earlier empirical evidences supporting the hypothesis include Antle (1984), Fellner (1971), Hayami and Ruttan (1970, 1985), Karagiannis and Furtan (2008), Kawagoe et al. (1986), Lambert and Schonkwiler (1995), Thirtle et al. (1995) and Thirtle et al. (2002). These earlier supporting empirical evidences of the induced innovation hypothesis were often criticized for inadequate data and inappropriate statistical methods which were corrected and improved by later studies. However, there remain other studies that found unsupportive evidences (Esposti and Pierani, 2003; Liu and Shumway, 2009; Machado, 1995; Olmstead and Rhode, 1993), uncertain cases (Armanville and Funk, 2003; Chavas et al., 1997; Liu and Shumpway, 2006; Tiffin and Dawson, 1995) or reverse causality (Khatri et al., 1998) of the induced innovation hypothesis. These unexplained determinants of the direction of technical change demand other models to explain the bias of technical change. In the next section, I propose the directed technical change model developed by Acemoglu (2002, 2007, 2009) as an alternative theory.

3. The Directed Technical Change Model

Since the introduction of the directed technical change model by Acemoglu (2002), several studies have applied it to explain skill-biased technical change and wage inequality (Afono, 2006, 2008; Cozzi and Impullitti, 2010; Foellmi and Zweimüller, 2006; Weiss, 2009) and recently on energy-saving technical change and carbon emissions (Carraro et al., 2009; Gillingham et al., 2008; Grimaud and Rouge, 2008; Otto et al., 2008) particularly in the aggregate growth model. This model has not been applied to the agricultural sector, and could provide a better understanding of the direction of technical change that the induced innovation theory could not. Building upon Acemoglu's directed technical change model (Acemoglu, 2002, 2007, 2009), I will show the application of this model in the context of the agricultural economy.

3.1 Defining Relative Bias

The focus of this paper is on the relative equilibrium bias of technical change. It is different from factor augmented technical change in general endogenous growth models. To understand the distinction between factor augmentation and factor bias, let's first look at the definitions of the two. A technical change is (everywhere) *A*-augmenting if the production function can be written as F(aA, L) while F(A, aL) corresponds to a *L*-augmenting technical change (Acemoglu, 2009). On the other hand, the relative equilibrium bias of technology is defined as the impact of technology on relative factor prices at given factor proportions (Acemoglu, 2007). Consider the agricultural sector consists of constant supplies of two factors: land (A) and labor (L), denoted by $\overline{A} \in R_+$ and $\overline{L} \in R_+$, respectively. Their corresponding equilibrium factor prices are denoted by ω_A and ω_L. The agricultural production function of aggregate final output (Y) employing A and L is given as

$$Y = F(A, L, a). \tag{1}$$

where $\bar{a}(t) \in R_+$ represents technology. The technology is *A*-biased if it increases the relative marginal product of land compared to that of labor. Given the production function in (1), it is mathematically expressed as

$$\frac{\partial \frac{\partial F(A,L,a)/\partial A}{\partial F(A,L,a)/\partial L}}{\partial a} \geq 0.$$

In contrast, the reverse inequality corresponds to a *L*-biased technical change. A biased technical change towards a particular factor will shift that factor demand curve outward; thus, for given factor proportions (relative factor quantities) its relative factor price will increase.

3.2 Defining Weak and Strong Relative Biases

The relative equilibrium biases can be classified into two types: weak relative equilibrium bias and strong relative equilibrium bias. To illustrate the difference between them, consider the example of CES production function given as

$$Y = \left[\gamma_L (a_L L)^{\frac{\sigma-1}{\sigma}} + \gamma_A (a_A A)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma-1}{\sigma}}.$$

where a_L and a_A are separate technology factors specific to each factor, and γ_L and γ_A are weighted parameters determining the importance of labor and land in the production function, and $\gamma_L + \gamma_A = 1$. The elasticity of substitution between two factors is $\sigma \in [0, \infty]$. Note that given the CES production function, two factors are perfect substitutes when $\sigma = \infty$. When there is no substitution between two factors, $\sigma = 0$, the production function is Leontief. For a unit elasticity of substitution, $\sigma = 1$, the function is Cobb-Douglas. Specifically to CES function, the two inputs are gross substitutes when $\sigma > 1$, and they are gross complements when $\sigma < 1$.

A technical change is *weak relative biased* when an increase in the relative factor supply induces a technical change biased towards the relatively more abundant factor. For example, a decrease in the relative supply of agricultural labor or equivalently an increase in the relative supply of land, *A/L*, induces the *A*-biased technical change. It is mathematically expressed as

$$\frac{\partial \mathrm{MP_A/MP_L}}{\partial \mathrm{a_A/a_L}} \cdot \frac{\mathrm{da_A/a_L}}{\mathrm{dA/L}} \geq 0 .$$

When an increase in the relative factor supply induces a sufficient large bias towards the relative more abundant factor so that the marginal product of the more abundant factor relative to that of less abundant factor increases, the technical change is *strong relative biased*. For example, an increase in A/L induces a sufficient large A-biased technical change so that MP_A relative to MP_L increases. It is mathematical expressed as

$$\frac{\mathrm{dMP_A/MP_L}}{\mathrm{dA/L}} > 0 .$$

In equilibrium BGP (balance growth path), the relative factor price ratio is given as

$$\omega^{*} \equiv \left(\frac{\omega_A}{\omega_L}\right)^{*} = \left(\frac{MP_A}{MP_L}\right)^{*}.$$

The strong equilibrium bias means, in other words, when an increase in a relatively abundant factor induces a bias in technical change that increases the relative price of the more abundant factor so that the endogenous-technology relative factor demand curve becomes upward sloping.

3.3 Demand for Technology (machineries and fertilizers/seed varieties)

The final aggregate agricultural output, Y, consists of two intermediate outputs: Y_A , land-intensive output, and Y_L, labor-intensive output. To simplify the analysis, consider a CES aggregate production function

$$Y = \left[\gamma_L Y_L^{\frac{\varepsilon-1}{\varepsilon}} + \gamma_A Y_A^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon-1}{\varepsilon}}, \qquad (2)$$

where $\varepsilon \in [0, \infty]$ is the elasticity of substitution between two intermediate outputs, and $\gamma \in [0, 1]$ is the distribution parameter which determines how important the two outputs are in the aggregate production. The two intermediate outputs are produced competitively with the following production functions

$$Y_L = \frac{1}{1-\beta}\left(\int_0^{N_L} x_L(\nu)^{1-\beta}\, d\nu\right) L^{\beta}, \text{ and} \qquad (3)$$

$$Y_A = \frac{1}{1-\beta}\left(\int_0^{N_A} x_A(\nu)^{1-\beta}\,d\nu\right)A^{\beta}, \tag{4}$$

where $\beta \in [0,1]$, L and A are total supplies of labor and land, $\nu \in [0, N]$ is a variety of technology, and $x_L(\nu)$ and $x_A(\nu)$ are quantities of corresponding complementary intermediates. Thus, the labor-intensive output is produced from labor and a range of labor-complementing inputs. I will refer to $x_L(\nu)'s$ as quantity of machineries. Likewise, land-intensive output is produced from land and a range of land-complementing inputs. I will refer to $x_A(\nu)'s$ as quantity of fertilizers (or seed varieties). A range of machineries that can be used by labor is $[0, N_L]$ while a range of fertilizers (or seed varieties) complementing the use of land is $[0, N_A]$.

It is assumed that the new innovation of technology variety ν is supplied by a technology monopolist who sets the price of the technology variety. A technical change can be interpreted as the increase in innovation ranges of complementary intermediates, N_A and N_L, supplied by technology monopolists who set the prices of machineries, $p_L^x(\nu)$, and the prices of fertilizers (or seed varieties), $p_A^x(\nu)$. As we will see later the difference in factor-complementing inputs used in the production of two intermediate outputs allows for a biased technical change.

The producers of two intermediate outputs maximize their profits. For a given price of labor-intensive output, p_L, rental price of machineries, p_L^x(vv, and the range of machineries, N_L, the profit maximization problem of labor-intensive output producers can be written as

$$\max_{L,[x_L(\nu)]_{\nu\in[0,N_L]}} p_L Y_L - \omega_L L - \int_0^{N_L} p_L^x(\nu)\, x_L(\nu) d\nu . \qquad (5)$$

Substituting production function of labor-intensive output from (3) into (5) gives

$$\max_{L,[x_L(\nu)]_{\nu\in[0,N_L]}} p_L \frac{1}{1-\beta}\left(\int_0^{N_L} x_L(\nu)^{1-\beta} d\nu\right) L^{\beta} - \omega_L L - \int_0^{N_L} p_L^x(\nu)\, x_L(\nu) d\nu .$$

The profit maximization problem of land-intensive output producers is similarly expressed as

$$\max_{A,[x_A(\nu)]_{\nu\in[0,N_A]}} p_A Y_A - \omega_A A - \int_0^{N_A} p_A^x(\nu)\, x_A(\nu) d\nu . \qquad (6)$$

The substitution of (4) into (6) gives

$$\max_{A,[x_A(\nu)]_{\nu\in[0,N_A]}} p_A \frac{1}{1-\beta}\left(\int_0^{N_A} x_A(\nu)^{1-\beta} d\nu\right)^{\beta} A - \omega_A A - \int_0^{N_A} p_A^x(\nu)\, x_A(\nu) d\nu$$

where p_A is the price of land-intensive output, $p_A^x(\nu)$ is the price of fertilizers (or seed varieties), and the range of fertilizers (or seed varieties) is N_A. The first order conditions for the maximization problems of intermediate output producers give the quantity demand for machineries as

$$x_L(\nu) = \left(\frac{p_L}{p_L^x(\nu)}\right)^{1/\beta} L, \text{ for all } \nu \in [0, N_L], \qquad (7)$$

and the demand for fertilizers (or seed varieties) as

$$x_A(\nu) = \left(\frac{p_A}{p_A^x(\nu)} \right)^{1/\beta} A \text{, for all } \nu \in [0, N_A]. \tag{8}$$

As the price of labor-intensive output increases, there is a higher demand for labor-complementary input. The higher the product price is, the higher are the values of marginal products of all factors, including that of machineries; thus producers demand more machineries in their labor-intensive production. The increase in labor employment increases the demand for machineries as they are complementary inputs, but the price of machineries decreases the demand for machineries. By the same token, the demand for fertilizers or seed varieties increases as the price of land-intensive output and land use increase, but decreases as land rent increases.

By substituting the derived demands for labor and land in (7) and (8) into the production function of intermediate outputs given in (3) and (4), the derived production functions are written as:

$$Y_L = \frac{1}{1-\beta} p_L^{\frac{1-\beta}{\beta}} N_L L \text{ , and} \tag{9}$$

$$Y_A = \frac{1}{1-\beta} p_A^{\frac{1-\beta}{\beta}} N_A A . \tag{10}$$

3.4 Relative Factor Prices as a Function of Factor Supplies

Let $p \equiv \frac{p_A}{p_L}$ be the relative price of intermediate outputs. Given the aggregate final output production in (2), the market clearing condition of competitive intermediate output markets imply that the prices of intermediate output are equal to their marginal products. Thus,

$$\frac{p_A}{p_L} = \left(\frac{\gamma_A}{\gamma_L}\right)\left(\frac{Y_A}{Y_L}\right)^{-\frac{1}{\varepsilon}}. \tag{11}$$

This implies that the higher the supply of land relative to the supply of labor, the lower is the relative rental price of land to wage rate. The response of relative prices to the relative supplies of inputs depends on the elasticity of substitution between two intermediate outputs.

Substituting (9) and (10) into (11) gives

$$p = \left(\frac{\gamma_A}{\gamma_L}\right)\left(p^{\frac{1-\beta}{\beta}}\frac{N_A A}{N_L L}\right)^{-\frac{1}{\varepsilon}}$$

$$p = \left(\frac{\gamma_A}{\gamma_L}\right)^{\frac{\varepsilon\beta}{\sigma}}\left(\frac{N_A A}{N_L L}\right)^{-\frac{\beta}{\sigma}}, \tag{12}$$

where $\sigma \equiv \varepsilon - (\varepsilon - 1)(1-\beta) = 1 + (\varepsilon - 1)\beta$, and $\sigma \geq 0$ is the derived elasticity of substitution between land and labor. Two inputs are gross substitutes if $\sigma > 1$, and $\sigma = 0$ implies no substitutability between the two. This says that $\sigma > 1$ if and only if $\varepsilon > 1$; thus, land and labor are gross substitutes if and only if land-intensive output, and labor-intensive output are gross substitutes.

In equilibrium, the first order conditions of maximization problems of the intermediate output producers with respect to L and A provide the respective factor prices as

$$\omega_L = \frac{\beta}{1-\beta} p_L \left(\int_0^{N_L} x_L(\nu)^{1-\beta} d\nu \right) L^{\beta-1}, \text{ and} \tag{13}$$

$$\omega_A = \frac{\beta}{1-\beta} p_A \left(\int_0^{N_A} x_A(\nu)^{1-\beta} d\nu \right) A^{\beta-1}. \tag{14}$$

Define relative factor prices as rental price of land compared to wage rate as $\omega \equiv \frac{\omega_A}{\omega_L}$. Similar to the intermediate output markets, the market clearing price of a factor is equal to its marginal product. The relative marginal products of land to labor using the definition of intermediate output production functions in (2) and (3) provide relative factor prices as

$$\omega = p^{\frac{1}{\beta}} \frac{N_A}{N_L}. \tag{15}$$

By substituting (12) into (15),

$$\omega = \left(\frac{\gamma_A}{\gamma_L} \right)^{\frac{\varepsilon}{\sigma}} \left(\frac{N_A}{N_L} \right)^{\frac{\sigma-1}{\sigma}} \left(\frac{A}{L} \right)^{-\frac{1}{\sigma}}. \tag{16}$$

We could see from (16) that the elasticity of substitution between land and labor defined above, by definition is equal to

$$\sigma = -\left(\frac{\mathrm{dlog}\omega}{\mathrm{dlog}(\frac{A}{L})} \right)^{-1} .$$

The last term on the right hand side of (16) implies that an increase in relative supply of land to labor always lowers the relative rental price of land to wage rate, this can be interpreted as a standard *substitution effect*. The ratio of $\left(N_A/N_L\right)$in (16) is called the relative *physical productivity* of the two factors or the ratio of factor-augmenting technologies. The relative wage, however, does not depend on just the relative physical productivity, but the value of$\left(N_A/N_L\right)^{\frac{\sigma-1}{\sigma}}$. The impact of an increase in $\left(N_A/N_L\right)$on the direction of change in $\left(\omega_A/\omega_L\right)$ depends on σ. When two factors are gross substitutes: $\sigma > 1$, an increase in $\left(N_A/N_L\right)$increases $\left(\omega_A/\omega_L\right)$. On the contrary, when two factors are gross complements: $\sigma < 1$, an increase in $\left(N_A/N_L\right)$ decreases $\left(\omega_A/\omega_L\right)$.

3.5 Relative Profits: Price Effect and Market Effect

Assuming that the marginal cost of producing all machineries and fertilizers/seed varieties is the same, and equals to ψ. The technology monopolists maximize their profit of producing labor-complementing machinery ν, which can be written as

$$\pi_L(\nu) = \left(p_L^x(\nu) - \psi\right)x_L(\nu) . \tag{17}$$

The profit of a monopolist producing land-complementing fertilizers or seed varieties can be written in the same fashion as

$$\pi_A(\nu) = \left(p_A^x(\nu) - \psi\right) x_A(\nu). \tag{18}$$

The price of technology monopolists set a constant markup over marginal cost given the constant elasticity demand curve for machineries and fertilizers/seed varieties in (7) and (8) so that and $p_L^x(\nu) = \frac{\psi}{1-\beta}$[1]. By normalizing the marginal cost to simplify the analysis, $\psi \equiv 1-\beta$, equilibrium prices of all machineries and fertilizers/seed varieties are equal to $p_L^x(\nu) = p_A^x(\nu) =$ 1 for all ν. Taking the demands derived in (7) and (8) and normalized marginal costs and prices of technology varieties, the profit in (17) and (18) can now be written as

$$\pi_L(\nu\nu = \beta p_L(\nu)^{1/\beta} L, \text{ and} \tag{19}$$

$$\pi_A(\nu\nu = \beta p_A(\nu)^{1/\beta} A. \tag{20}$$

From (19) and (20), the profits of monopolists depend only on the sector of technology there are supplying. To compare the relative

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[1] To simplify the illustration, normalizing p_L to 1. The maximization of labor-intensive output producer becomes $\max_{L,[x_L(\nu)]_{\nu\in[0,N_L]}} \frac{1}{1-\beta}\left(\int_0^{N_L} x_L(\nu)^{1-\beta} d\nu\right) L^\beta - \omega_L L - \int_0^{N_L} p_L^x(\nu) x_L(\nu) d\nu$ yielding derived demand for machineries as $x_L(\nu) = p_L^x(\nu)^{-1/\beta} L$. The maximization problem of machineries monopolists is $\max \pi_L(\nu) = \left(p_L^x(\nu) - \psi\right) p_L^x(\nu)^{-1/\beta} L$ which gives the first order condition as $p_L^x(\nu) = \psi/(1-\beta)$.

profits of the two sectors, the relative profit of monopolists in fertilizers- and seed varieties- producing sector to that of monopolists in machineries-producing sector is written as

$$\frac{\pi_A}{\pi_L} = \underbrace{\left(\frac{p_A}{p_L}\right)^{1/\beta}}_{\text{price effect}} \quad \underbrace{\frac{A}{L}}_{\text{market size effect}} \quad . \tag{21}$$

The first term on the right hand side of (21) is called a *price effect*, and the second term is called a *market size effect*. The price effect suggests more incentives to invent technology complementing scarce inputs because the price of output that is produced intensively from scarcer input is relatively more expensive. Intuitively the price effect gives more incentives to develop technology when goods produced by these technology command higher price while the market size effect makes technology that has a larger market more profitable.

An increase in relative supply of inputs generates two opposing effects on relative profits. When there is an increase in relative land to labor (A/L), its relative price (p_A/p_L) decreases. Thus, while the market size effect increases relative profit (π_A/π_L) from an increase in (A/L), the price effect from a decline in (p_A/p_L) decreases it. Whether there will be more incentive to develop land-complementing technology or labor-complementing technology depends on these two opposing effects. The larger the profit from fertilizers and seed variety sector relative to profit from machineries sector, the higher are the incentives to develop land-complementing technology, N_A, than labor-complementing technology, N_L.

To illustrate the effects of relative prices and the market size on the relative profits, substituting the relative intermediate output prices in

(12) into (21) gives the relative profits of technology monopolists which can be expressed as

$$\frac{\pi_A}{\pi_L} = \left(\frac{\gamma_A}{\gamma_L}\right)^{\frac{\varepsilon}{\sigma}} \left(\frac{N_A}{N_L}\right)^{-\frac{1}{\sigma}} \left(\frac{A}{L}\right)^{\frac{\sigma-1}{\sigma}}. \qquad (22)$$

If $\sigma > 1$, an increase in (A/L) increases (π_A/π_L). When factors are gross substitutes, the market effect dominates the price effect so that there are more incentives to improve the productivity of abundant factor. In contrast, when factors are gross complements, $\sigma < 1$, the price effect dominates the market size effect, and there will be more incentives to improve the productivity of scarce factor.

3.6 Endogenous Directed Technical Change

Aside from factor supplies, the endogenous technical change takes into account other factors determining the supply of technology. On the supply side of technology, the incentives for developing new technology determine the directions of technical change. The production of new innovations is constrained by the innovation possibility frontier, which was introduced by Kennedy (1964) as a relationship between two new technologies that reduce the cost shares of two inputs. Consider two endogenous technical change models: lab equipment model and knowledge-driven model (Rivera-Baltiz and Romer, 1991. The *lab equipment model* requires only the final goods as inputs, and there is no knowledge spillover of past research to current productivity for sustainable growth). The *knowledge-driven model*, on the other hand, uses scarce input (labor) for research and development. Thus, sustainable growth requires that scarce factors' productivity increases so that marginal productivity does not decline and there will be a knowledge spillover from previous research (Acemoglu, 2002).

Allowing the costs of developing different technology to be different, consider first the lab equipment model of technology development. The specification of the lab equipment model is given as

$$\dot{N}_L = \eta_L R_L \text{ and } \dot{N}_A = \eta_A R_A, \qquad (23)$$

where η_L and $\eta_A > 0$, and $\dot{N}_L$ and $\dot{N}_A$[2] are the growths in new varieties of machinery and fertilizers/seed varieties, respectively. The growth of new machinery varieties depends on the R&D spending (in terms of labor-intensive output) on developing labor-complementary machineries, R_L. The growth of new fertilizers/seed varieties depends on the R&D spending (in terms of land-intensive output) on developing land-complementary fertilizers/seed varieties, R_A. η_L represents marginal incremental change in new innovations of machineries from one unit of R&D spending directed at discovering new machineries, and also one unit of R&D spending on developing fertilizers/seed varieties gives η_A new varieties of fertilizers and seed. The difference in η_L and η_A implies that the cost of inventing two types of technology may be different. Equation (23) can be considered as the innovation possibilities in the context of this model.

Since there is no knowledge spillover or zero state dependence, it is found from (23) that $\left(\partial \dot{N}_A / \partial R_A\right) / \left(\partial \dot{N}_L / \partial R_L\right) = \eta_A / \eta_L$. The ratio of marginal changes in new varieties of two types of technologies is

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[2] Simplifying the notation without lost of generosity of time derivative, $\dot{N}(t) \equiv dN(t)/dt$.

independent of the levels of $\dot{N}_A$ and $\dot{N}_L$. In the steady state equilibrium, prices of both intermediate outputs, p_L and p_A, are constant; the ratio of profits (π_A/π_L) is constant and equal to (η_L/η_A). This implies that the technology monopolists in machineries and fertilizers/seed sectors have incentives to innovate in both sectors. The market clearing condition in the technology market is as follows

$$\eta_A\pi_A/\eta_L\pi_L . \tag{24}$$

As long as there are possibilities for innovations in both technology sectors, $\dot{N}_A$ and $\dot{N}_L > 0$, it is equally profitable to invest in R&D directed at labor- and land- complementary technologies. Substituting the monopolists' technology profits in (19) and (20) in the market clearing condition (24), and using relative intermediate output prices in (12), we can solve for the relative physical productivity of innovations in both sectors as

$$\frac{N_A}{N_L} = \left(\frac{\eta_A}{\eta_L}\right)^{\sigma}\left(\frac{\gamma_A}{\gamma_L}\right)^{\varepsilon}\left(\frac{A}{L}\right)^{\sigma-1} \tag{25}$$

The endogenous technical change in (25) suggests that the relative bias of technology, a change in relative physical productivities (N_A/N_L), is determined by the relative supply of factors (A/L), and the elasticity of substitution between two factors, σ. Recall from (16) that the direction of change in (ω_A/ω_L) depends also on (N_A/N_L).

The impact of relative factor supplies on relative profits and relative factor prices depend on the elasticity of substitution between two factors. To see whether the elasticity of substitution between factors influences the weak and strong biased technical change, consider endogenous lab equipment technical change model. From (25), if $\sigma > 1$, an increase in (A/L) increases (N_A/N_L); an increase in relative factor supplies will increase the relative physical productivity of more abundant factor. As (16) suggests when $\sigma > 1$, an increase in (N_A/N_L) will increase (ω_A/ω_L). Thus, when two factors are gross substitutes, the endogenous technical change is biased towards more abundant factor. When $\sigma < 1$, (25) suggests that an increase in (A/L) will decrease (N_A/N_L). However, a decrease in (N_A/N_L) will increase (ω_A/ω_L) when $\sigma < 1$ as suggested in (16). Thus, when two factors are gross complements, technical change is also biased in favor of relative more abundant factor. As long as the production function is not Cobb-Douglas (when $\sigma = 1$), an increase in relative more abundant factor always endogenously biased in favor of relative more abundant factor; this is the *weak induced-bias hypothesis* of endogenous directed technical change model.

Substituting (25) into (16) yields

$$\frac{\omega_A}{\omega_L} = \left(\frac{\eta_A}{\eta_L}\right)^{\sigma-1} \left(\frac{\gamma_A}{\gamma_L}\right)^{\varepsilon} \left(\frac{A}{L}\right)^{\sigma-2}. \qquad (26)$$

By allowing (N_A/N_L) to adjust when (A/L) changes in the endogenous technical change model, the response of relative factor prices to a change in (A/L) in (26) is greater than that in (16)[3]. From (26), an increase in (A/L) will increase (ω_A/ω_L) when $\sigma > 2$. As defined earlier, the *strong induced-bias hypothesis* states that when the

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[3] $\sigma-2 > -1/\sigma$

elasticity between two factors are sufficiently large, an increase in relative abundant factor will increase relative price of more abundant factor, or an upward sloping factor demand curve. In this model, when σ > 2, there is a strong relative bias technical change. Intuitively, when the elasticity of substitution between two factors is large enough, the market size effect outweighs the price effect and also outweighs the normal substitution effect, for a given technology.

In the knowledge-driven model, the future relative costs of innovation, which implies the innovation possibilities, are influenced by current stage of research and development. The degree of this dependency is captured by state dependence, δ*;* and $\delta \in [0,1]$. Assuming that there are constant supplies of scientists devoted to R&D in each technology sectors, the production functions of innovations are specified as

$$\dot{N}_L = \eta_L N_L{}^{(1+\delta)/2} N_Z{}^{(1-\delta)/2} S_L \text{ and } \dot{N}_A = \eta_A N_L{}^{(1-\delta)/2} N_A{}^{(1+\delta)/2} S_A, \quad (27)$$

where S_L and S_A are number of scientists conducting R&D in machineries and fertilizers/seed varieties, respectively. When $\delta = 0$, $(\partial \dot{N}_A / \partial S_A)/(\partial \dot{N}_L / \partial S_L) = \eta_A / \eta_L$ and there is no state dependence, providing similar results to the lab equipment model.

The technology market clearing condition became

$$\eta_A N_A^{\delta} \pi_A = \eta_L N_L^{\delta} \pi_L . \quad (28)$$

Note that (28) exactly to (24) when δ = 0. Using (12), (19) and (20), the equilibrium relative technology is

$$\frac{N_A}{N_L}=\left(\frac{\eta_A}{\eta_L}\right)^{\frac{\sigma}{1-\delta\sigma}}\left(\frac{\gamma_A}{\gamma_L}\right)^{\frac{\varepsilon}{1-\delta\sigma}}\left(\frac{A}{L}\right)^{\frac{\sigma-1}{1-\delta\sigma}}. \tag{29}$$

In this model, response of relative physical productivities to change in relative factor supplies depend not only on σ, but also on δ. Unless there is no state dependency, an increase in (A/L) increases (N_A/N_L); an increase in relative factor supplies will increase the relative physical productivity of more abundant factor. There is always a *weak relative bias*. By substituting (29) into (16), relative factor prices became

$$\frac{\omega_A}{\omega_L}=\left(\frac{\eta_A}{\eta_L}\right)^{\frac{\sigma-1}{1-\delta\sigma}}\left(\frac{\gamma_A}{\gamma_L}\right)^{\frac{(1-\delta)\varepsilon}{1-\delta\sigma}}\left(\frac{A}{L}\right)^{\frac{\sigma-2+\delta}{1-\delta\sigma}}. \tag{30}$$

Consider only stable conditions e.g. $\sigma < 1/\delta$, the direction of changes in relative factor prices from an increase in (A/L) depends on whether $\sigma > 2-\delta$. Presuming that $\sigma > 2-\delta$, if $\delta = 0$, an increase in (A/L) will increase (ω_A/ω_L) when $\sigma > 2$, just like in the lab equipment model that the *strong relative bias* requires elasticity of substation between factors to be greater than two. By contrast, in an extreme state dependence when $\delta = 1$ and $\sigma > 2-\delta$, $\sigma > 1$ implies $\sigma > 1/\delta$, and the system is unstable. An increase in (A/L) will not increase (ω_A/ω_L) in the long-run. There is no strong relative bias when $\delta = 1$. As long as $\delta < 1$ *strong relative bias* occurs when $\sigma > 2-\delta$. When elasticity of substitution is large enough, the market size effect dominates the price effect and also the substitution effect at given technology. Thus the direction of technical change is biased in favor of relative more abundant factor.

Consider a decrease in relative factor supply, the substitution effect as in (16) suggests an increase in relative price of scarcer factor. The induced innovation hypothesis implies that it will induce the development of technology to save relative scarcer input. The directed technical change, on the contrary, suggests that it will induce innovations that decrease relative physical productivity of scarcer factor; in other words, there will be more innovations to increase physical productivity of less scarce factor. And if two factors have sufficiently large substitutability, the technical change would result in a decrease in relative price of scarcer factor.

4. Illustration of Directed Technical Change Model in Agricultural Sector

Continuing from the previous section, assume that the aggregate agricultural output, Y, is produced from two intermediate outputs: Y_A being an aggregate land-intensive output such as grains, cotton, and timber, and Y_L being an aggregate labor-intensive output such as fruits and vegetables. As a country becomes more industrialized, more agricultural labor is moving to the industrial sector; the relative supply of agricultural labor to arable land becomes smaller or the land to labor ratio becomes larger. As labor becomes scarcer relative to land, the price of labor-intensive commodities relative to the price of land-intensive commodities increases; in other words, (p_A/p_L) decreases. The price effect in (21) suggests that it is less profitable to develop new fertilizers and seed varieties relative to developing new machineries. Thus, there will be more incentives to invent new machineries complementing labor-intensive production than inventing new fertilizers and seed varieties such as new complementing land-intensive production. The price effect favors the technology complementing the scarce factor—machinery. The market size effect in (21), on the other hand, favors the technology complementing abundant inputs. As land becomes more abundant relative to labor, there is higher relative utilization of land to labor employment. The demand for fertilizers and seed varieties is expanding more rapidly than the demand for machineries; as a result, there are more incentives to invent new fertilizers and seed varieties.

Suppose that land and labor are gross complements ($\sigma < 1$) in agricultural production, (22) suggests that the price effect dominates the market size effect, and there will be more incentives to develop new machineries such as harvesters and seeding machines than new fertilizers and seed varieties. As the relative arable land to agricultural labor increases in this example, the endogenous directed technical change model, e.g. in (25), proposes that the number of innovations in machineries relative to the number of innovations in fertilizers and seed varieties $\left(N_L / N_A\right)$ will increase in the long-run. Because land and labor are assumed to be complements, the relative rental price of land to wage rate will increase, e.g. in (16), and we will observe a weak relative biased towards land—a more abundant factor--induced by a relative increase in arable land to agricultural labor supply.

From Figure 1, at the initial supply, $(A/L)_0$, and initial demand, D_{SR}, relative land rent to wage rate equate at $(\omega_A/\omega_L)_0$. After an exogenous increase in relative agricultural land to labor from $(A/L)_0$ to $(A/L)_1$, it will generate a substitution effect in the short-run when there is no change in technology (constant N_A / N_L). The relative rental price of land to wage rate will drop to $(\omega_A/\omega_L)_1$. The directed technical change model suggests that there will be an induced land-biased technical change—a *weak induced bias* towards relatively more innovations in fertilizers and seed varieties resulting in a higher rental price of land to wage rate at $(\omega_A/\omega_L)_2$, compared to without a biased technical change $(\omega_A/\omega_L)_1$.

At a larger supply of land to labor than $(A/L)_0$, an increase in the relative land to labor supply will shift the technology demand curve to the right while at a smaller supply than $(A/L)_0$, it will shift the technology demand to the left. A long-run endogenous technology demand curve will shift to D_{LR1}. This graph suggests that a long-run technology demand curve is more elastic than the short-run technology demand curve (Acemoglu, 2002, 2009), the analogy similar to *LeChatelier Principle*.

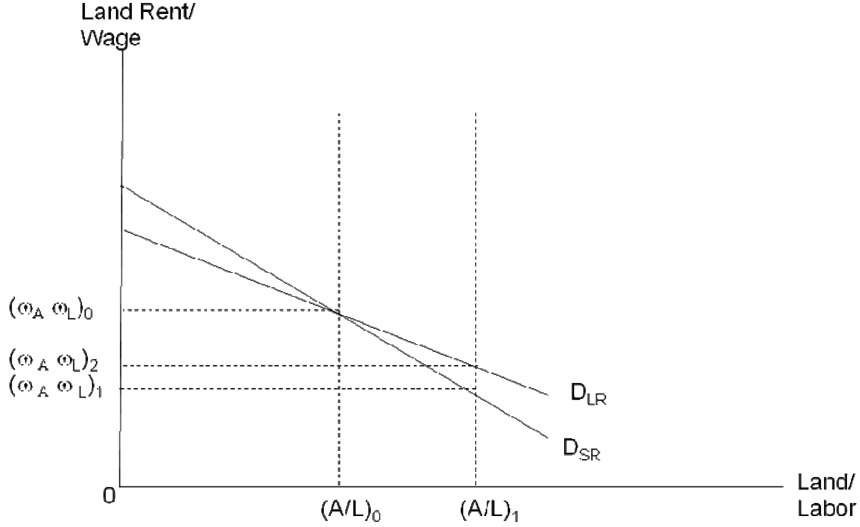

Figure 1. Short-run and long-run response to an increase in relative land to labor supply, assuming land and labor are complements
Source: Adapted from Acemoglu (2009).

What the directed technical change model suggests in this example, when labor and land are complements and when agricultural labor becomes scarcer relative to arable land, is that we will observe a decline in relative land rent to wage rate, but the degree of this decrease in price ratio will not be as large as if the state of technology was held constant. In the long-run, we will observe more innovations of machineries relative to fertilizers and seed varieties.

To compare with the induced innovation theory, Hayami and Ruttan (1970) model assumes that land and labor are substitutes in the U.S. agricultural production. A decrease in an agricultural labor to land ratio will result in a higher wage rate relative to land rent; thus, induce a labor-saving technology such as mechanical innovation. As Olmstead and Rhode (1993) criticized the induced innovation evidence of Hayami and Ruttan (1970) that the price of land to wage rate in the U.S. during that period was rising instead of falling, the directed technical change model, when assumes that land and labor are substitutes, could suggest an increase in land rent relative to wage rate—a strong relative bias if the elasticity of substitution between the two factors are sufficiently large.

5. Conclusion

Because the direction of technical change is favorable to certain groups of stakeholders and not the others, understanding its economic process gives important policy implications for which group to embrace. While the induced innovation theory has been extensively applied to agricultural sector, it left unexplained empirical evidences which require a more appropriate model. This paper explains the directed technical change model, and applies it to a hypothetical situation. The directed technical change model suggests the results that can explain what the induced innovation theory has left out.

References

Acemoglu, D. 2002. Directed Technical Change. *Review of Economic Studies*. 69(4): 781-809.

Acemoglu, D. 2007. Equilibrium Bias of Technology. *Econometrica.* 75(5): 1371-1409.

Acemoglu, D. 2009. *Introduction to Modern Economic Growth*. Princeton: Princeton University Press.

Afonso, O. 2008. The Impact of Government Intervention on Wage Inequality without Scale Effects. *Economic Modelling*. 25(2): 351-362.

Afonso, O. 2006. Skill-biased Technological Knowledge without Scale Effects. *Applied Economics*. 38(1): 13-21.

Ahmad, S. 1966. Theory of Induced Inventions. *Economic Journal*. 76(302): 344-357.

Antle, J. M. 1984. The Structure of United States Agricultural Technology, 1910-78. *American Journal of Agricultural Economics*. 66(4): 414-421.

Armanville, I. and P. Funk. 2003. Induced Innovation: An Empirical Test. *Applied Economics* 35: 1627–47.

Binswanger, H. 1974a. A Microeconomic Approach to Induced Innovation. *The Economic Journal.* 84(336): 940-958

Binswanger, H. 1974b. The Measurement of Technical Change Biases with Many Factors of Production. *The American Economic Review*. December 1974: 164-176.

Binswanger, H. and V. Ruttan. 1978. *Induced Innovation: Technology, Institutions, and Development*. Baltimore: Johns Hopkins University Press.

Carraro, C., E. Massetti, and L. Nicita. 2009. How Does Climate Policy Affect Technical Change? An Analysis of the Direction and Pace of Technical Progress in a Climate-Economy Model. *Energy Journal*. 30(Special Issue 2): 7-37.

Chavas, J.P., M. Aliber, and T.L. Cox. 1997. An Analysis of The Source and Nature of Technical Change: The Case of US Agriculture. *Review of Economics and Statistics.* 79(3): 482-492.

Cozzi, G. and G. Impullitti. 2010. Government Spending Composition, Technical Change, and Wage Inequality. *Journal of the European Economic Association*. 8(6): 1325-1358.

Esposti, R. and P. Pierani. 2003. Public R&D Investment and Cost Structure in Italian Agriculture, 1960-1995. *European Review of Agricultural Economics*. 30(4): 509-37

Fellner, W. 1971. Empirical Support for Theory of Induced Innovations. *Quarterly Journal of Economics.* 85(4): 580-604.

Foellmi, R. and J. Zweimüller. 2006. Income Distribution and Demand-induced Innovations. *Review of Economic Studies*. 73(4): 941-960.

Fuglie, K.O., K. Day-Rubenstein, P. Heisey, R. Karmarkar-Deshmukh, J. King, C.E. Pray, D. Schimmelpfennig, and S.L. Wang. 2010. Private-Sector Research Investments in Agriculture, Food and Biofuel. *Forthcoming*.

Funk, P. 2002. Induced Innovation Revisited. *Economica*. 69(273): 155-171.

Gillingham, K., R.G. Newell, and W.A. Pizer. 2008. Modeling Endogenous Technological Change for Climate Policy Analysis. *Energy Economics*. 30(6): 2734-2753.

Grimaud, A., L. Rouge. 2008. Environment, Directed Technical Change and Economic Policy. *Environmental & Resource Economics*. 41(4): 439-463.

Hayami, Y. and V. Ruttan. 1970. Factor Prices and Technical Changes in Agricultural Development: The United States and Japan, 1880-1960. *Journal of Political Economy*, 78 (September/October 1970),

Hayami, Y. and V. Ruttan. 1985. *Agricultural Development: An International Perspective.* Baltimore: Johns Hopkins University Press, 1971, revision edition 1985

Kawagoe, T., K. Otsuka, and Y. Hayami. 1986. Induced Bias of Technical Change in Agriculture: The United State and Japan, 1880-1980. *Journal of Political Economy.* 94(3): 523-544.

Kennedy, C. 1964. Induced Bias in Innovation and the Theory of Distribution. *Economic Journal.* 74(295): 541-547

Khatri, Y., C. Thirtle, and R. Townsend. 1998. Testing the Induced Innovation Hypothesis: An Application to UK Agriculture, 1953-90. *Economics of Innovation and New Technology*. 6(1): 1-28.

Liu, Q.H. and C.R. Shumway. 2006. Geographic Aggregation and Induced Innovation in American Agriculture. *Applied Economics*. 38(6): 671-682.

Liu, Y.L. and C.R. Shumway. 2009. Induced Innovation in US Agriculture: Time-series, Direct Econometric, and Nonparametric Tests. *American Journal of Agricultural Economics*. 91(1): 224-236.

Machado, F.S. 1995. Testing the Induced Innovation Hypothesis Using Cointegration Analysis. *Journal of Agricultural Economics*. 46(3): 349-360.

Olmstead, A.L. and P. Rhode. 1993. Induced Innovation in American Agriculture-A Reconsideration. *Journal of Political Economy*. 101(1): 100-118.

Otto, V. M., A. Loschel, and J. Reilly. 2008. Directed Technical Change and Differentiation of Climate Policy. *Energy Economics*. 30(6): 2855-2878.

Rivera-Baltiz, L.A. and P. Romer. 1991. Economic Integration and Endogenous Growth. *Quarterly Journal of Economics*. 106(2): 531-555.

Samuelson, P. 1965. A Theory of Induced Innovation along Kennedy-Weisacker Lines. *The Review of Economics and Statistics*. 47(4): 343-356.

Thirtle, C., R.F. Townsend, and J. Van Zyl. 1995. *Testing the Induced Innovation Hypothesis in South African Agriculture (An Error Correction Approach).* World Bank Policy Research Working Paper No. 1547.

Thirtle, C.G., D.E. Schimmelpfennig, and R.F. Townsend. 2002. Induced Innovation in United States Agriculture,1880-1990: Time Series Tests and An Error Correction Model. *American Journal of Agricultural Economics*. 84(3): 598-614.

Tiffin, R. and P.J. Dawson. 1995. Induced Innovation in American Agriculture. *Oxford Agrarian Studies* 23:87–98.

Weiss, M. 2009. On the Evolution of Wage Inequality in Acemoglu's Model of Directed Technical Change. *Applied Economics Letters*. 16(6): 591-595.