# Equilibrium Effects of Agricultural Technology Adoption

## The Case of Induced Output Price Changes

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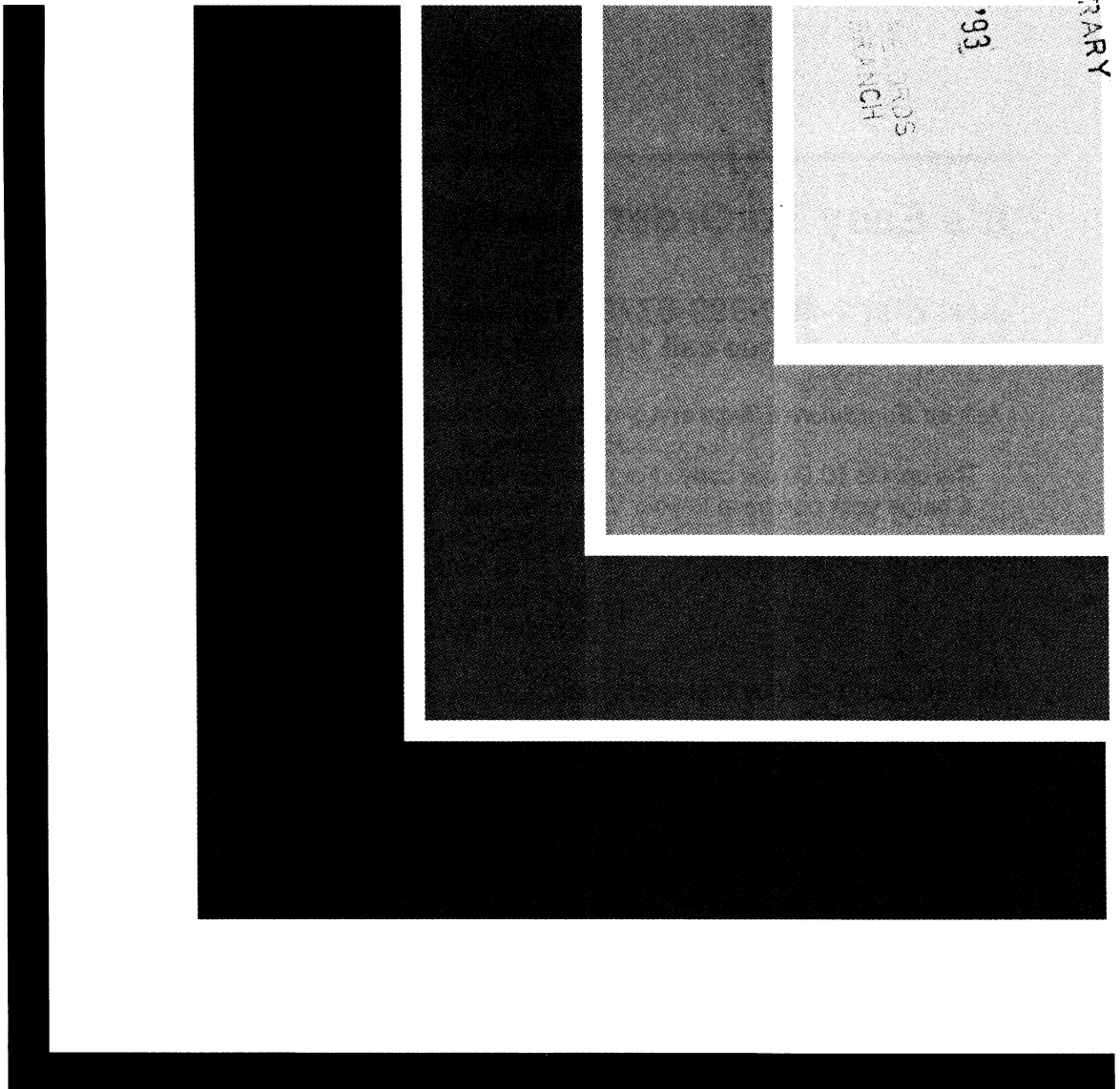Herndon, VA 22070

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**Equilibrium Effects of Agricultural Technology Adoption: The Case of Induced Output Price Changes.** By Margriet F. Caswell and Robbin A. Shoemaker. Resources and Technology Division, Economic Research Service, U.S. Department of Agriculture. Technical Bulletin No. 1823.

# Abstract

Pollution from agricultural activity depends on the agricultural practices or technologies that farmers employ. Adoption of less polluting practices can be induced by a variety of policy instruments. Cost-sharing by the government to reduce the costs of technology adoption and/or implementation for producers is an instrument widely used by the U.S. Department of Agriculture. This report examines the problem of designing economically efficient cost-sharing programs. The adoption decision for a farm is based on a comparison of the relative profitability of the existing technology and a new, less polluting one where the profitability of each technology depends on land quality. The problem for government is to determine the optimal subsidy rates that will induce a level of adoption sufficient to achieve some exogenous pollution goal. A benchmark (or first best) solution to the pollution problem serves as a reference against which to compare the optimal cost-sharing policy with imperfect targeting of land. The authors also examine the importance of specifying the land on which a technology should be used and of varying subsidy rates across inputs.

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# Summary

Pollution from agricultural activity depends on the agricultural practices or technologies that farmers employ. Adoption of less polluting practices can be induced by a variety of policy instruments. Cost-sharing by the government to reduce the costs of technology adoption and/or implementation for producers is an instrument widely used by the U.S. Department of Agriculture. This report examines the problem of designing economically efficient cost-sharing programs. The adoption decision for a farm is based on a comparison of the relative profitability of the existing technology and a new, less polluting one where the profitability of each technology depends on land quality. The problem for government is to determine the optimal subsidy rates that will induce a level of adoption sufficient to achieve some pollution goal. A benchmark (or first best) solution to the pollution problem serves as a reference against which to compare the optimal cost-sharing policy. The authors also examine the importance of specifying the land on which a technology should be used and of varying subsidy rates across inputs.

New technologies often are developed and introduced to improve agricultural productivity. The adoption of a new technology may not encompass an entire sector, however, due to differences among farms with respect to environmental assets such as soil quality or topographical uniformity. Policies designed to encourage the use of a pollution-reducing technology may have to be targeted to farms having certain resource characteristics to be cost effective.

The widespread adoption of new agricultural technologies may affect output supply for the sector. An increase in overall yield will lower the equilibrium crop price that farmers receive for their output. The change in revenues then will affect profits which, in turn, will affect the incentive to adopt the new technology. The strength of this feedback effect will depend on the responsiveness of product demand to the change in price. The authors used a numerical simulation to show the effect of an increase in input costs on output price and supply, profits, input demand, and technology use. In the irrigation example presented in the report, an increase in water costs shows how the adoption of low-volume irrigation systems would be affected and what the subsequent feedback effects would be. The effects of the cost change depend on the price elasticity of demand for the crop. The authors introduced government policies to maintain output levels and income to the model and compare their effects. A production goal can be met, but at the expense of industry profits. An alternative policy to maintaining aggregate output is to support a level of industrywide net income or profits. Although aggregate profits may be held constant, the distribution of profits between adopters and nonadopters becomes increasingly disparate.

Some changes are likely when a new technology is introduced, and some of the changes may have negative effects. The study shows that the introduction of a conserving technology does not necessarily reduce input use. The example in the study shows that low-volume irrigation systems may greatly increase yields on farms that previously used flood methods. Although the water-use efficiency of the new technology is better (defined as the amount of water used per unit of output), the large increase in yield results in the total

amount of water being greater. This result depends on the responsiveness of crop growth to the technology.

Government policies aimed at preserving output price for an industry may reduce the impact of indirect effects. Thus, those policies will tend to extend the degree of adoption and the range of assets used in the industry beyond the amount sustainable under competition. If the cost of the new technology declines, an artificially high crop price may increase adoption, generate higher crop inventories, and increase the extent of the gap between supply and demand and the need for government intervention. Price support policies may also result in overuse of the variable input. Therefore, policies designed to encourage the adoption of pollution-reducing technologies should be assessed in an equilibrium context that includes direct and indirect effects.

# Equilibrium Effects of Agricultural Technology Adoption

## The Case of Induced Output Price Changes

### Margriet F. Caswell and Robbin A. Shoemaker

## Introduction

New technologies often are developed and introduced to improve production possibilities. The adoption of the new technology may not encompass an entire sector, however, due to heterogeneity of fixed assets. A government may design a technology policy to encourage adoption to increase output or to reduce input use. Assessment of such policies should include the indirect effects of adoption-induced supply changes (shifts in the supply curve) on equilibrium output price. Endogenous price changes will affect the final output supply, input demand, and the distribution of income.

The nature of technological change itself may affect output supply and input demand; that is, a cost-reducing technological change will have a different effect on output supply and input demand than will an output-enhancing technological change (Reilly, 1988).[1] Regardless of the distinction between output-enhancing or cost-reducing technological change, the characteristics of the market in which the technology is adopted have the more important effect on output and factor demands.

Current farming methods in many countries are being questioned because resulting chemical residuals are perceived to degrade the environment and to be hazardous to human health. Because nutrient and pesticide contamination of surface and ground waters has become a serious problem, an example of a technology policy has been for governments to encourage farmers to change chemical-intensive practices. Policies are being developed to "encourage" farmers to adopt technologies that will reduce chemical loadings and improve water management. However, expectations about resulting environmental improvements may be too large because indirect effects of adoption were not included in the estimates. If the introduction of a new technology results in changes in market supply of a crop, the price of that crop may adjust. The resulting change of profitability will affect the final gains from adoption. The assessments of new technologies and of policies designed to encourage adoption must include economic and physical factors in an equilibrium context. Price feedback effects should be included within an analysis of technology choice.

## Technology Adoption

Individual adoption decisions can be modeled using an economic framework based on standard profit maximization assumptions. David (1975) introduced the threshold model which showed that adopters and nonadopters from a heterogeneous population could be separated by a critical (threshold) level of the heterogeneous characteristic. The source of heterogeneity could be associated with the farmer (for example, education) or with the farm (for example, resource quality). The critical level itself is determined by prices and costs. Therefore, changes in the underlying economic variables will affect the critical level for adoption. The

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[1] We demonstrate in this report that the distinction between cost-reducing and output-enhancing technological change is based on the elasticity of the marginal product of the technologically augmented resource.

aggregate effects on output supply and input demand of a change will be determined by the distribution of the critical variable. If there are few potential adopters with a particular characteristic near the threshold value, then the effect of a price change would be considerably smaller than if many individuals shared that characteristic. The threshold model represents an equilibrium condition derived from the rational choices of individual agents.

Later extensions of the threshold model were used to explain the adoption and diffusion of agricultural technologies with the assumption that prices were exogenous (Davis, 1979; Stoneman, 1983; Caswell and Zilberman, 1986). Such an assumption would not be reasonable, however, if output price is sensitive to changes in supply. The "technological treadmill" model developed by Cochrane (1958) described the reduction in gains from adoption that could be caused by a negatively sloped demand for output. The indirect effects caused by the price change could be large and may substantially reduce the expected benefits of adoption.

This report derives an aggregate model that can be used to predict both direct and indirect feedback effects that might be expected from the introduction of a new technology when output price is endogenous. The direct effects are reflected on the supply side (agricultural production). The indirect effects stem from the interrelationships between supply and demand that result in the equilibrating adjustment of output price. The endogenous price change feedback to the supply side is the indirect effect of technology adoption in the agricultural sector. The significance of the indirect effect depends on the nature of the market. For example, in a market for specialty products (such as avocadoes or artichokes) where demand is expected to be fairly elastic, a technological change that shifts the supply curve will have small price effects and surplus gains for producers. In a market where demand is more inelastic (such as for foods like milk and other nonspecialty goods), technological changes will result in larger price changes and surplus gains for producers. Important technological advances (such as the cotton picker) will result in significant output and price effects regardless of the market, but the nature of the market will enhance or dampen the supply-side changes.

Although a modern irrigation technology will be used in the following discussion, the theory can be used for analyzing any resource-quality-augmenting innovation. The next section briefly reviews the model of technology adoption by individual decision units introduced by Caswell and Zilberman (1986). In this report, we extend that basic threshold model to derive the aggregate effects of adoption on output supply and input demand in the short run. The industry equilibrium when output price is endogenous will then be developed, and the implications of the indirect market effects will be discussed for both individual adoption decisions and the dynamic behavior of output supply and variable input demand. A numerical simulation illustrates the importance of the equilibrium feedback effects in determining the effects of technology adoption. Three price elasticities of demand show the influence of market conditions on output supply, input demand, and farm profitability. The effects of investment cost subsidies and technological efficiency gains are also explored. The concluding section discusses the importance of the model for policy analysis.

## The Model

We use low-volume irrigation technologies to illustrate the adoption process associated with resource-quality-augmenting innovations, but the model is easily generalized to many other technologies used in developed and developing nations. The discussion will deal with an innovation that has a relative advantage over traditional methods and that advantage depends on the quality of the fixed input. For ease of exposition, we assume that advantage has a negative correlation with resource quality. The framework presented here can be easily modified to analyze a technology with a positive correlation; that is, the technology has a larger comparative advantage at high resource qualities (Caswell, 1989).

We assumed that farmers in a competitive industry will try to maximize profits and that they have the choice of more than one irrigation technology. A manager would calculate the profits to be earned for each technology given the quality of their fixed input, $a$, market prices for output, P, and variable inputs, W. Then he or she would choose the technology that would yield the highest profit. For the irrigation example, asset quality can represent the water-holding capacity of the soil, a basic measure of land quality. To avoid confusion, we chose $a$ to be an index ranging from 0 (the worst quality) to 1 (the best).

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Production of an output per asset unit, q, using technology i is a function of the amount of the variable input, e, which is usable within the production process [$q_i = f(e_i)$] where f($\cdot$) is a standard production function with f(0) = 0, f'($\cdot$) > 0, f"($\cdot$) < 0 (primes denote derivatives). For the irrigation example, q would be the crop yield per acre, and e would be the amount of water available to the crop. Although we compared only two technologies, the theory is easily generalized to assess the choice among several technologies. Let i=0 represent the traditional irrigation technology (flood or furrow) and i=1 designate the modern water delivery system (drip or minisprinklers). The amount of water available to the crop, e, will depend on the amount of water actually applied to the field, a, the application technology, and the quality of the fixed asset (land quality, $a$). Let $e_i$ = $h_i(a)a_i$ represent the effective water use when $a_i$ is applied with technology i and $h_i(a)$ is the quality-augmenting effect (irrigation efficiency) for that technology. For convenience, we normalized the quality-augmentation factor on the traditional system so that $h_0 = a$, $h_1(a) \geq a$, and $h_1'(a) \geq 0$. Therefore, a technology switch is equivalent to a change in asset quality from $a$ to $h_1(a)$. When the relative advantage of the new technology is negatively correlated with asset quality, h" < 0 (h" > 0 for technologies that are positively correlated). For the best quality of land, well-managed traditional irrigation systems have high water-use efficiencies that approach those of modern technologies. The efficiency levels for the traditional methods decline more quickly than for modern systems as land quality worsens (for example, if the soil is sandier or the terrain is sloped).

We also assumed that the annualized investment cost, I, for the new technology is greater than for the traditional one ($I_1 > I_0$), and that investment costs do not depend on the asset quality. Although the latter assumption is not strictly true, including a more realistic function adds complexity but no further insights into the theory. Therefore, the operational profit that can be earned for any asset quality can be written as:[2]

$$\pi_i(\alpha) = Pf(h_i(\alpha)a_i) - Wa_i - I_i. \tag{1}$$

Using (1), we can find the optimal variable input use for each technology. The first-order condition that must hold at the optimum is

$$Pf'h_i = W. \tag{2}$$

The effects of asset quality and prices on variable input demand, effective input use, and output levels are derived from totally differentiating the first-order condition with respect to input use. These effects are

$$\begin{bmatrix} \dfrac{da}{d\alpha} & \dfrac{de}{d\alpha} & \dfrac{dq}{d\alpha} \\[2ex] \dfrac{da}{dP} & \dfrac{de}{dP} & \dfrac{dq}{dP} \\[2ex] \dfrac{da}{dW} & \dfrac{de}{dW} & \dfrac{dq}{dW} \end{bmatrix} \equiv \begin{bmatrix} -\dfrac{a\eta}{\alpha}\cdot\left[1-\dfrac{1}{\epsilon}\right] & \dfrac{e\eta}{\alpha\epsilon} & \dfrac{q\phi\eta}{\alpha\epsilon} \\[2ex] \dfrac{a}{P\epsilon} & \dfrac{e}{P\epsilon} & \dfrac{q\phi}{P\epsilon} \\[2ex] -\dfrac{a}{W\epsilon} & -\dfrac{e}{W\epsilon} & -\dfrac{q\phi}{W\epsilon} \end{bmatrix}. \tag{3}$$

The comparative static results derived from (2) are messy. Therefore, for expositional ease, three variables are introduced in (3): $\eta_i(a) \equiv [h_i'(a)\cdot a]/h_i(a)$ is the elasticity of the quality-enhancing effect with respect to asset quality (for the two-technology case described here), $\eta_0(a) = 1$ and $0 < \eta_1(a) < 1$; $\phi(e) \equiv [f'(e)\cdot e]/f(e) \geq 0$ is the elasticity of production with respect to the effective variable input use; and $\epsilon(e) \equiv -[f'(e)\cdot e]/f'(e) \geq 0$ is the

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elasticity of the marginal productivity (EMP) of the effective variable input use.[3] A high value of EMP ($\epsilon > 1$) implies a strong decline in the marginal productivity as effective input use increases.

EMP has important implications for defining the difference between output-enhancing and cost-reducing or resource-conserving technological change. Whether actual input use increases or declines with resource quality depends on EMP; that is, $da/d\alpha \gtrless 0$ if $\epsilon \lessgtr 1$. The implication of this result can be significant. For example, if water supply is scarce, and the production process is characterized by a low EMP ($\epsilon < 1$), then a farm that adopted drip irrigation (because of the increase in output) would use more water per acre than was used with the traditional system even though the modern system can be considered a "resource-conserving" technology. Therefore, any technological change that augments a fixed resource will enhance output, but it may not reduce cost or conserve the resource. The distinction between output-enhancing and cost-reducing technological changes occurs when the technological change is applied to a fixed resource (Reilly, 1988), but the distinction is maintained only when EMP is low ($\epsilon < 1$). The equations in (3) also show that an increase in output price or a reduction in variable input price will increase output, actual variable-input use, and effective variable-input use. In addition, an increase in resource quality will increase output and increase the optimum level of the effective variable use.

Profits can be calculated for each technology choice and then compared. Optimal values of a, denoted $a^*$, result in the indirect profit function. With the envelope theorem, differentiation of the indirect profit function with respect to land quality yields

$$\frac{d\pi_i}{d\alpha} = [W \cdot \eta_i \cdot a_i^*] \, / \, \alpha > 0. \tag{4}$$

The positive sign suggests that there will be an asset quality, $\alpha_{im}$ where $\pi_i(\alpha_{im}) = 0$.[4] Assets of a quality greater than this marginal quality would earn the operator positive profits using technology i, and below that level use of technology i would not be profitable. $\alpha_{im}$ is therefore the extensive margin of production; that is, for qualities of $\alpha$ below this margin, profits are less than zero and production ceases. When both technologies are used, there will be at least one asset quality, $\alpha_s$, for which profits will be equal for both modern and traditional technologies $[\pi_1(\alpha_s) = \pi_0(\alpha_s)]$.[5] We refer to $\alpha_s$ as the switching quality. For technologies with a negative correlation between the quality-augmenting characteristic and resource quality, profits for farms with the highest level of asset quality will earn more profits using the traditional technology than by converting to drip irrigation $(\pi_1(1) < \pi_0(1))$.

The above relationship between profits is demonstrated in figure 1. Figure 1 presents the hypothetical profits for a traditional and a negatively correlated technology. The negatively correlated technology has a relative advantage over the traditional technology under lower quality resource conditions, (as $\alpha \rightarrow 0$), so the modern technology will determine the extensive margin $\alpha_{1m}$. Therefore, for resource qualities between $\alpha_{1m}$ and $\alpha_s$, profits from the modern technology would be larger than for those gained using the traditional technology. At environmental quality $\alpha_s$, profits are equal for the two technologies, and farmers are indifferent between the two technologies. For farms with better resource conditions, the relative advantage of the negatively correlated technology decreases. Thus, beyond the critical asset quality, $\alpha_s$, profits from the traditional technology dominate.

The range of asset qualities that can be used profitably is increased with the introduction of the new technology from $\alpha_{0m}$ to $\alpha_{1m}$. Farms with assets between $\alpha_{0m}$ to $\alpha_s$ will switch from the traditional to modern technology,

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[3] For example, $\dfrac{da}{dP} = -\dfrac{f'h}{Ph^2f''} \cdot \left[\dfrac{a}{a}\right] = \dfrac{a}{P\epsilon}$ .

[4] The use of a technology could result in positive profits being earned even on the worst land, but policy implications of this analysis are richer when one assumes that a marginal quality exists.

[5] Cases where the profits of one technology dominate over the entire range ($\pi_j(\alpha) > \pi_k(\alpha) \; \forall \; \alpha$) will not be included. The curvatures of the relevant profit functions will determine the number of switching points. For ease of exposition, a single point is discussed here.

**Figure 1**
Relationships of profits for negatively correlated modern and traditional technologies

Profits

Traditional
$\pi_0(P, W; \alpha)$

$\pi_0$

$\pi_1$

Modern
$\pi_1(P, W; \alpha)$

0    $\alpha_{1m}$    $\alpha_{0m}$    $\alpha_S$    1
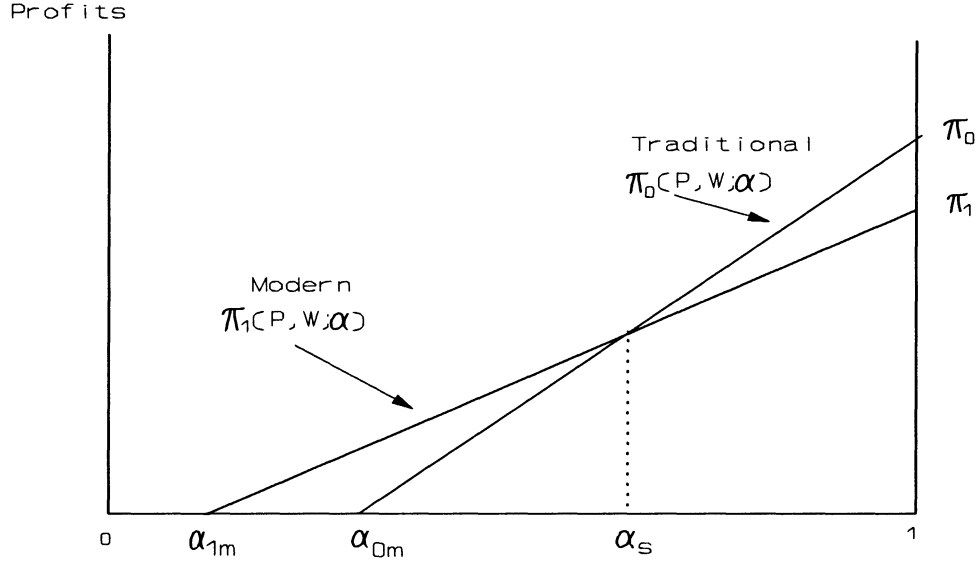
while those farms with high-quality assets $(\alpha > \alpha_s)$ will not find it profitable to adopt the new technology. The actual number of acres on which the modern technology is used will depend on the distribution of land qualities. For the remainder of this report, $\alpha_{1m} = \alpha_m$ and will be referred to as the marginal land quality (that is, the extensive margin of production).

The values of $\alpha_m$ and $\alpha_s$ are derived from the profit function and are functions of output and input prices and investment costs $(P, W, I_0, I_1)$. To study the effects on the critical asset qualities of changes in the underlying economic variables, one totally differentiates the equations $\pi_i(\alpha_m) = 0$ and $\pi_1(\alpha_s) = \pi_0(\alpha_s)$. The effects of economic conditions on the switching and marginal qualities are presented in the identity (5).[6]

$$\begin{bmatrix} \dfrac{\partial \alpha_s}{\partial P} & \dfrac{\partial \alpha_m}{\partial P} \\[2ex] \dfrac{\partial \alpha_s}{\partial W} & \dfrac{\partial \alpha_m}{\partial W} \\[2ex] \dfrac{\partial \alpha_s}{\partial I_1} & \dfrac{\partial \alpha_m}{\partial I_1} \\[2ex] \dfrac{\partial \alpha_s}{\partial I_0} & \dfrac{\partial \alpha_m}{\partial I_0} \end{bmatrix} \equiv \begin{bmatrix} -\dfrac{\alpha_s(q_0-q_1)}{W(a_0-a_1\eta)} & \dfrac{q_1\alpha_m}{Wa_1\eta} \\[2ex] -\dfrac{\alpha_s(a_0-a_1)}{W(a_0-a_1\eta)} & \dfrac{\alpha_m}{W\eta} \\[2ex] -\dfrac{\alpha_s}{W(a_0-a_1\eta)} & \dfrac{\alpha_{m*}}{Wa_1\eta} \\[2ex] \dfrac{\alpha_s}{W(a_0-a_1\eta)} & 0^* \end{bmatrix}$$

(5)

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[6] The * in identity (5) refers to the simplifying assumption that shifts in the investment costs do not result in $\alpha_{0m} < \alpha_{1m}$.

The results show that an increase in output price will expand the range of assets on which the new technology will be used ($\partial \alpha_s/\partial P > 0$ and $\partial \alpha_m/\partial P < 0$). Investment costs affect the marginal and switching qualities in the expected manner ($\partial \alpha_s/\partial I_0 > 0$, $\partial \alpha_s/\partial I_1 < 0$, and $\partial \alpha_m/\partial I_1 > 0$). An increase in water costs will reduce the irrigated land base ($\partial \alpha_m/\partial W > 0$), but the effect on the switching point depends on the EMP. If $\epsilon > 1$ such that input demand with the modern technology is less than for the traditional one, then there will be a switch to the new system on more acres ($\partial \alpha_s/\partial W \geq 0$ if $\epsilon \geq 1$ and $\partial \alpha_s/\partial W < 0$ if $\epsilon < 1$).

## Aggregate Output Supply and Input Demand

To obtain aggregate amounts of industry output (crop production) and the demand for the variable input (water use), the distribution of asset quality, $g(\alpha)$, must be known. Assume that $g(\alpha) \geq 0$ for $0 \leq \alpha \leq 1$. Aggregating over the relevant asset qualities, the total output supply ($Q^s$) and input demand ($A^d$) of the industry are

$$Q^S(P,W,I_0,I_1) = \int_{\alpha_m}^{\alpha_s} q_1(\alpha)\,g(\alpha)\,d\alpha + \int_{\alpha_s}^{1} q_0(\alpha)\,g(\alpha)\,d\alpha$$

$$A^d(P,W,I_0,I_1) = \int_{\alpha_m}^{\alpha_s} a_1(\alpha)\,g(\alpha)\,d\alpha + \int_{\alpha_s}^{1} a_0(\alpha)\,g(\alpha)\,d\alpha.$$

The marginal effects of changes on the parameters of the aggregate functions are obtained using the Leibnitz rule (Kamien and Schwartz, 1981). A general expression for these effects is

$$X_Z \equiv \frac{dX}{dZ} = \frac{\partial \alpha_m}{\partial Z}[x_1(\alpha_m)\,g(\alpha_m)] - \frac{\partial \alpha_s}{\partial Z}[x_1(\alpha_s)-x_0(\alpha_s)]g(\alpha_s)$$

$$+ \int_{\alpha_m}^{\alpha_s} \frac{\partial x_1}{\partial Z}\,g(\alpha)\,d\alpha + \int_{\alpha_s}^{1} \frac{\partial x_0}{\partial Z}\,g(\alpha)\,d\alpha$$

(6)

where X can be either $Q^s$ or $A^d$; Z can be P, W, $I_0$, or $I_1$; and x = q when $X = Q^s$; x = a when $X = A^d$. For instance, $Q_P^s$ is the derivative of output supply with respect to output price.

A change in Z may affect the aggregate value through its effect on (1) the extensive margin for asset quality, $\alpha_m$, expressed by the first term on the right-hand side of (6), (2) the switching quality, $\alpha_s$ (expressed by the second term), and (3) the intensive margin (expressed by the integrals). Not all of these components will necessarily be of the same sign. The effect of a change in the technology-switching quality may be of the opposite sign as the other two effects, depending on the magnitude of the EMP. Therefore, the total direction of change will be determined by the production characteristics of the new technology. Table 1 summarizes the results of this analysis.

As expected, aggregate supply tends to increase with a higher output price and a lower fixed cost of the modern technology ($Q_P^s > 0$ and $Q_I^s < 0$); and aggregate demand for water declines with that input's price ($A_W^d < 0$).

The effects of a change in water price on aggregate supply or the effects of a change in output price and investment costs on aggregate water demand will depend, however, on the size of the EMP. For instance, in the low EMP case when a switch to the new technology will increase input use, aggregate input use will increase in response to an increase in output price, the expected result. If, however, the new technology conserves a resource, the net effect on input use of an increase in output price will depend on the relative strengths of changes in the critical qualities and the number of farms with those qualities.

**Table 1--Effect of change In output price (P), input price (W), and fixed cost of modern technology ($I_1$) and traditional ($I_0$) technologies on output (Q) and input use (A)**

| Variable | Extensive margin effect | Switching margin effect | Intensive margin effect | Total effect |
|---|---|---|---|---|
| $Q_P^s$ | + | + | + | + |
| $Q_W^s$ | - | ± if $\epsilon \gtrless 1$ | - | - if $\epsilon < 1$ |
| $Q_{I1}^s$ | - | + | 0 | - |
| $Q_{I0}^s$ | 0 | - | 0 | + |
| $A_P^d$ | + | ± if $\epsilon \lessgtr 1$ | + | + if $\epsilon < 1$ |
| $A_W^d$ | - | - | - | - |
| $A_{I1}^d$ | - | ± if $\epsilon \gtrless 1$ | 0 | - if $\epsilon < 1$ |
| $A_{I0}^d$ | 0 | ± if $\epsilon \lessgtr 1$ | 0 | - if $\epsilon > 1$ |

Here $\epsilon$ represents $\epsilon_1(a_s)$.

# Industry Equilibrium When Output Price Is Endogenous

When the population of potential adopters is pricetaking in both output and input markets, the framework above is sufficient to yield the competitive equilibrium behavior of aggregate output and input quantities, land-use patterns, and the equilibrium rental rate (operational profit) that will determine asset price. In many cases, however, the pricetaking assumption is not realistic. Although each firm is a pricetaker, the population of firms may be large enough to face a negatively sloped output demand curve or a positively sloped input supply curve. For this analysis, we will consider only the case with a downward sloping demand so that the output price is endogenous. This circumstance is generally relevant to agricultural production and has important policy ramifications. Later work will expand the framework to consider the case when input price is endogenous.

Let output demand be denoted by $Q^d(P)$ where $Q_P^d < 0$. Output price is determined by the equilibrium condition

$$Q^d(P) = Q^s(P, W, I_0, I_1). \qquad (7)$$

Equilibrium in the inputs market is characterized by

$$A^d(P, W, I_0, I_1) = A^s \qquad (8)$$

where $A^d(W,P,I_0,I_1)$ denotes aggregate input demand.[7] Changes in the exogenous variables (W, $I_0$, $I_1$) have direct and indirect effects. The direct effects are associated with the initial output price (table 1). The indirect effects result from the equilibrating changes in the endogenously determined price. Comparative statics were used to obtain the sum of these effects using (3), (7), and (8). To analyze the reaction of the system to parametric changes, let the elasticities, v, of aggregate output be denoted by $v_z^n$ where n = d for demand relationships and n = s for supply relationships and z can be P, W, $I_0$, or $I_1$. For instance, $v_W^s$ represents the elasticity of output supply with respect to input price.

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[7] The supply of the variable input is assumed to be fixed.

Table 2 presents some of these results. It shows the marginal effects of changes in W and $I_1$ with indirect effects resulting from the longrun changes in the endogenously determined output price. The comparative statics results show the following:

(1) An increase in input price will reduce aggregate variable input use. Higher input cost will increase output price for all cases when $Q_W^s < 0$.[8] The equilibrium effect (the total direct and indirect effect) of a change in input price on aggregate output will never be greater than the direct effect, regardless of the sign of the direct effect, $Q_W^s$. The first element in table 2 shows the output dampening effect. The quantity within the square brackets will always be nonnegative and less than one. The magnitude of the output dampening effect will depend on the relative price effects on demand and supply, that is, the relative magnitudes of $Q_P^d$ and $Q_P^s$.

In high EMP cases, when the technology-switching quality effect is dominant, $Q_W^s > 0$, an increase in the price of the variable input tends to increase output due to the increase in yields on the land where the new technology has been adopted and the equilibrium output price will fall. A competitive market-determined price dampens the adoption of a technology relative to an exogenously set (fixed) price case.[9] This effect implies that in a situation where commodity prices are set by a government (for example, target prices for U.S. feed grains) the indirect effects are greatly reduced. An artificially high price will extend adoption and the range of asset qualities devoted to the new technology beyond the level associated with a market determined price. Subsidized commodity prices will also increase the intensive margin, increasing the use of the variable input.

(2) A decrease in the fixed cost of the modern technology increases aggregate output and decreases output price. Because of the lower output price, input use and output for firms that retain the traditional technology may be reduced as well as the rents for their fixed asset. A lower fixed cost of the modern technology may

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[8] As shown in table 1, $Q_W^s < 0$ when EMP < 1 and if EMP is high but the marginal quality and intensive margin effects dominate the switching quality effect.

[9] The fixed-price case corresponds to the situation where demand is infinitely elastic.

**Table 2--Marginal effects on endogenous variables due to changes in price of water (W) and per acre cost of modern ($I_1$) technology for a water-pricetaking industry[1]**

| Dependent variable | Marginal effects of changes in -- | |
| --- | --- | --- |
| | Water price | Fixed-cost modern technology |
| Aggregate output, Q | $Q_W^s\left[1+\dfrac{Q_P^s}{Q_P^d-Q_P^s}\right]$ | $Q_{I_1}^s\left[1+\dfrac{Q_P^s}{Q_P^d-Q_P^s}\right]$ |
| Output price, P | $\dfrac{Q_W^s}{Q_P^d-Q_P^s}$ | $\dfrac{Q_{I_1}^s}{Q_P^d-Q_P^s}$ |
| Aggregate water, A | $A_W^d\left[1+\dfrac{Q_P^s Q_W^s}{(Q_P^d-Q_P^s)A_W^d}\right]$ | $A_{I_1}^d\left[1+\dfrac{A_P^d Q_{I_1}^s}{(Q_P^d-Q_P^s)A_{I_1}^d}\right]$ |
| Marginal land quality, $\alpha_m$ | $\dfrac{\alpha^m}{W\eta_1}\left[1-\dfrac{v_W^s}{v_P^d-v_P^s\phi_1(\alpha^m)}\right]$ | $\dfrac{\alpha^m}{W\eta_1 a_1}\left[1-\dfrac{Pq_1 v_{I_1}^s}{I_1(v_P^d-v_P^s)}\right]$ |
| Technology switching land quality, $\alpha_s$ | $\dfrac{\alpha^s(a_0-a_1)}{W(a_0-\eta_1 a_1)}\left[1-\dfrac{P(q_0-q_1)v_W^s}{W(a_0-a_1)(v_P^d-v_P^s)}\right]$ | $-\dfrac{\alpha^s}{W(a_0-\eta_1 a_1)}\left[1+\dfrac{P(q_0-q_1)v_{I_0}^s}{I_0(v_P^d-v_P^s)}\right]$ |

[1] For definition of the variables, see text.

even decrease aggregate input use, a counterintuitive outcome occurring, for example, when EMP is high and the technology-switching quality effect is dominant. If the fixed investment share of revenue is high, the indirect effect will be dominant. An increase in the fixed cost of the traditional technology also tends to increase aggregate output and reduce output price.

The magnitude of these effects at any time will depend on the distribution of resource quality. Because the adoption of the technology will tend to reduce output price due to the yield-increasing effect, the indirect effects of adoption may result in a lower final level of adoption. The quality of the marginal resource will also be higher than that predicted when only the direct effects of adoption are considered; hence, unemployed productive capacity will increase. These results are consistent with the observation that many new technologies are adopted more slowly than expected and may never saturate the entire market.

Another result of a negative price response to increased output supply would be to reduce the value of the natural resource (or any threshold characteristic) owned by nonadopting producers. The introduction of negatively correlated technology will make owners of high-quality resources worse off in absolute terms because the decreased revenues would cause rent to the fixed asset (the "hedonic" price of quality) to decline.

## Simulation of Technology Adoption with Endogenous Commodity Prices

Policymakers may need to consider the potential feedback effects of policies designed to enhance the adoption of targeted technologies because these effects will determine output supply, land use, input demand, and farm sector profitability. This section presents a simulation model of dichotomous choice for technology adoption. The model includes the effects of an endogenous commodity price that arise from adoption-induced changes in aggregate supply. We assumed that the production function takes the form $q_i(a_i) = 1 - e^{-a_i/h_i(a)}$.[10] The land quality augmenting effect of technology i, $h(a)$, is defined as $h_i(.) = a^{\gamma}$, where $\gamma = 1$ for the traditional technology and $0 \le \gamma \le 1$ for the new technology.[11] Total supply, Q, is the sum of production from the two technologies aggregated over the distribution of land qualities in production. In this example, land is distributed over a logistic density function, which is positively skewed. This distribution is consistent with observations of U.S. agricultural land data (USDA, 1992). The equilibrium commodity price is found by equating total supply with a constant elasticity demand function. The importance of the market equilibrium feedback effects depends on the price elasticity of demand for the product under consideration. Therefore, we performed a sensitivity analysis over various price elasticities of demand. The simulation model solves directly for the extensive margin of new technology adopters, $a_m$, the equal profit switching point, $a_s$, and the equilibrium commodity price.[12] A complete description of the model and discussion of the benchmark calibration is presented in the appendix. Tables 3 and 4 show how the equilibrium market effects and technology adoption depend on the nature of the market (that is, the demand for the product). A supply-side effect will result in a larger (smaller) change in output the greater (lesser) the elasticity of demand.[13] The magnitude of the shift in the commodity supply curve depends on changes in the amount of land going into or out of production (the extensive margin), changes in technology use (the switching margin), and changes in input use on farms (the intensive margin). In this example, an increase in water costs shifts the extensive margin to the right under situations of nonzero price elasticities, reducing the total amount of all asset qualities employed (table 3).[14] Comparing demand elasticities at -0.4 and -3, we find the more elastic case results in the greatest decline in production (-30 percent compared with -9 percent) and smaller price effects as would be expected.

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[10] This functional form, chosen for its simplicity, is a variant of the Mitscherlich-Baule production function (Beattie and Taylor, 1985).

[11] In this example, the value of $\gamma$ is set a 0.3. This figure is consistent with water-use efficiencies obtained with drip irrigation in California.

[12] The system of equations is solved using MathCAD 2.5 version software which uses a modified quasi-Newton algorithm for solving a system of nonlinear simultaneous equations.

[13] The price elasticities used in the simulation were chosen to represent a large range of elasticities. The more moderate and realistic value of -0.4 reflects an average price elasticity estimated for major commodities such as corn, wheat, and cotton (Tyers and Anderson, 1986).

[14] A rightward shift in $a_m$ indicates the extensive margin moves from lower quality to a higher quality asset level.

Underlying these supply-side effects is the adoption of different technologies and distribution of these technologies over asset qualities. The resulting equilibrium distribution of these technologies clearly depends on the elasticity of demand. In the more inelastic cases, $\xi = 0$ and $\xi = -0.4$, increasing the price of water resulted in an increase of asset qualities devoted to the new technology by 27 percent and 18 percent (table 3). In the most elastic case, $\xi = -3$, asset qualities devoted to the new technology actually declined.

What drives the above results is seen by examining the change in the distribution of profits. Table 4 shows the change in profits for the different technology users. This distribution of profits determines the mix of technology users. For example, as the price of water increases, some firms shift to the new technology to offset production costs. In the inelastic case, the cost increase encourages adoption. Profits increase for adopters while profits for those continuing to use the traditional technology decline in total.[15] In the most elastic case, profit for the new technology declines in total (relative to the benchmark) such that at the margin, profits are less than the investment cost. Thus, the total range of qualities devoted to the new technology declines.

## Simulations of Variable Costs and the Sensitivity to Demand Elasticities

Increasing demands for water have forced up the price of water (either the direct price in areas where there are markets or the shadow price). In this first simulation, the properties of the model are examined by analyzing the case where the price of water rises by 50 percent under three different price elasticities. Table 3 presents the changes in the extensive and switching margins, the commodity price, total production, and variable total demand under three different price elasticities. Table 4 presents changes in industrywide profits, under the new and traditional technologies and also under the various elasticities.

## Investment Subsidy To Maintain Aggregate Output Levels

A policy often used in developing countries is to maintain the total level of food production to ensure adequate food supplies for urban populations. Where there are scarcities of inputs such as water, subsidizing the adoption of resource-conserving technologies can be used to achieve a production goal. For example, in the previous case, a 50-percent increase in water costs resulted in a 9-percent decrease in aggregate production (when $\xi = -0.4$). To increase production levels, the efficient technology could be subsidized. Because the new technology is more efficient with respect to resource use, the loss in aggregate output could be somewhat offset

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[15] Profits earned by the traditional technology users are positive, but the total amount of profits earned by all traditional technology users is less than in the benchmark.

**Table 3--The effect of a 50-percent increase in water costs on the extensive and switching margins, output price, total output, and total input demand under different price elasticities of demand**

| Item | Price elasticities of demand ($\xi$) | | |
|---|---|---|---|
| | 0 | -0.4 | -3 |
| | *Percent change from benchmark* | | |
| Extensive margin ($\sigma_m$) | -20 | 20 | 120 |
| Switching margin ($\sigma_s$) | 20 | 16 | 5 |
| Portion of asset qualities in new technology, $(\sigma_s - \sigma_m)/(1 - \sigma_m)$ | 27 | 18 | -13 |
| Output price (P) | 38 | 20 | 12 |
| Total output (Q) | 0 | -9 | -30 |
| Total input demand (A) | -6 | -18 | -40 |

if more producers adopted the new technology. In the following simulation, adoption is encouraged through a policy where investment costs are subsidized (table 5).[16]

The first column suggests that to maintain production at the initial level (before the water-price increase), more than a 100-percent investment cost subsidy is required. A full subsidy results in virtually all land qualities being employed with the new technology (the extensive margin shifts to the left to 0.02 and the switching margin shifts right to 1.0). As a result, there is no problem of some farmers gaining at the expense of others, and industrywide profits increase 243 percent.

The second column in table 5 demonstrates how a model such as this can be used to combine policy simulation and technology forecasting. To meet the production goal for this example, a 50-percent increase in technical

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[16] In the simulation model, existing adopters cannot be distinguished from new adopters. The subsidy scheme probably acts as a rebate for prior adopters and an investment subsidy for new adopters.

**Table 4--The effect of a 50-percent increase In water costs on the distribution of industrywide profits under different price elasticities of demand**

| Item | Price elasticities of demand ($\xi$) | | |
|---|---|---|---|
| | 0 | -0.4 | -3 |
| Profits under: | *Percent change from benchmark* | | |
| New technology | 108 | 28 | -60 |
| Traditional technology | -17 | -24 | -35 |
| Total industry profits | 43 | 1 | -46 |

**Table 5--The effects of Investment cost subsidy and change in technical efficiency ($\gamma$) In maintaining total output given a 50-percent Increase In water costs[1]**

| Item | Percent investment cost subsidy | | |
|---|---|---|---|
| | -100 | -100 | 0 |
| | | Percent change in technical efficiency ($\gamma$) | |
| | | 50 | 75 |
| | *Percent change from benchmark* | | |
| Profits under new technology ($\pi_1$) | 243 | 220 | -17 |
| Profits under old technology ($\pi_0$) | -100 | -100 | -60 |
| Total production (Q) | -6 | 0 | 0 |
| Commodity price (P) | 16 | 2 | 1 |
| Subsidy per total profits (S/$\pi$) | 72 | 78 | n.a. |
| Subsidy per total value of output (S/(P $\times$ Q)) | 27 | 29 | n.a. |
| Extensive margin ($\sigma_m$)[2] | .02 | 0.0 | .02 |
| Switching margin ($\sigma_s$) | 1.0 | 1.0 | .58 |

n.a. = Not applicable.
[1] The elasticity of demand is set at -0.4 for this scenario.
[2] $0 \leq \sigma_k \leq 1$, where k = m,s.

efficiency would be necessary (combined with the 100-percent subsidy). Again, all land qualities are employed ($a_m = 0$ and $a_s = 1$). The last column in the table suggests that a 75-percent increase in technical efficiency could maintain production levels without using an investment subsidy but at a loss in profits for both adopters and nonadopters relative to the benchmark.

Table 5 indicates that the budgetary consequences of aggregate output maintenance policy may make the policy prohibitive. The budgetary costs (total subsidy outlays) of this policy are more than 70 percent of profits and 30 percent of the value of production. The latter figure implies that for every dollar of government outlay, total production (in value terms) increases only 30 cents.

The loss in output due to the water-price increase is difficult to recover when the relative advantage of the new technology is negatively correlated with land quality. The implication of this assumption is that, as the switching margin shifts to the right, the relative increase in the marginal product of land diminishes. Therefore, while the average product of land increases, its rate of increase diminishes such that the aggregate supply curve does not return to its original level, before the water-price increase.

### Investment Subsidy To Maintain Profit Levels

An alternative policy to maintaining aggregate output is to support a level of industrywide net income or profits. In this case, the price elasticity of demand is significant. For commodities that are more price elastic, a policy designed to maintain total sectoral profits through subsidized investment cost will require ever-increasing subsidy rates (table 6). But while aggregate profits remain constant, the distribution of profits between adopters and nonadopters becomes increasingly disparate.

At price elasticities greater than -0.5, the increase in water costs results in enough of an increase in profits for the adopters that aggregate profits are greater than the initial level rendering the investment subsidy unnecessary. At elasticities more elastic than the -0.5 level, investment subsidies must increase. The result of the subsidy is a widening gap of profits between groups. Between the -0.5 and -1.0 elasticity levels, the share of total profits going to nonadopters falls from 27 percent to 13 percent.

**Table 6--The effect of price elasticity of demand assumptions on the distribution of profits and adoption of investment subsidies under an aggregate profits maintenance policy**

| Item | Demand price elasticities ($\xi$) | | |
|------|------|------|------|
| | -0.5 | -0.7 | -1 |
| | | *Percent* | |
| Subsidy | 22 | 40 | 53 |
| | | *Dollars* | |
| $\pi_1$ | 15 | 17 | 18 |
| $\pi_0$ | 6 | 4 | 3 |
| $\pi_1 + \pi_0$ | 21 | 21 | 21 |
| | | *Percent* | |
| $\pi_0/(\pi_1 + \pi_0)$ | 27 | 18 | 13 |

# Conclusions

Many innovations augment the quality of a fixed input. Some exogenous changes are likely when a new technology is introduced. If the demand for the crop is not perfectly elastic, the introduction of a modern technology will reduce the rental rate and value of the assets belonging to farms that retain the traditional technology. When output demand is inelastic, the introduction of an asset-quality-augmenting technology may actually reduce the range of assets used in the industry, in the long run, instead of increasing the range. Furthermore, the introduction of such a "conserving" technology does not necessarily reduce input use. When a modern technology has a strong output-increasing effect (in low EMP cases), it will actually increase aggregate variable input use unless the elasticity of demand is sufficiently low so that indirect effects from a lower output price cause reduced input use. The output-increasing characteristics of the technology may have a stronger effect on adoption effects than would cost-reducing factors.

Government policies aimed at preserving output price for an industry may reduce the indirect effects. As a result, such policies will tend to extend the degree of adoption and the range of assets used in the industry beyond the amount sustainable under competition. If the cost of the new technology declines, an artificially high crop price may increase adoption, generate higher crop inventories, and increase the extent of the gap between supply and demand and the need for government intervention. Price support policies may also result in overuse of the variable input. Therefore, policies designed to encourage the adoption of pollution-reducing technologies need to be assessed in an equilibrium context that includes direct and indirect effects.

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# Appendix

Two margins must be found that indicate the level or extent of technology adoption, the extensive $(\alpha_m)$ and switching margins $(\alpha_s)$. These margins and the output price are found by solving a system of three equations. The production function is assumed to the form, $q_i(a_i) = 1 - e^{-a_i \alpha^{\gamma_i}}$, for i = 0,1 where 0 denotes the traditional technology and the new technology is denoted by 1. $\alpha^{\gamma_i}$ is the land quality augmenting effect of technology i where $\gamma_0 = 1$ for the traditional technology and $0 \le \gamma_1 \le 1$ for the new technology. Profits are defined as revenues net of variable input and investment costs,

$$\pi_i = P\left[1 - e^{-a_i \alpha^{\gamma_i}}\right] - W a_i - I_i. \tag{A1}$$

The model assumes that there are no investments in the traditional (existing) technology; therefore $I_0 = 0$. The optimal variable input is found as

$$a_i^* = -\frac{1}{\alpha^{\gamma_i}} \cdot \ln\left(\frac{W}{P\alpha^{\gamma_i}}\right) \tag{A2}$$

The extensive margin is found by substituting equation (A2) into (A1) and solving for $\alpha$; such profits are zero. Substitution yields the indirect profit function

$$P\left[1 - \frac{W}{P\alpha_m^{\gamma_1}}\right] + \frac{W}{\alpha_m^{\gamma_1}} \cdot \ln\left(\frac{W}{P\alpha_m^{\gamma_1}}\right) - I_1 = 0 \tag{A3}$$

The switching margin is the margin where profits are equal for adopters and nonadopters. Therefore, $\alpha_s$ is found by equating profits

$$P\left[1 - \frac{W}{P\alpha_s^{\gamma_1}}\right] + \frac{W}{\alpha_s^{\gamma_1}} \cdot \ln\left(\frac{W}{P\alpha_s^{\gamma_1}}\right) - I_1 - \left\{P\left[1 - \frac{W}{P\alpha_s^{\gamma_0}}\right] + \frac{W}{\alpha_s^{\gamma_0}} \cdot \ln\left(\frac{W}{P\alpha_s^{\gamma_0}}\right)\right\} = 0 \tag{A4}$$

Total industry supply is found by integrating individual supplies over the distribution of asset quality from the extensive margin, $\alpha_m$ to the upper limit $\alpha = 1$. Asset quality is distributed over a logistic function written as

$$G(\alpha) = \frac{e^{-(b_0 + b_1\alpha + b_2\alpha^2)}}{\left[1 + e^{-(b_0 + b_1\alpha + b_2\alpha^2)}\right]^2} \tag{A5}$$

The output price is endogenized by equating total supply with a constant elasticity demand expressed as $Q^D = \delta P^{\xi}$. Equating demand with total supply determines output price as

where L is the total supply of land. The simulation model consists of three simultaneous equations and three unknowns, $\alpha_m$, $\alpha_s$, and P. The three equations are (A3), (A4), and (A6). Benchmark values for the three

$$\delta P^{\xi} - \left\{ \int_{\alpha_m}^{\alpha_s} \left[ 1 - \frac{W}{P\alpha^{\gamma_1}} \right] \cdot G(\alpha) \cdot L \cdot d\alpha + \int_{\alpha_s}^{1} \left[ 1 - \frac{W}{P\alpha^{\gamma_0}} \right] \cdot G(\alpha) \cdot L \cdot d\alpha \right\} = 0 \tag{A6}$$

where L is the total supply of land.  The simulation model consists of three simultaneous equations and three unknowns, $\alpha_m$, $\alpha_s$, and P.  The three equations are (A3), (A4), and (A6).  Benchmark values for the three unknowns are: $\alpha_m = 0.1$, $\alpha_s = 0.5$, and P = 1.  The system of equations is solved using MathCAD 2.5 version software which uses a modified quasi-Newton algorithm for solving a system of nonlinear simultaneous equations.