Incentive-based Policies for Conservation Technology Adoption: Implications for Pollution and Output

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Abstract

This paper quantitatively analyzes the cost-effectiveness of alternative green payment policies designed to achieve a targeted level of pollution control by heterogeneous microunits. These green payment policies include cost-share subsidies and input-reduction subsidies. The paper shows that unlike a pollution tax, a cost-share subsidy and an input-reduction subsidy are much more restricted in the types of incentives they provide for conservation of polluting inputs and adoption of a conservation technology to control pollution. Costs of abatement with alternative policies and implications for production and government payments are compared using a simulation model for controlling drainage from irrigated cotton production in California.

Keywords: technology adoption, conservation, environmental policy, green payment.

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Agricultural runoff of nutrients and sediment is a primary cause of water quality degradation and this has drawn attention towards encouraging the adoption of conservation or efficiency-enhancing technologies. By increasing the effectiveness with which inputs are used, technologies such as drip irrigation, integrated pest management and site-specific farming have the potential to not only increase input productivity but, according to the law of material balances[1], also reduce the portion of input wasted and converted into pollution. Private incentives to adopt such technologies may lead to suboptimal adoption rates because of the external nature of the costs of pollution, necessitating government intervention.

When farmers are heterogeneous, a pollution tax or firm-specific input taxes are the least cost approach to internalizing external costs (Griffin and Bromley). These policies are difficult to implement because of political difficulties of imposing the "polluter pays principle" on farmers and the high costs of identifying and monitoring the heterogeneous sources generating the non-point pollution. Instead there has been a multitude of "green payment" programs, such as the Agriculture Conservation Program and the Environmental Quality Incentives Program that provide subsidies for taking actions to reduce pollution.

The first objective of this paper is to develop a generic microeconomic framework to quantitatively analyze and compare the cost-effectiveness of alternative green payment policies designed to achieve a targeted level of pollution control by inducing the adoption of a conservation technology. The second objective is to explore the impact of the technical attributes of the conservation technology for the design and cost-effectiveness of alternative policies. The green payment policies considered here are cost-share subsidies to share the fixed costs of adoption of a conservation technology and input-reduction subsidies to reduce the use of a polluting input. We examine two versions of each policy, one where entitlement is restricted to currently operating units and the other that allows unrestricted entry.

The framework developed here consists of a micro-level model of a discrete choice between technologies and selection of input-use levels by units that are heterogeneous in land quality. It incorporates an explicit linkage between input-use and pollution and integrates it with the threshold model of adoption (David) to examine incentives to adopt a conservation technology. This framework is used to compare the differential impact of alternative policies on entry-exit decisions, on input-use and production levels and the extent to which they provide incentives for technology adoption. The relative costs of abatement with alternative policies is an empirical question and we examine that by developing a simulation model for control of drainage from cotton production in Western San Joaquin Valley, California.

The paper builds on and expands the framework developed by Caswell et al. that distinguishes between applied input and effectively used input (input consumed by crops). They assume that the conservation technology increases the productivity of the applied input and can therefore be considered to be *input-augmenting* or *land-quality-augmenting*. Agronomic research[2] suggests that conservation technologies may also have productivity-enhancing attributes that apply to all inputs including land (survey in Khanna and Zilberman). We refer to this as the *neutral productivity-augmenting* attribute of the conservation technology. Neutral technical change may raise yield per acre over and above that due to input-augmenting technical change alone. This paper analyzes the implications of a combination of land-quality and neutral productivity-augmenting characteristics of a conservation technology. Unlike Caswell et al. that analyze the impact of pollution taxes and input prices on adoption of a land-quality-augmenting technology by a single microunit this paper compares the cost-effectiveness of alternative green payment policies relative to a pollution tax. Additionally, it develops a method to aggregate profit-maximizing responses across heterogeneous microunits to examine the effect of alternative policies and technical attributes of conservation technologies for market surplus, aggregate production and government payments.

Other studies analyzing the implications of second-best policies aimed at controlling nonpoint pollution include Abler, Wu et al, Helfand and House, and Huang and Uri. These studies focus on input taxes and input-use restrictions to reduce pollution while assuming that technology is constant[3]. Wu and Babcock analyze the cost-effectiveness of promoting greater conservation effort by a given number of producing units through cost-share subsidies relative to mandatory programs while Segerson and Micelli examine conditions under which cost-share subsidies are required and successful in inducing socially optimal levels of abatement by a firm relative to mandatory approaches. These studies do not consider the impact of subsidies on entry decisions and its impact on the cost-effectiveness of the policy.

The framework developed here is more general in that it allows for pollution generated by heterogeneous microunits to be reduced in three ways - switching towards a conservation technology, reducing the intensity of input-use and exiting from the industry. It shows that differences in the cost-effectiveness of alternative polices arise because of differences in the extent to which they rely on these three mechanisms to reduce pollution. Moreover, unlike a pollution tax, green payment policies that promote land-quality-augmenting and neutral technical change can induce idle land into production. The magnitude of these differences across policies varies with the relative strengths of the land-quality-augmenting and neutral productivity-enhancing characteristics of the technology. Simulations show that the cost of abatement with an input-reduction subsidy is not significantly higher than that under a pollution tax. This cost is substantially lower than with an unrestricted cost-share subsidy. Input-reduction subsidy policies impose much smaller costs on the government and have negligible impacts on marginal land induced into production and on aggregate production as compared to an unrestricted cost-share policy. However, the inefficiency of a cost-share subsidy relative to an input-reduction subsidy and a pollution tax is considerably reduced if it is restricted to units currently operating or if the conservation technology embodies both land-quality-augmenting and neutral productivity-enhancing characteristics and there is a constraint on the availability of idle land.

Theoretical Model

We now develop a micro-economic model to analyze the impact of a pollution tax policy, a cost-share subsidy and an input-reduction subsidy on input-use and technology choice by heterogeneous microunits in a region. Each microunit produces a single crop with a constant returns to scale technology using a single variable input and land. Microunits make a discrete choice between two technologies, a traditional ($i=1$) and a conservation technology ($i=2$). The production function under technology i is: $y_i=b_i f_i(h_i x_i)$ where y_i is output per acre, x_i is applied input per acre, h_i is the input-use efficiency or fraction of the applied input that is actually utilized by a crop and b_i is a neutral productivity-enhancing factor. The function $f(.)$ has the regular properties of a neo-classical production function with $f(0)=0$, $f¢>0$, $f¢¢<0$.

Typically only a fraction of the applied variable input is utilized by a crop. The efficiency of input use with technology i is h_i and is defined as the ratio of applied input x_i to effective input use e_i; thus $e_i=h_i x_i$. We assume that the efficiency of input-use is a function of technology choice and land quality represented by an index a. The index a is scaled to correspond to input-use efficiency with the traditional technology [i.e. $h_1(a)°a$] and can assume values from 0 to 1. Efficiency of input-use with the conservation technology is $h_2=h_2(a)$ with $h_2'>0$ and $h_2''<0$.

The conservation technology increases the efficiency of input-use with a given land quality such that $h_2(a)>h_1(a)°a$ for $0<a<1$, while $h_2(0)=0$ and $h_2(1)=1$.This is the *land-quality-augmenting-effect*. The assumptions about h_2 imply that the gap between h_2 and h_1 decreases as a increases. The *neutral productivity-enhancing* characteristic of the conservation technology is represented by $b_2>b_1$ =1. It implies that the technology raises yield per acre associated with a given level of effective input-use independently of the land-quality-augmenting-effect.

The variable input, not utilized by the crop may be a source of environmental contamination. Pollution per acre with technology i is represented as: $z_i=g_i(a)x_i$, where g_i is the pollution coefficient per unit of applied input with technology i. We assume that $g_i¢(a)£0$, which implies that as land quality increases, the pollution per unit applied input decreases. In some cases, all of the input wasted becomes a polluting residual and $g_i=[1-h_i]$. Since a conservation technology augments input-use efficiency or land quality, it is reasonable to assume that it lowers the pollution coefficient; thus $g_2(a)<g_1(a)$. We refer to this as the *pollution-intensity-effect* of adoption and its magnitude is expected to decline as a increases.

The adoption of a conservation technology requires fixed expenditures per acre on human or physical capital because this technical change is embodied either in management and time intensive skills or new equipment. The annualized fixed costs of adoption per acre k_2 are assumed to be larger than those required with the traditional technology; thus $k_2>k_1$ and the same for all a. While the choice of technology to be adopted on a particular acre by a microunit with efficiency a is a discrete decision, the share of its land acres on which it adopts technology i is a continuous variable $d_i(a)$. Thus, $d_i(a)=1$ if technology i is adopted on all acres with efficiency a, $d_i(a)=0$ if technology i is not adopted on any land acres of efficiency a. Some microunits may be indifferent between using technology 1 or 2 and for them $0£d_i(a)£1$ with $0\leq\sum_{i=1}^{2}d_i(a)\leq 1$.

We define the *elasticity of marginal productivity* (EMP) with technology i with respect to e_i by $e_i= -f¢¢(e_i)e_i/f¢(e_i)$. EMP approaches infinity when $f¢$ is zero and EMP approaches 0 when e_i approaches zero and the marginal productivity of e_i approaches its maximum. Thus, $0<e_i<¥$ in the economic region of production (where $f¢>0$ and $f¢¢<0$). *Elasticity of efficiency*, h_2, with respect to $\boldsymbol{a}$ is defined by $\boldsymbol{h}_2 = h_2¢\boldsymbol{a} / h_2$ and $0 < \boldsymbol{h}_2 £ 1 = \boldsymbol{h}_1$. *Elasticity of output* with respect to e_i is $\boldsymbol{f}_i = f¢e_i/f$. In the economic region of production, $\boldsymbol{f}_i$ decreases from *1* to *0* as e_i increases[4].

Micro-Level Decision Making with a Pollution Tax Policy

We first consider the implications of imposing a pollution tax $\boldsymbol{q}$ designed to achieve a predetermined level of total pollution. Each microunit takes its land quality, prices and the tax rate as given and chooses the quantity of variable input and the share of its land acres on which to adopt each technology to maximize its quasi-rents, subject to the constraint that the sum of the technology shares is less than or equal to one. Quasi-rents are defined in (1) as revenue minus variable costs, annualized fixed costs and tax payments and $\boldsymbol{r}$ is a Lagrange multiplier:

$$\underset{x_i, \boldsymbol{d}_i}{Max}\, \boldsymbol{P}_i(\boldsymbol{a}) = \sum_{i=1}^{2} \boldsymbol{d}_i(\boldsymbol{a})[P\boldsymbol{b}_i f(h_i(\boldsymbol{a})x_i - wx_i - k_i - \boldsymbol{q}\boldsymbol{g}_i(\boldsymbol{a})x_i\,] + \boldsymbol{r}\{1 - \sum_{i=1}^{2} \boldsymbol{d}_i(\boldsymbol{a})\} \qquad (1)$$

The first order conditions are:

$$\frac{¶\, L}{¶\, x_i} = P\boldsymbol{b}_i\, f'\, h_i - w - \boldsymbol{q}\boldsymbol{g}_i = 0; \qquad \forall \boldsymbol{a} \text{ and } i = 1{,}2 \qquad (2)$$

$$\frac{¶\, L}{¶\boldsymbol{d}_i(\boldsymbol{a})} = Py_i - wx_i - k_i - \boldsymbol{q}\boldsymbol{g}_i x_i - \boldsymbol{r} \le 0; \;\; \boldsymbol{d}_i(\boldsymbol{a})(\frac{¶L}{¶\boldsymbol{d}_i(\boldsymbol{a})}) = 0; \forall \boldsymbol{a} \text{ and } i = 1{,}2 \qquad (3)$$

Condition (2) implies that the optimal level of input-use x_i* is chosen such that the value of its marginal product ($P\boldsymbol{b}_i\, f'\, h_i$) is equated to its per unit post-tax price, $v_i = w + \boldsymbol{q}\boldsymbol{g}_i$ where $\boldsymbol{q}\boldsymbol{g}_i$ is the tax burden per unit of applied input. The pollution tax is equivalent to a firm-specific input tax, $\boldsymbol{q}\boldsymbol{g}_i(\boldsymbol{a})$ (as shown by Griffin and Bromley). As the pollution tax $\boldsymbol{q}$ increases, the post-tax price of the applied input increases and this tends to reduce input-use with a given technology[5]. Since $g_2 < g_1$, the increase in post-tax input price and the negative effect on input-use is smaller for microunits using the conservation technology. The framework developed here can be used to further characterize the mechanisms by which the pollution tax controls pollution. Total differentiation of (2) can be used to obtain the elasticity of input-use with respect to the tax:

$$\frac{dx_i^*\theta}{d\theta\, x_i^*} = -\frac{\theta\gamma_i x_i^*}{P\beta_i f(e_i^*)\phi_i\varepsilon_i} < 0. \quad (4)$$

This suggests that the pollution tax has a negative intensive margin effect on input use. If the share of tax payments in total revenue is small and if β_i and elasticities ε_i and ϕ_i are large then the intensive margin effect of the tax is small and input-use with a given technology will not change significantly relative to its unregulated level unless a very high tax rate is imposed.

Condition (3) implies that technologies with negative post-tax quasi-rent will not be adopted, that is, $\delta_i^*(\alpha)=0$, if $\Pi_i^*(\alpha) = Py_i^* - v_i x_i^* - k_i < 0$. The marginal land quality with each technology, α_i^{m*}, is defined as the land quality at which quasi-rents per acre are zero:

$$\Pi_i^*(\alpha_i^{m*}(\theta))=0. \quad (5)$$

Since $\Pi_i^*(\alpha)$ is a monotonically increasing concave function of α, there exists a unique value of α_i^{m*} for each technology[6]. Total differentiation of (5) leads to the elasticity of marginal land quality with respect to θ: $\frac{d\alpha_i^{m*}\theta}{d\theta\, \alpha_i^{m*}} = \frac{\theta z_i^*}{P\beta_i f(e_i^*)\phi_i\eta_i} > 0$. This implies that an increase in the tax rate raises the marginal land quality by inducing microunits with low α to exit the industry. Condition (3) also shows that adoption of the conservation technology occurs when its quasi-rent is positive and larger than that of the traditional technology, that is:

$$\Pi_1^*(\alpha) = Py_1^* - v_1^* x_1^* - k_1 < Py_2^* - v_2^* x_2^* - k_2 = \Pi_2^*(\alpha) > 0 \quad (6)$$

This also implies that ρ can be interpreted as the per acre rent for land with quality α[7].

The difference in quasi-rent per acre with the two technologies for a given land quality can be represented by:

$$\Pi_2^* - \Pi_1^* = \Delta\Pi^* = P\Delta y^* - w\Delta x^* - \Delta k - \theta\Delta z^* \quad (7)$$

where Δ represents the difference in the level of a variable (y, x, k and z) with the two technologies. Factors that affect this quasi-rent differential include the impact of adoption on input-use, Δx^*, on output level, Δy^*, and on the pollution generated, Δz^*, as well as the levels of input price, output price, pollution tax rate and fixed costs of adoption. Condition (7) shows that the larger the output-increasing ($\Delta y^*>0$), input-saving ($\Delta x^*<0$) and pollution-reducing ($\Delta z^*<0$) effects of the conservation technology, the more likely is the differential to be positive.

Caswell et al. showed that adoption of a land-quality-augmenting conservation technology by itself (in the absence of a pollution tax) increases yield per acre but reduces input-use per acre and pollution per acre only when the elasticity of marginal productivity, $\varepsilon_1>1$. When the conservation technology has both land-quality-augmenting and neutral productivity-enhancing attributes, these attributes operate in opposite directions in their effect on input-use and pollution per acre (as shown in the Appendix, equation A.1). Now adoption is input-saving only if $\varepsilon_1>1$ *and* the neutral productivity-enhancing effect is small. A pollution tax supplements this input-saving effect of adoption through its intensive margin effect as in (4).

The effect of adoption on pollution per acre depends on its effect on input-use and on the magnitude of the pollution-intensity effect. If the conservation technology is input-saving, its pollution-reducing-effect will be larger than its input-saving effect because $\gamma_1>\gamma_2$ and adoption reduces the pollution. Even if the conservation technology is not input-saving it may still be pollution-reducing if the pollution-intensity effect is large (as seen in A.3). The larger the neutral productivity-enhancing effect of adoption the smaller is its pollution-reducing-effect.

Both the land-quality-augmenting and neutral productivity-enhancing attributes have a positive effect on output per acre (as shown in A.4). When output per acre under the traditional technology approaches its maximum (that is φ_1 approaches zero) the output-increasing effect of adoption declines. When adoption is induced by a pollution tax, this positive effect could be offset by the negative intensive margin effect of the tax which lowers applied input-use per acre.

Caswell et al. also showed that the profit differential ($\Pi_2^*-\Pi_1^*$) for a land-quality augmenting technology is expected to decline as α increases. This can also be seen by analyzing the sign of $\Omega = \frac{\partial(\Pi_2^* - \Pi_1^*)}{\partial \alpha}$ as in A.5 in the Appendix. The larger the input-saving effect of adoption, the more negative is the sign of Ω and the larger the decline in the profit differential as α increases. Since Δk is the same for all land qualities it implies that the profit differential is likely to be at its largest when α is low and that the conservation technology is more likely to be adopted on low quality land. This pattern of adoption could however be diluted or reversed if the technology has a neutral productivity-enhancing effect, since that reduces the input-saving effect of adoption. This would reduce the rapidity with which Ω declines or even make Ω positive. One could then expect to see relatively greater adoption by microunits with higher land quality than in the case of a conservation technology that is land-quality-augmenting only.

The analysis above implies that when the conservation technology is adopted by the lower land qualities and $\alpha_2^{m*} < \alpha_1^{m*}$, the adoption of the conservation technology leads to expansion of land under production. As β_2 increases, it will further reduce α_2^{m*} as shown above. Mundlak shows conditions under which land-augmenting technical change is land expanding. The analysis here shows that with land-quality-augmenting and neutral technical change also there can be expansion of land under production if adoption occurs on low quality land.

We can define a switching land quality, α^{s*}, as the level at which both technologies yield the same profits per acre: $\Pi_1^*(\alpha^{s*}(\theta)) = \Pi_2^*(\alpha^{s*}(\theta))$. (8)

If $\Omega<0$ for all α, it implies that the conservation technology is likely to be adopted by $\alpha_2^{m*} < \alpha < \alpha^{s*}$ whereas if $\Omega>0$ it implies that the conservation technology is likely to be adopted by $\alpha^{s*} < \alpha < 1$ while other land qualities will use the traditional technology. Total differentiation of this condition shows that the elasticity of the switching land quality with respect to θ is:

$$\frac{d\alpha^{s}*\theta}{d\theta\,\alpha^{s}*}=\frac{(z_2*-z_1*)\theta}{W(\alpha^{s}*)}\quad \begin{array}{l} >0 \text{ if } z_2^{*}<z_1^{*} \text{ and } W(\alpha^{s}*)<0 \\ <0 \text{ if } z_2^{*}<z_1^{*} \text{ and } W(\alpha^{s}*)>0 \end{array} \tag{9}$$

This shows that irrespective of the pattern of adoption, an increase in the pollution tax, will induce some microunits to switch from the traditional technology to the conservation technology if the latter is pollution-reducing. If the pollution-reducing effect of adoption is small, or the tax rate is low, the switching effect will be small and the adoption rate in the unregulated case could be close to that under a pollution tax policy.

Micro-Level Decision-Making with a Conservation Technology Cost-Share Policy

Suppose a cost-share subsidy c is provided to lower the proportion of the fixed cost of adoption. The microunit's objective function can be written as follows:

$$\underset{x_i,\delta_i}{Max}\,\Pi_i(\alpha)=\sum_{i=1}^{2}\delta_i(\alpha)[P\beta_i f(h_i(\alpha)x_i)-wx_i]-\delta_1 k_1-\delta_2(\alpha)(1-c)k_2+\rho\{1-\sum_{i=1}^{2}\delta_i(\alpha)\} \tag{10}$$

Input-use, marginal and switching land quality are now determined such that:

$$Pf'\beta_i h_i(\alpha)-w=0 \tag{11}$$

$$Py_2(\alpha^{sc})-wx_2(\alpha^{sc})-(1-c)k_2=Py_1(\alpha^{sc})-wx_1(\alpha^{sc})-k_1 \tag{12}$$

$$Py_2(\alpha_2^{mc})-wx_2(\alpha_2^{mc})-(1-c)k_2=0 \tag{13}$$

A microunit chooses its quasi-rent maximizing levels of input-use, x_2^{c}, by equating the value of marginal product to the input price. Unlike a pollution tax, a cost-share policy does not have any intensive-margin-effect. If the pattern of adoption is such that the conservation technology is adopted by the microunits with a high α, the cost-share subsidy will not affect the marginal land quality level. Otherwise, the cost-share subsidy will lower the marginal land quality level by lowering the fixed costs. Total differentiation of (11) shows that the elasticity of marginal land quality (with $i=2$) α_2^{mc} with respect to c is: $\frac{d\alpha_2^{mc}c}{dc\,\alpha_2^{mc}}=-\frac{ck_2}{P\beta_2 f(e_2^{c})f_2\eta_2}<0$. The policy will then have a positive extensive-margin effect and be land expanding. The larger the share of the subsidy payments in the total revenue and the smaller are β_2, ϕ_2 and η_2 the larger is the extensive-margin effect.

The effect of a cost-share subsidy policy on the switching land quality level, α^{sc} can be analyzed by deriving the elasticity of switching land quality level with respect to c as follows:

$$\frac{d\alpha^{sc} c}{dc\alpha^{sc}} = -\frac{ck_2}{\Omega(\alpha^{sc})} \begin{cases} >0 & \Omega(\alpha^{sc})<0 \\ <0 & \Omega(\alpha^{sc})>0 \end{cases} \tag{14}$$

The elasticity is positive if the denominator is negative which is the case when the low land quality microunits are adopting the conservation technology and negative otherwise. Either way the cost-share policy induces microunits previously using the traditional technology to switch to the conservation technology.

A technology cost-share policy achieves pollution control through a technology switching effect only. Since pollution reduction through this effect could be partly offset by a positive extensive-margin effect, a cost-share is an effective policy tool for reducing pollution only if the technology switching effect is large and if the conservation technology has a large pollution-reducing effect. To achieve the same level of pollution control as a pollution tax, the cost-share policy must induce higher rates of adoption than the tax policy. A restricted cost-share policy that restricts the subsidy to microunits that are already operating does not have an extensive margin effect. It therefore requires a smaller technology switching effect and a smaller subsidy rate to achieve a given level of pollution reduction.

Micro-Level Decision-Making with an Input-Reduction Subsidy policy

Instead of a subsidy based on technology choice, microunits could be given a subsidy for reducing the use of a polluting input below the privately optimal level. Suppose a uniform subsidy rate of r per unit of input reduction below the privately optimal level x^o is provided. The microunit's objective function can then be written as follows:

$$\underset{x_i,\delta_i}{Max}\ \Pi_i(\alpha)=\sum_{i=1}^{2}\delta_i(\alpha)[P\beta_i f(h_i(\alpha)x_i - wx_i - k_i + r(x^o - x_i)] + \rho\{1-\sum_{i=1}^{2}\delta_i(\alpha)\} \qquad (15)$$

Input-use, switching land quality and marginal land quality are now determined such that:

$$Pf'\beta_i h_i(\alpha) - w - r = 0 \qquad (16)$$

$$Py_2(\alpha^{sr}) - wx_2(\alpha^{sr}) - k_2 + r(x^o - x_2(\alpha^{sr})) = Py_1(\alpha^{sr}) - wx_1(\alpha^{sr}) - k_1 + r(x^o - x_1(\alpha^{sr})) \qquad (17)$$

$$Py_2(\alpha_i^{mr}) - wx_2(\alpha_i^{mr}) - k_i + r(x^o - x_2(\alpha_i^{mr})) = 0 \qquad (18)$$

Condition (16) shows that the subsidy raises the costs of input-use and creates incentives to reduce input-use with both technologies, like a pollution tax. Total differentiation of (16) shows that the elasticity of input-use with respect to r is: $\frac{dx_i^r r}{dr\, x_i^r} = -\frac{rx_i^r}{P\beta_i f(e_i^r)\varphi_i\varepsilon_i}$ <0. However, since the subsidy rate, r, does not vary with technology choice or with land quality, unlike a firm-specific input tax, $\theta\gamma_i(\alpha)$, the negative-intensive margin effect of the two policies differs. Since $\theta\gamma_i(\alpha)$ is relatively smaller for microunits with high α, the intensive-margin effect of an input-reduction subsidy will be larger than that of the pollution tax for microunits with high α and those using the conservation technology. It will be relatively lower for microunits having a low α and those using the traditional technology. The intensive-margin effect of the input-reduction subsidy is therefore not as well targeted towards the polluters as a pollution tax.

The impact of the input-reduction subsidy on the marginal land quality combines elements of the pollution tax and the cost-share subsidy. Like the cost-share subsidy, the payment of rx^o lowers the fixed costs of adoption and creates incentives for farmers that did not otherwise find it profitable to operate to start operating. However, these incentives for entry are partially offset since the subsidy also induces a reduction in input-use. The net extensive-margin effect of the input-reduction subsidy is non-negative unlike a pollution tax but is likely to be smaller than that of the cost-share subsidy. The elasticity of marginal land quality with respect to

r is: $\frac{d\alpha_i^{mr} r}{dr\ \alpha_i^{mr}} = \frac{(x^o - x_i^r)r}{Py_i^r \beta_i \phi_i \eta_i} \geq 0$. The larger the share of subsidy payments in total revenue and the smaller is β_i and the other elasticities, the larger is the extensive-margin effect. The elasticity of the switching land quality with respect to r can be obtained as follows:

$$\frac{d\alpha^{sr} r}{dr\,\alpha^{sr}} = \frac{(x_2^r - x_1^r)r}{\Omega(\alpha^{sr})} \quad \begin{array}{l} > 0 \text{ if } x_2^r < x_1^r \text{ and } \Omega(\alpha^{sr}) < 0 \\ < 0 \text{ if } x_2^r < x_1^r \text{ and } \Omega(\alpha^{sr}) > 0 \end{array} \tag{19}$$

This indicates that an increase in the input-reduction subsidy would induce some microunits to switch towards an input-saving technology. Comparing the switching effect of the pollution tax and an input-reduction subsidy, we see that while the former depends on the magnitude of the pollution-reducing effect, the latter depends on the input-saving effect. Instead of providing the input reduction subsidy to all farmers, the subsidy could be restricted to those farmers that had been operating previously. The extensive margin effect would then be zero and a lower subsidy rate would be required to achieve a given level of abatement.

Regional Implications of Alternative Policies

To examine the effect of alternative policies on aggregate input-use, output, pollution and quasi-rents in a region we define a continuous density function $g(\alpha)$ that represents the frequency density of acres of land that have land quality α. Representing the lowest land quality level that characterizes land in the region by α_L and the highest by 1, we can sum up the number of acres with each land quality level $\alpha_L \leq \alpha \leq 1$ to obtain the total acreage M in the region, such that total acreage is $\int_{\alpha_L}^{1} g(\alpha) = M$. Aggregate output supply, Y, aggregate input use, X, and aggregate pollution, Z, are determined by aggregating the micro-level profit maximizing choices using the density function of land quality $g(\alpha)$, the adoption pattern as determined above, and the marginal and switching land quality levels (α_i^m and α^s). Assuming that adoption occurs on low α (that is

$W<0$) aggregate output, input-use, pollution and quasi-rents are:

$$Y(P,w,t) = \int_{a_2^m}^{a^s} y_2\, g(a)da + \int_{a^s}^{1} y_1\, g(a)da\,; \quad X(P,w,t) = \int_{a_2^m}^{a^s} x_2\, g(a)da + \int_{a^s}^{1} x_1\, g(a)da$$

$$Z(P,w,t) = \int_{a_2^m}^{a^s} g_2 x_2\, g(a)da + \int_{a^s}^{1} g_1 x_1\, g(a)da\,; \quad P(P,w,t) = \int_{a_2^m}^{a^s} P_2\, g(a)da + \int_{a^s}^{1} P_1\, g(a)da \qquad (20)$$

We define market surplus as the sum of consumer surplus, quasi-rents of producing units and government surplus. It excludes the monetized environmental damages due to pollution. Because we are focusing on a small region we assume that commodity prices and thus consumer surplus are not affected significantly by the changes in output. Government surplus is positive and equal to the tax revenues in the case of a pollution tax policy and is negative and equal to subsidy payments with the green payment policies. Costs of abatement are defined as the difference between market surplus in the unregulated situation and the surplus with the policy. The magnitude of the difference in costs of abatement among alternative polices is an empirical issue and we examine it in the next section by developing a numerical programming model.

Numerical Simulation

This simulation analyzes the implications of alternative policies for reducing drainage from cotton production in California's San Joaquin Valley where cotton is grown on about 400,000 irrigated acres in the western portion. To keep the analysis simple we assume there are two irrigation technologies. Furrow is the traditional irrigation technology while drip is the conservation technology. We specify a quadratic production function as in Caswell et al and Hanemann et al., $y_i = f(e_i) = -1589+2311e_i - 462e_i^2$, and assume $b_i=1$ We compare the impact of two alternative values of b_2, 1 and 1.005, while assuming b_1=1.

We use efficiency with furrow technology as a measure of land quality ($h_1(a)=a$) as in Caswell et al. Land quality ranges from 0.2 (steep sandy soils) to 0.8 (level fields with heavy soils) (State Water Control Board Report) and the data are distributed in a unimodal pattern. For this simulation we use these parameters to construct a symmetric Beta distribution of land quality with a mean efficiency of 0.5 and variance 0.013. Hanemann et al find that when the efficiency of water use with furrow is 0.6 the adoption of drip irrigation increases efficiency of water use to 0.95. We use this information together with the assumption that $h_1=\alpha=1$ implies $h_2=1$, to calibrate a constant elasticity function to relate the efficiency with drip to that with furrow irrigation for each land quality. The function obtained is $h_2(\alpha)=\alpha^{0.1}$. We specify the pollution generation function as $g_i=(1-h_i)^{k_i}$. As water-use efficiency increases, the pollution coefficient decreases. We calibrate this function using the information that with $h_1=\alpha=0.6$, g_1 drainage coefficient with furrow, is 0.175, and that with $h_2=0.95$, the drainage coefficient with drip is 0.04 (Hanemann et al.). We obtain $k_1=1.902$ and $k_2=1.074$. The fixed cost of adoption of furrow irrigation and drip irrigation is \$500 per acre and \$633 per acre, respectively. Water price is assumed to be \$55 per acre-foot while price of cotton is assumed to be \$0.6 per pound.

Implications of Alternative Policies with Land-Quality Augmenting Change

With these prices, in the absence of any regulation and with $b_2=1$, we find that land with quality less than 0.41, which is 24% of the land area will be idle. Adoption of drip occurs on land with low quality, $0.41\leq\alpha\leq0.47$, while land with high quality continues to use furrow irrigation. Total quasi-rents in the region are \$11.2 million, total water use is 1.13 million acre-feet, cotton production is 390 million pounds and drainage generated is 204.76 thousand acre-feet.

Table 1 shows the implications of alternative policies designed to achieve a 40% reduction in drainage relative to the unregulated level. The restricted cost-share policy and both forms of the input-reduction subsidy lead to market surplus levels that are very close to each other and not substantially lower than that under a least cost pollution tax. The restricted cost-share policy is the most cost-effective among these green payment policies and with a 40% abatement target it lowers market surplus by 3% while the restricted input-reduction subsidy lowers it by 4% relative to the pollution tax. The unrestricted input-reduction subsidy policy imposes costs of abatement that are very similar to those with the restricted input-reduction subsidy because it does not induce a large extensive margin effect. The costs of abatement of a restricted cost-share policy and a restricted input-reduction subsidy are similar because the intensive-margin effect of the latter is small. The input-reduction subsidy achieves abatement primarily through the technology-switching effect, like the cost-share subsidy. Both forms of the input-reduction subsidy and the restricted cost-share subsidy therefore have very similar effects on water-use, switching land quality levels and output.

On the other hand, the unrestricted cost-share subsidy leads to a large reduction (14%) in market surplus relative to a pollution tax. The inefficiency of green payment policies increases considerably as the abatement target increases, particularly for the unrestricted cost-share policy (Figure 1). As expected, the two restricted subsidy policies are always more cost-effective than the unrestricted subsidy policies. At the 60% abatement level, market surplus is lower relative to a pollution tax policy by 13% under a restricted cost-share subsidy, by 15% under a restricted input-reduction subsidy, by 22% under an unrestricted input-reduction subsidy and by 38% under an unrestricted cost-share subsidy.

As suggested by the theoretical analysis, these differences in cost-effectiveness among policies arise because they differ in the ways that they provide incentives for abatement. A pollution tax causes 30% of the land operating in the base case to exit the industry. Marginal land quality level increases from 0.41 to 0.51. A pollution tax also creates incentives for 15% of land previously under furrow to switch to drip irrigation and raises the switching land quality level. Total water use declines by 38% relative to the unregulated level. In contrast, an unrestricted cost-share increases water use by 5%. It also has a large entry effect and induces all idle marginal land (24% of land in the region) into production. It controls pollution by inducing 27% of the land to switch from furrow to drip while the other green payment policies induce 19-20% of the land to switch (Figure 2). Hence, while creating incentives to adopt a conservation technology and reduce pollution, an unrestricted cost-share subsidy increases water use and land use.

While the unrestricted cost-share policy leads to the lowest level of market surplus it leads to the highest level of farm income and aggregate production indicating a conflict among the objectives of social efficiency, supporting farm income and increasing cotton production at existing prices. It leads to 72% higher level of farm income as compared to the base case, 34% more as compared to the restricted cost-share policy and 52% more than with the input-reduction subsidy policies. A pollution tax would have reduced farm income by 33% relative to the base case. However, the unrestricted cost-share subsidy also imposes costs on the government that are almost five times higher than those under the input-reduction subsidies at the 40% abatement level. This cost differential increases as the abatement target increases as shown in Figure 3. These policies also differ considerably in their impact on aggregate output. While a pollution tax reduces aggregate output by 39% relative to the base case, the restricted cost-share and the restricted input-reduction subsidy policies have a very marginal impact on total production. The unrestricted cost-share policy increases aggregate output by 32%.

Policy Implications of Combination of Land-Quality-Augmenting and Neutral Technical Change

The specification of the technology affects the land qualities that find it profitable to operate and the private incentives to adopt the technology. Even with a small increase in b_2 by 0.5% to b_2=1.005 there is a significant increase in the range of land qualities over which it is privately profitable to operate. Ninety-five percent of the total land area in the region, having a land quality greater than 0.32 would now be under production, showing that neutral technical change is land expanding. There is also an increase in the incentives for voluntary adoption of drip irrigation among higher land qualities and the switching land quality level increases by 12% to 0.46. As expected from the analysis in the Appendix, there is an increase in total water use by 16%, an increase in total output produced by 25% and in total drainage by 3% as compared to the case with $b_2=1$. The increased rate of adoption, however, results in a reduction in the pollution-output ratio from 0.52 to 0.42 acre-feet of drainage per thousand pounds of output.

The specification of the technology also has several implications for policy. With the higher b_2 of 1.005, a higher tax rate/subsidy rate is required to achieve targeted levels of abatement under all policies, with the exception of the unrestricted cost-share subsidy. The higher tax/subsidy rate is required to control the additional pollution generated by the large influx of marginal land into production (relative to the case with $b_2=1$) whose contribution to pollution is not completely offset by stronger voluntary incentives among existing units to adopt drip irrigation. Additionally, in the case of the pollution tax and input-reduction subsidy this occurs because an increase in b_2 reduces the intensive-margin effect of the tax/subsidy as suggested by the theoretical analysis.

In the case of the unrestricted cost-share subsidy, however, a lower subsidy rate is required, because the increase in b_2 to 1.005 does not induce any additional land into production relative to the case with $b_2=1$ which had already brought all idle land into production while achieving the 40% abatement target. Instead the increased voluntary incentives for adoption with the higher b_2 lead to a reduction in the cost-share rate required to achieve the targeted abatement. This result is conditional on the assumption of a fixed amount of land on which cotton production can be expanded in the short or medium term.

The higher pollution tax rate required with the higher b_2 to achieve the targeted abatement raises the costs of abatement relative to the case with b_2=1. The pollution tax now lowers market surplus by 13% instead of by 7% relative to the base case while achieving 40% abatement (Table 2). The higher subsidy rates required with the higher b_2 also increase the relative inefficiency of the restricted cost-share and both input-reduction subsidy policies. However, the ranking of the policies remains unchanged. The major impact of a higher b_2 is that it significantly lowers the costs of abatement under an unrestricted cost-share and brings it closer to those with the other three green payment policies and the pollution tax policy. This occurs because the higher b_2 raises the pollution tax rate while lowering the unrestricted cost-share subsidy rate. It also reduces the negative intensive-margin and the negative extensive-margin effects of the tax while reducing the positive extensive-margin effect of the unrestricted cost share subsidy. The four green payment policies now have very similar market surplus (Fig. 4).

The larger land area that finds it profitable to operate with b_2=1.005 results in a considerably expanded tax base under the pollution tax and a larger subsidy base under the restricted cost-share subsidy and both types of input-reduction subsidies relative to the case where b_2=1. This together with the higher tax/subsidy rate required to achieve the targeted abatement raises the pollution tax revenue by 14% as well as the subsidy payments required by 69% under a restricted cost-share subsidy policy and by 14% to 16% under the input reduction subsidies (Table 2). However, it lowers the payments required under an unrestricted cost-share subsidy by 15% relative to the case with b_2=1 since the subsidy base is unchanged and the required subsidy rate is lower. The specification of the technology also impacts the relationship between pollution control and production under the alternative policies, with the most significant differences occurring with a pollution tax and an unrestricted cost-share subsidy policy. On the one hand, an increase in b_2 decreases the negative impact of the pollution tax on output (from

39% to 24% at the 40% abatement level). On the other hand, it decreases the positive impact of the unrestricted cost share subsidy on aggregate output from 32% (with b_2=1) to 5% (b_2 =1.005).

Conclusions

This paper develops a microeconomic framework to quantitatively analyze the cost-effectiveness of alternative policies that seek to reduce non-point pollution by influencing the observable decision variables of heterogeneous microunits, namely technology choice and input-use. It examines the implications of the specification of the technical attributes of the conservation technology for cost-effectiveness, for the fiscal impact of policies and for the relationship between pollution reduction and output at the regional level.

Our theoretical analysis shows that unlike a pollution tax that achieves abatement through three mechanisms – a negative extensive margin effect, a negative intensive margin effect and a technology switching effect, a cost-share subsidy and an input-reduction subsidy are much more restricted in the incentives they provide. Additionally, these subsidy policies differ from a tax in that they have positive extensive-margin effects unless specifically restricted to prevent entry of marginal land. The magnitude of these three effects decreases while the tax/subsidy base increases as the neutral productivity-enhancing effect of the technology becomes stronger which raises the costs of abatement to achieve a given percentage reduction in pollution. The neutral productivity enhancing effect of a conservation technology also reduces the input-saving and pollution-reducing effect of adoption while increasing its output-increasing effect.

The analysis shows that a restricted cost-share and input-reduction subsidy policy have similar costs of abatement and these costs are close to those with a pollution tax even at fairly high levels of abatement. The budgetary cost of a restricted cost-share policy is however twice as large as that of an input-reduction subsidy. In the event that a restricted green payment policy is politically difficult to implement and an unrestricted policy needs to be implemented, an input-reduction subsidy is preferable to a cost-share subsidy. It has relatively low costs of abatement and government costs. It also leads to conservation of water-use and is not as land-expanding. However, if the conservation technology has both land-quality-augmenting and neutral productivity-enhancing attributes, the inefficiency of an unrestricted cost-share subsidy relative to other policies is considerably reduced, if the availability of idle land is constrained.

The analysis in this paper is based on the assumption of a perfectly elastic demand but could be easily extended to include the effects of alternative policies on output price. If demand is relatively inelastic, then a pollution tax can be expected to increase output price, while green payment policies will reduce output price. This output price change will create secondary influences on the intensive-margin, extensive-margin and technology-switching effects of an environmental policy. The analysis also shows the value of having data from a geographic information system on the distribution of land quality that can influence the performance of conservation technologies. This data could be used to expand upon the simulation done here to empirically analyze the regional implications of alternative policies.

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[1] This law states that the mass of inputs applied must equal the mass of final products plus the mass of residuals discharged to the environment minus the mass of materials recycled.

[2] Conservation technologies, such as drip irrigation and site-specific farming, reduce biological stress on plants by targeting inputs precisely to appropriate areas in the field and avoiding deficiencies and excesses in input-use (Wallace and Wallace). Insufficient water during critical plant growth periods can lead to plant stress that can reduce the yield of grain sorghum by 10 to 30% (Council for Agricultural Science and Technology). Studies show that a switch to modern irrigation systems for cotton not only leads to water savings of 25% but also to yield increases of 17- 40% as compared to furrow (Fangmeier).

[3] The analysis by Wu et al. focuses on nitrate pollution control and while it allows for technology choice for irrigation it assumes that the nitrogen application technology is fixed. Huang and Uri consider alternative crop rotation patterns but assume the input application technology is fixed.

[4] $\partial\phi_i/\partial e_i = \phi_i\,[1-\varepsilon_i-\phi(e_i)]\,/e_i$. As e_i increases ϕ_i decreases, and ϕ_i has a value of 1 when e_i is zero and $\varepsilon_i=0$. It has a value of 0 when e_i increases to the point that $f'(e_i)=0$. This implies that $\partial\phi_i/\partial e_i \leq 0$ and therefore that $[1-\varepsilon_i-\phi(e_i)] \leq 0$ and that ϕ_i has a maximum value of 1 when $1-\varepsilon_i=\phi_i$,

[5] The second order condition for maximization of quasi-rents per acre with each technology is $P\beta_i^2 f''\eta_i^2 < 0$. Concavity of the production function ensures that this condition is met.

[6] $\frac{\partial \Pi_i^*}{\partial \alpha} = PY_i\varepsilon_i\eta_i - \theta\gamma_i'\,x_i > 0 \text{ since } \gamma_i' < 0; \frac{\partial^2 \Pi_i^*}{\partial \alpha^2} = x_i[P\beta_i f'\eta_i'' + P\beta_i f''\eta_i'^2 - \theta\gamma_i''] < 0 \text{ since } \gamma_i'' > 0$

[7] Condition (3) implies that $\rho^*(\alpha) = max[\Pi_1^*(\alpha), \Pi_2^*(\alpha), 0]$ and can be interpreted as the per unit rental rate of land with quality α.

Table 1: Implications of Alternative Policies with Land-Quality Augmenting Technical Change and a 40% Abatement Target

	Base case	Pollution tax	Restricted Cost-share Policy	Unrestricted Cost-Share Policy	Unrestricted Input-Reduction Subsidy	Restricted Input-Reduction Subsidy
Idle Land Area (%)	24	54	24	0	22	25
Switch in land area away from furrow (%)	-	15	20	27	19	19
Marginal Land Quality	0.412	0.513	0.412	0.20	0.405	0.412
Switching Land Quality	0.475	0.52	0.537	0.56	0.540	0.536
Water Use (M Acre-feet)	1.13	0.70	0.98	1.19	0.98	0.96
Output (M lbs.)	390.80	237.88	391.78	517.04	401.02	389.90
Drainage ('000 acre-feet)	204.76	122.86	122.86	122.86	122.86	122.86
Tax Revenue/Subsidy Payments ($ M)	0	2.78	4.40	10.43	2.83	2.72
Farm Income ($ M) (inclusive of subsidy/net of tax)	11.19	7.55	14.4	19.27	12.72	12.66
Market Surplus ($ M)	11.19	10.33	9.99	8.84	9.89	9.94
Cost of Abatement ($M)		0.86	1.2	2.35	1.3	1.25

Table 2: Implications of Alternative Policies with Land-Quality Augmenting and Neutral Technical Change and a 40% Abatement Target

	Base case	Pollution tax	Restricted Cost-share Policy	Unrestricted Cost-Share Policy	Unrestricted Input-Reduction Subsidy	Restricted Input-Reduction Subsidy
Market Surplus[a] ($M)	12.39	10.66	10.29	10.03	10.18	10.23
Cost of Abatement (M)	-	1.73	2.10	2.36	2.21	2.16
Tax Revenues/Subsidy ($ M)	-	3.16	7.41	8.85	3.22	3.15
Farm Income ($ M)	12.39	7.49	17.71	18.89	13.41	13.39
Output (M lbs.)	490.51	368.604	490.84	518.75	495.48	488.52

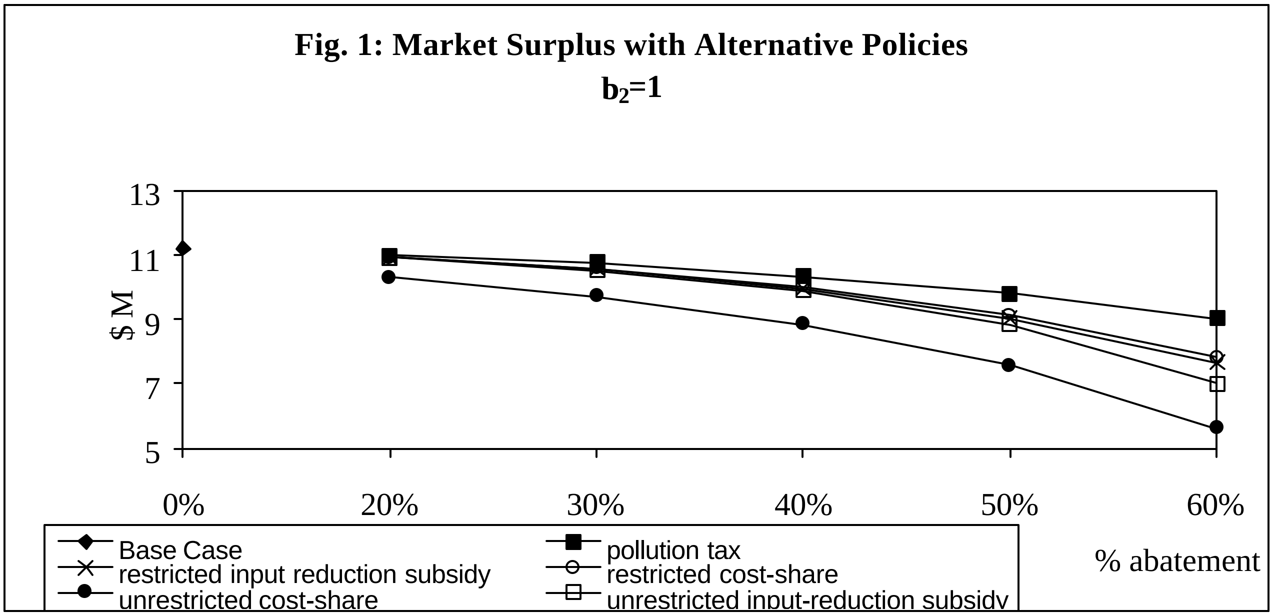


Fig. 1: Market Surplus with Alternative Policies
b2=1
13
11
9
7
5
$ M
0%
20%
30%
40%
50%
60%
% abatement
Base Case
pollution tax
restricted input reduction subsidy
restricted cost-share
unrestricted cost-share
unrestricted input-reduction subsidy

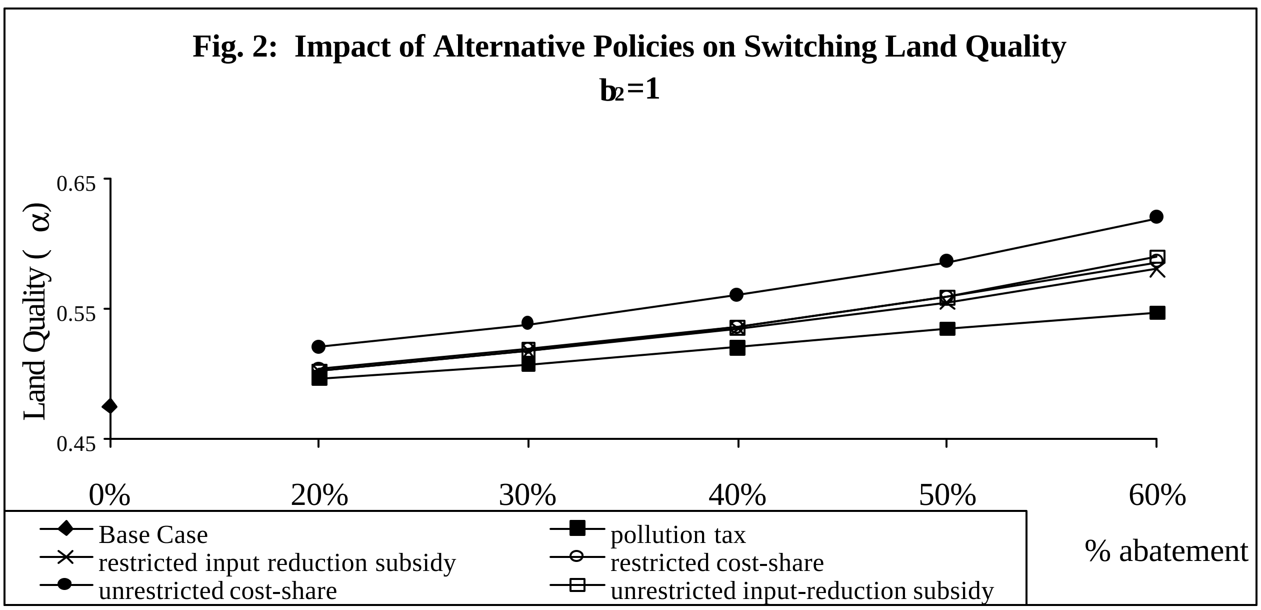


Fig. 2: Impact of Alternative Policies on Switching Land Quality
b2=1
0.65
0.55
0.45
Land Quality (α)
0%
20%
30%
40%
50%
60%
% abatement
Base Case
pollution tax
restricted input reduction subsidy
restricted cost-share
unrestricted cost-share
unrestricted input-reduction subsidy

Fig. 3: Impact of Green Payment Policies on Government Costs
b_2=1

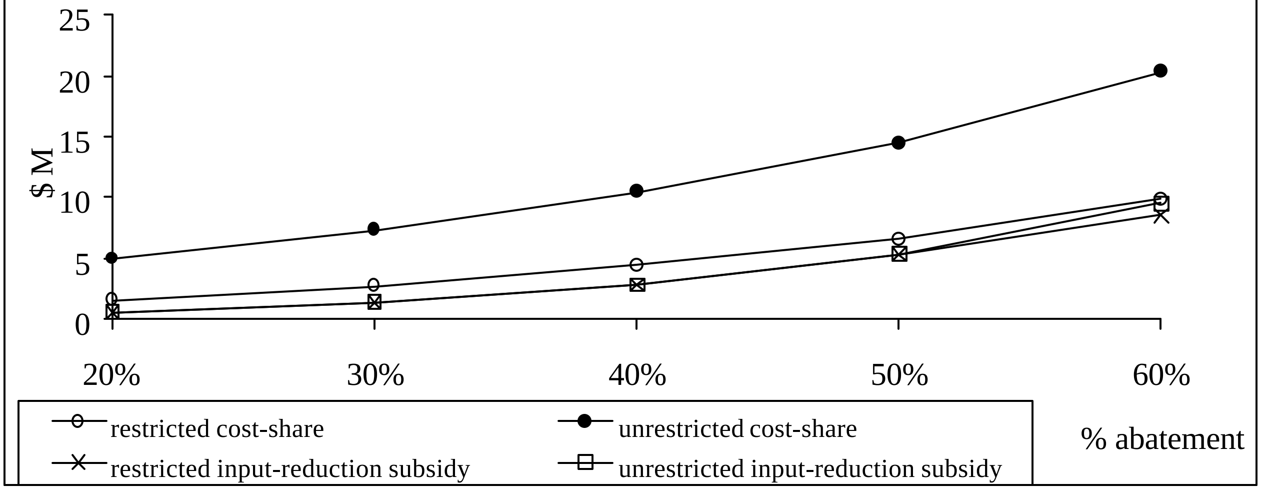
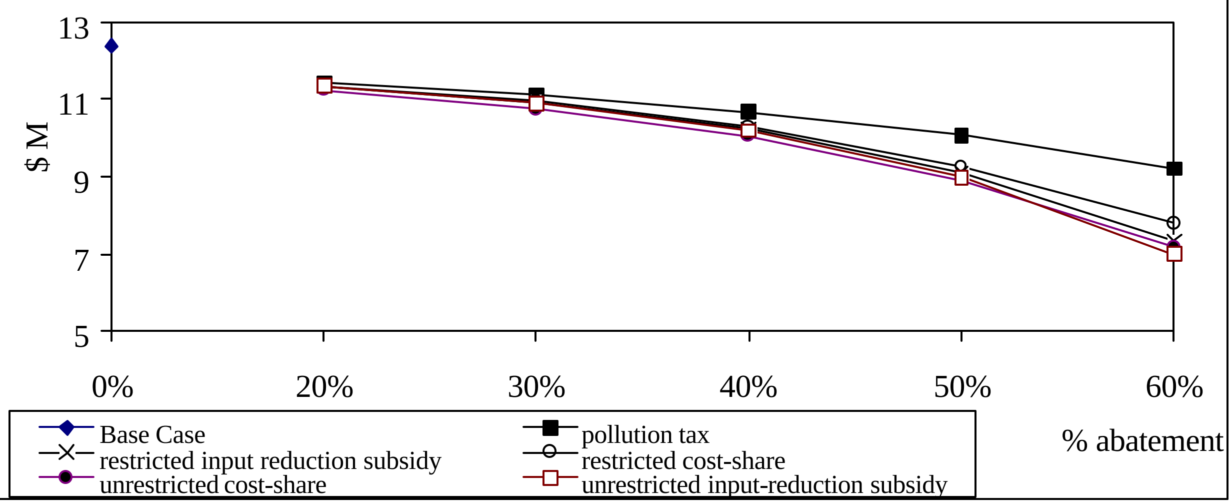


Fig. 4: Market Surplus with Alternative Policies
b_2=1.005



Appendix

Impact of Technology Adoption on Input-Use, Output and Pollution

The adoption of a conservation technology could impact variable input-use for two reasons: (a) it augments the efficiency of the variable input from $h_1(\alpha)$ to $h_2(\alpha)$ and (b) it augments the productivity of effective input-use from β_1 to β_2 which also indirectly raises the productivity of applied input-use.

The difference in a microunit's input-use and pollution per acre due to adoption itself (in the absence of any environmental policy) can be approximated by:

$$\Delta x = x_2 - x_1 \cong \frac{\partial x_1}{\partial \alpha}(h_2 - \alpha) + \frac{\partial x_1}{\partial \beta}(\beta_2 - \beta_1) = \frac{x_1}{\alpha}\left[\frac{1-\varepsilon_1}{\varepsilon_1}\right](h_2 - \alpha) + \frac{x_1}{\varepsilon_1}(\beta_2 - \beta_1)$$

$$\Rightarrow \frac{\Delta x}{x_1} = \frac{(1-\varepsilon_1)}{\varepsilon_1}\left[\frac{h_2 - \alpha}{\alpha}\right] + \frac{1}{\varepsilon_1}[\beta_2 - \beta_1] \qquad \text{(A.1)}$$

The first term on the right is the effect of the land-quality-augmenting attribute of the conservation technology on input-use and the second term is the effect of neutral productivity-enhancing effect. In the presence of a pollution tax, impact of adoption on input-use can be approximated by:

$$\frac{x_2{*} - x_1{*}}{x_1{*}} = \frac{(1-\varepsilon_1)}{\varepsilon_1}\left[\frac{h_2 - \alpha}{\alpha}\right] + \frac{1}{\varepsilon_1}[\beta_2 - \beta_1] - \frac{\gamma_i}{\varepsilon_i}\frac{[v_2 - v_1]}{v_1} \qquad \text{(A.2)}$$

The effect of adoption on pollution per acre is: $\Delta z = \gamma_2 \Delta x - x_1(\gamma_1 - \gamma_2)$ (A.3)

If $\Delta x < 0$ in A.1 then the pollution-reducing effect of adoption is larger than its input-saving effect since $\gamma_1 > \gamma_2$. While the land-quality-augmenting effect and the neutral productivity-enhancing attributes affect pollution generated indirectly by influencing input-use, the pollution intensity effect influences it directly.

The impact of adoption on output per acre in the absence of any environmental regulation can be approximated by:

$$\frac{\Delta y}{y_1} \cong \frac{\phi}{\varepsilon_1}\left[\frac{h_2 - \alpha}{\alpha} + (\beta_2 - \beta_1)\right] \qquad \text{(A.4)}$$

The land-quality-augmenting-effect and neutral productivity-enhancing effect work in the same direction to increase output per acre with adoption.

The Pattern of Adoption

In order to examine the pattern of adoption across heterogeneous land qualities, we differentiate the change in the profit differential ($\Pi_2{*}$-$\Pi_1{*}$) with respect to α, and evaluate it at $\theta = 0$, to obtain:

$$\Omega = \frac{\partial(\Pi_2{*} - \Pi_1{*})}{\partial \alpha} = \frac{1}{\alpha}[w\eta_2(x_2{*} - x_1{*}) + (\eta_2 - 1)wx_1{*}] \qquad \text{(A.5)}$$

The first term on the right hand side is negative if the technology is input-saving. The second term is always negative since $\eta_2 \leq 1$.

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