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Cost-effectiveness of alternative green payment policies for conservation technology adoption with heterogeneous land quality

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Abstract

This paper quantitatively analyses 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 that share the fixed costs of adoption of a conservation technology and/or input reduction subsidies to reduce the use of a polluting input. The paper 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 types of incentives they provide for conservation of polluting inputs and adoption of a conservation technology to control pollution. Moreover, they may lead to varying levels of expansion of land under production. 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, with drip irrigation as a conservation technology.

Keywords: Technology adoption; Conservation; Environmental policy; Green payments

1. Introduction

Increasing concern about environmental quality degradation is drawing attention towards alternative strategies and policies to reduce agricultural run-off of nutrients and sediment. Run-off may be reduced either by reducing the use of polluting inputs and/or by encouraging the adoption of conservation technologies that increase the effectiveness with which inputs are used by plants and reduce the portion of input that is wasted and converted into pollution. Such technologies have also been referred to as input-augmenting technologies and as complementary technologies; the former because they increase input productivity and reduce the use of polluting inputs per unit output (Abler and Shortle, 1995), and the latter because they have the potential to provide both economic and environmental benefits (Office of Technology Assessment, 1995). Examples include precision technologies that can reduce nitrogen use per bushel of corn and nitrate run-off (National Research Council, 1997; Khanna and Zilberman, 1997), drip irrigation that can reduce water use and polluted drainage per unit output (Caswell and Zilberman, 1986), high accuracy

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pesticide application technologies that increase the efficiency of pesticide applications (Hall and Fox, 1997), integrated pest management (IPM) and genetically modified seeds such as Bt cotton that reduce pesticide use per unit output (Klotz-Ingram et al., 1999).

The extent to which these technologies are input-saving, pollution-reducing and/or yield-increasing varies across microunits with heterogeneous land quality is analyzed by Caswell and Zilberman (1986) and Caswell and Shoemaker (1993). While there exist some private incentives to adopt such technologies (Cooper and Keim, 1996), these incentives may be insufficient to induce socially desired levels of adoption due to the external nature of the costs of pollution, thus, necessitating government intervention (National Research Council, 1997).

Efficient government intervention can be achieved through a Pigouvian tax that equates the marginal benefit of pollution control with the marginal costs of abatement (Baumol and Oates, 1988). Difficulties in measuring and monetising the marginal benefits of abatement have led to the development of the standards and pricing approach to policy choice, that seeks to achieve a predetermined environmental standard at least cost by pricing pollution appropriately (Baumol and Oates, 1971). One of several agro-environmental programs with predetermined abatement targets is the Conservation Reserve Enhancement Program in Illinois, which seeks to reduce sediment loadings in the Illinois River Basin by 20% and nutrient loadings by 10%.

A tax on the pollutant to be abated would be a cost-effective approach to achieve such aggregate standards in the presence of heterogeneity among polluting sources. However, such a tax would be inappropriate for controlling non-point pollution, which is difficult to observe and measure at reasonable cost and is stochastic due to natural variation in weather and other environmental processes. Consequently, policies to control non-point pollution must be based on those aspects of the non-point pollution process that are more likely to be observable, such as input-use and technology choice. The design of such policies and their efficiency can vary with the extent of information about individual behavior and the ease with which it can be monitored. Since information is costly to obtain, policy makers have to weigh the costs of information acquisition against the gains from a more cost-efficient policy.

Additionally, the choice of environmental policy is also determined by the explicit or implicit assignment of property rights to a clean environment. Agro-environmental policy in the US has been based on the implicit assignment of property rights to the farmer and the provision of financial incentives, 'green payments', to farmers for voluntarily changing their observable choices (input use or technology) so that they are more environmentally friendly (Ribaudo and Caswell, 1999). An example of such a green payment program in the US is the Environmental Quality Incentives Program (EQIP).

The increasing reliance on such programs to achieve environmental goals in the agricultural sector both in the US and in Europe has drawn the attention of the World Trade Organization because these subsidies can influence agricultural production and create trade distortions. The Uruguay Round Agreement on Agriculture provides 'green box' exemption for only those green payment programs, such as EQIP, that have minimal distorting effects on agricultural production and trade (Vasavada and Warmerdam, 1998). However, there have been no systematic studies to examine the impact of green payments on agricultural production.

This paper focuses on two issues associated with green payment policies. First it analyses the cost-effectiveness of alternative green payment policies relative to a least cost pollution tax. This provides an order of magnitude for the extent to which it would be worth incurring the higher costs of information associated with more efficient policies. Second, it examines the implications of green payment policies for agricultural production. The green payment policies considered in this paper are cost-share subsidies to share the fixed costs of adoption of a conservation technology, input reduction subsidies to reduce the use of a polluting input, and a combination of these two types of subsidy payments. Two versions of each policy are examined; one where entitlement is restricted to currently operating units and the other that allows unrestricted entry. By differing in the incentives they provide for alternative means of pollution control, these different types of green payments may diverge in their costs of abatement and production response, while achieving the same level of pollution control.

A generic framework that consists of a micro-level model of a discrete choice between input-augmenting technologies and selection of continuous input use levels by units that are heterogeneous in land quality is developed. It explicitly incorporates a technology and soil-quality specific production and pollution function that allows us to distinguish between the effect of changes in input use and conservation technology adoption on production and pollution. Within this framework, pollution generated by a microunit can be reduced in three ways—switching towards a conservation technology (switching effect), reducing input use with a given technology (intensive margin effect) and exiting from the industry (extensive margin effect). This micro-level model is used to aggregate profit-maximizing responses under alternative policy scenarios across heterogeneous microunits to analyze policy implications at a regional level for gross social welfare, aggregate production, and government payments.

Key assumptions of this analysis are that the policy maker: (i) knows the distribution of soil quality in the region, (ii) observes the aggregate pollution generated in a region, (iii) observes either input use and/or technology choice by farmers, and (iv) uses the above information as the basis for choosing the type and magnitude of green payments. The ability to observe and monitor compliance is a reasonable assumption in the case of some programs, such as EQIP, under which all subsidized activities must be carried out according to an approved conservation plan explaining what changes in farming practices are expected, and under which payments are made only after monitoring the implementation of those practices (Cattaneo, 2001).[1]

The implications of alternative green payments are examined empirically using a calibrated micro-level model for control of drainage from irrigated cotton production in the Western San Joaquin Valley, California. Green payments to induce adoption of modern irrigation technologies to reduce drainage are widely used in this region (San Joaquin Valley Drainage Program, 1990). Several water districts in California, in particular, the Central California Irrigation District, have implemented programs for sharing (with farmers) the costs of installing sprinkler irrigation systems and, thus, reducing water use and drainage since the early 1990s (MacDougall et al., 1992). In addition, Proposition 82 commits California to provide financial support for the adoption of improved efficiency on-farm irrigation systems (California Department of Water Resources, 2001). Finally, EQIP provided US$ 8 million in 1998, in the form of technical and cost-share assistance, to private landowners in California to adopt conservation measures. This represented the second largest allocation among the 50 states in the US (USDA, 1998).

2. Previous literature

There is a considerable literature examining the optimal design of green payment policies when regulators have either full information (Babcock et al., 1996, 1997; Horan et al., 1999) or asymmetric information (Wu and Babcock, 1995, 1996; Smith, 1995) about the types of farmers. In the latter case farmers may have an incentive to misrepresent their type to obtain favorable combination of production practices and green payments, and these studies design green payment policies that provide incentives for farmers to self-select the payments and practices intended for their type. However, there are very few studies analyzing the cost-effectiveness of green payment policies. These include a study by Wu and Babcock (1999) who analytically compare the cost-effectiveness of a tax with a cost-share subsidy to achieve environmental objectives, assuming there is full information on the costs of abatement. They show that the cost-effectiveness of a tax depends on the costs of enforcing/administering the tax and the social costs of government payments needed for the subsidy. Their analysis incorporates heterogeneity among farmers, but assumes that there is no exit or entry of land and that both policies induce all farmers to adopt the conservation practice. However, a key source of divergence between a tax and a subsidy policy is their different entry and exit effects (Baumol and Oates, 1988). The existence of heterogeneous land quality implies that while a tax might induce exit, a subsidy could induce entry by idle marginal land (or land that is currently not under crop

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[1] However, in the case of larger green payment programs, such as the Conservation Reserve Program and the Farmland Protection Program, monitoring is expensive and compliance with the provisions of the program is not always assured (Giannakas and Kaplan, 2001).

production). These slippage effects can be substantial as shown by Wu (2000) in the case of the Conservation Reserve Program. Additionally, pollution may be controlled not only through conservation technology adoption but also through a reduction in input use with either technology. The present paper therefore allows for the possibility that it may not be optimal to induce all heterogeneous microunits to adopt a conservation technology, but rather to achieve pollution control through varying combinations of input use reduction and technology adoption by different microunits.

While a few studies (Brooks et al., 1992; Love and Foster, 1990) have econometrically analyzed the effects of voluntary US agricultural commodity programs, such as the acreage diversion requirement, on incentives to divert production from low quality marginal land to high quality land to meet set aside requirements, we are not aware of studies that have examined the impact of green payment policies on agricultural production. The above studies show that in the presence of heterogeneous land quality, government programs can lead to significant changes in the land quality under production, and that these changes can influence the cost-effectiveness of those programs. Furthermore, both Mundlak (1997) and Caswell and Zilberman (1986) show that input-augmenting technologies can be land-expanding. This paper extends that research by examining the implications of alternative green payment policies that encourage adoption of input-augmenting technologies for the entry of land under production and for production levels.

This paper also expands the framework developed by Caswell et al. (1990) that focuses only on the incentives for adoption by a single microunit under a pollution tax. It analyses the incentives for adoption provided by green payments in a region with heterogeneous microunits as well as the differences in the extent to which alternative polices rely on these three mechanisms to reduce pollution listed above. Like Caswell and Shoemaker (1993), this paper also compares the intensive, extensive and switching effects of alternative policies. However, the framework developed in this paper differs conceptually from theirs by incorporating the notion of efficiency of input use in the production function and using it to explicitly link input use and pollution through the law of material balances.[2] Moreover, Caswell and Shoemaker (1993) compare the implications of a tax on the traditional pest management technology and a cost-share subsidy on a pesticide-reducing practice (such as IPM) for pesticide loadings only. In contrast, this paper examines a broader range of green payment policies and compares their cost-effectiveness relative to a least-cost pollution tax which achieves the same level of pollution control. It also examines the implications of these policies for production levels.

3. Theoretical model

Each microunit is assumed to be producing 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: $y_i = f(h_i x_i)$ where y_i is output per acre, x_i the applied input per acre, h_i the input use efficiency or the fraction of the applied input that is actually utilized by a crop (Caswell and Zilberman, 1986). The product $h_i x_i$ represents the amount of applied input that is effectively used. The function $f(\cdot)$ has the regular properties of a neo-classical production function with $f' > 0$, $f'' < 0$.

We assume that the efficiency of input use is a function of technology choice and land quality represented by an index α. Microunits are heterogeneous in their land quality. The index α is scaled to correspond to input use efficiency with the traditional technology (i.e. $h_1(\alpha) \equiv \alpha$) and can assume values from 0 to 1. Efficiency of input use with the conservation technology is $h_2 = h_2(\alpha)$ with $h_2' > 0$ and $h_2'' < 0$. The conservation technology is input-augmenting and increases the efficiency of input use with a given land quality such that $h_2(\alpha) > h_1(\alpha) \equiv \alpha$ for $0 \leq \alpha \leq 1$, while $h_2(0) = 0$ and $h_2(1) = 1$. We define $\eta_2 = h_2'\alpha/h_2$ as the elasticity of efficiency, h_2, with respect to α. The assumptions about h_2 imply that $\eta_2 < 1$ and that the gap between h_2 and h_1 (that is the input-augmenting effect) decreases as α increases and that $\eta_1 = 1$.

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[2] The law of material balances 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.

The variable input not utilized by the crop may be a source of environmental pollution. Non-point source pollution cannot be observed directly and is stochastic due to random variations in environmental conditions such as weather. For ease of analysis we focus on regulating the deterministic portion of this pollution (or the expected level of pollution) that is influenced by input use and technology choice (similar to the approach in Shortle et al., 1998). We define the pollution per acre with technology i as: $z_i = \gamma_i(\alpha)x_i$, where γ_i is the pollution coefficient per unit of applied input with technology i. In some cases all of the input wasted becomes a polluting residual and $\gamma_i = [1 - h_i]$. We assume the more general case where, $\gamma_i'(\alpha) < 0, \gamma_i''(\alpha) > 0$ which implies that as land quality increases, the pollution per unit input decreases.[3] Since a conservation technology augments input use efficiency or land quality, it is reasonable to assume that it lowers the pollution coefficient; thus, $\gamma_2(\alpha) < \gamma_1(\alpha)$.

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 α. Microunits take input price w and output price P as given.

3.1. Micro-level decisions in the absence of any government intervention

In the absence of any government intervention, a profit-maximizing microunit takes its land quality and prices as given and chooses the quantity of variable input and technology using a two-stage procedure. The microunit first chooses the optimal amount of the variable input for each technology and then chooses the technology yielding the highest profit. If $\Pi_i(\alpha)$ denotes the quasi-rent per acre (represented by the operational profit only and excluding the rental rate for the land) that can be earned using technology i, then:

$$\Pi_i(\alpha) = \max_{x_i}\{Pf(h_i(\alpha)x_i) - wx_i - k_i\}. \tag{1}$$

The optimal level of variable input is found by solving:

$$Pf'h_i(\alpha) - w = 0, \quad \forall\alpha \quad \text{and} \quad i = 1, 2; \tag{2}$$

for $x_i(\alpha)$ such that the value of its marginal product ($Pf'h_i$) is equated to its per unit price, w. In the second stage, the microunit chooses the technology that leads to the highest quasi-rent per acre, provided that this quasi-rent is non-negative. Adoption of the conservation technology occurs when its quasi-rent is positive and larger than that of the traditional technology, that is if:

$$\begin{aligned}\Pi_1(\alpha) &= Py_1 - wx_1 - k_1 < Py_2 - wx_2 - k_2 \\ &= \Pi_2(\alpha) > 0.\end{aligned} \tag{3}$$

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

$$\Pi_2 - \Pi_1 = \Delta\Pi = P\Delta y - w\Delta x - \Delta k, \tag{4}$$

where Δ represents the difference in the level of a variable (y, x, k and z) between the two technologies. Factors that affect this quasi-rent differential include the impact of adoption on input use (Δx) and on output level, (Δy) as well as the levels of input price, output price and fixed costs of adoption. Eq. (4) shows that the larger the output-increasing ($\Delta y > 0$) and input-saving ($\Delta x < 0$) effects of the conservation technology and the smaller the additional fixed costs of adoption, the more likely are its adoption. Given the assumptions of the model above, Caswell et al. (1990) show that adoption is always output increasing but that it is input-saving only if the elasticity of marginal productivity of effective input use, $\varepsilon_i = -f''h_ix_i/f' > 1$. In this paper, we focus on conservation technologies that are input saving. Both the output-increasing and input-saving effects of adoption decrease as land-quality, α, increases. Hence,

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[3] The amount of the wasted input that is converted into harmful pollution may depend on a number of factors, such as rainfall, temperature and soil quality. For example, in the case of nitrate run-off from fields, some of the applied fertilizer might denitrify and escape into the atmosphere and some may remain attached to soil particles and not cause much environmental damage. Only some of the residual nitrogen may dissolve in irrigation water or rainwater and run-off the field and degrade surface or ground water quality. Similarly, some of the irrigated water that is not absorbed by plants could evaporate before contaminating surface and ground water quality. The extent to which irrigated water runs-off or evaporates instead of being absorbed by plants depends on factors such as the water retention capacity of the soil, temperature and rainfall.

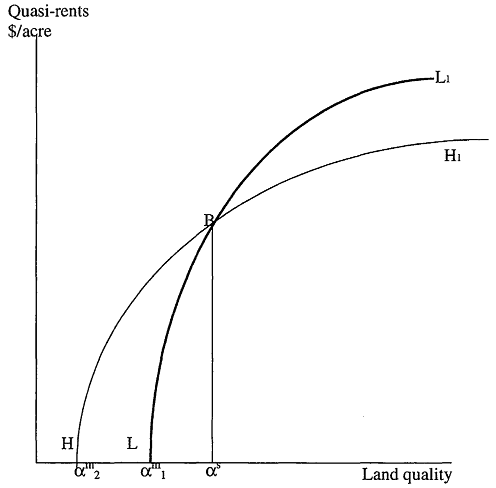

Fig. 1. Quasi-rents under alternative technologies with heterogeneous land quality.

with $k_2 > k_1$ the traditional technology is more profitable than the conservation technology when $\alpha = 1$. As land quality declines, profit declines faster under the traditional technology than under the conservation technology because the input-augmenting effect of the conservation technology becomes larger as α falls. This is shown in Fig. 1, where LL_1 and HH_1 represents the maximized profits with the traditional technology and the conservation technology, respectively, as a function of land quality. There is likely to exist some land quality level $0 < \alpha^{\mathrm{s}} < 1$ at which both technologies yield the same profits per acre. We define α^{s} as the land quality at which:

$$\Pi_1(\alpha^{\mathrm{s}}) = \Pi_2(\alpha^{\mathrm{s}}). \tag{5}$$

On land qualities lower than α^{s} the conservation technology is likely to lead to higher profits than the traditional technology and would therefore be adopted. For land qualities higher than α^{s} profits with the use of traditional technology are higher than with conservation technology. We also define a marginal land quality with each technology, a_i^{m}, at which quasi-rents per acre are zero, that is:

$$\Pi_i(\alpha_i^{\mathrm{m}}) = 0. \tag{6}$$

To determine aggregate input use, output, pollution and quasi-rents in a region we define a continuous land distribution 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 $\alpha_{\mathrm{L}} \leq \alpha \leq 1$ to obtain the total acreage M in the region, such that total acreage is $\int_{\alpha_{\mathrm{L}}}^{1} g(\alpha) M \,\mathrm{d}\alpha = M$. 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 marginal and switching land quality levels (a_i^{m} and α^{s}) and assuming that adoption of the conservation technology occurs on the lower land qualities. The privately optimal values of each of the variables, y_i, x_i, α_2^{m} and α^{s} are functions of w and P. Profit-maximizing choices for each α are summed across $\alpha \geq \alpha_2^{\mathrm{m}}$ to obtain:

$$Y(P, w) = \int_{\alpha_2^{\mathrm{m}}}^{\alpha^{\mathrm{s}}} y_2 g(\alpha) M \,\mathrm{d}\alpha + \int_{\alpha^{\mathrm{s}}}^{1} y_1 g(\alpha) M \,\mathrm{d}\alpha, \tag{7}$$

$$X(P, w) = \int_{\alpha_2^{\mathrm{m}}}^{\alpha^{\mathrm{s}}} x_2 g(\alpha) M \,\mathrm{d}\alpha + \int_{\alpha^{\mathrm{s}}}^{1} x_1 g(\alpha) M \,\mathrm{d}\alpha,$$

$$Z(P, w) = \int_{\alpha_2^{\mathrm{m}}}^{\alpha^{\mathrm{s}}} y_2 x_2 g(\alpha) M \,\mathrm{d}\alpha + \int_{\alpha^{\mathrm{s}}}^{1} y_1 x_1 g(\alpha) M \,\mathrm{d}\alpha,$$

$$\Pi(P, w) = \int_{\alpha_2^{\mathrm{m}}}^{\alpha^{\mathrm{s}}} \Pi_2 g(\alpha) M \,\mathrm{d}\alpha + \int_{\alpha^{\mathrm{s}}}^{1} \Pi_1 g(\alpha) M \,\mathrm{d}\alpha.$$

We define gross social welfare as the sum of consumer surplus, producer surplus and government surplus. However, we also assume that consumer surplus is zero because we are focusing on a small region and assume that commodity prices are fixed and not affected by changes in output in this region. We also assume that consumer surplus is not affected by changes in pollution levels. Producer surplus is defined as net of any emissions taxes and inclusive of any subsidies as shown in the sections below. Government surplus is, therefore, positive and equal to the tax revenues in the case of a pollution tax policy, and negative and equal to subsidy payments with the green payment policies. This measure of social welfare is a gross measure because it does not include the monetized environmental damages caused by pollution, due to the difficulties of measuring non-point pollution and estimating the monetary value of the damages it causes. Instead, we examine the costs of achieving a pre-determined level of abatement using alternative environmental policies as suggested by Baumol and Oates (1971). In the absence of any government intervention, gross social welfare is represented by $\Pi(P, w)$ in (7), which depicts its maximum value (Just et al., 1982). Costs of abatement are then defined as the difference in social welfare with and without an environmental policy.[4]

Environmental policies can influence micro-level decisions by inducing a reduction in input use x_i with either technology, inducing a switch to the conservation technology by raising α^{s} and influencing entry and exit decisions by changing a_2^{m}. We refer to these three policy effects as the intensive margin effect, the adoption effect and the extensive margin effect, respectively. We now compare the impact of a pollution tax, an input reduction subsidy and a technology cost-share subsidy on micro-level decisions.

3.2. Micro-level decisions under a pollution tax policy

Let $\Pi_i^{\mathrm{t}}(\alpha)$ denote the quasi-rent per acre that can be earned using technology i under a pollution tax policy, with:

$$\Pi_i^{\mathrm{t}}(\alpha) = \max_{x_i}[Pf(h_i(\alpha)x_i) - wx_i - k_i - \theta\gamma_i(\alpha)x_i]. \tag{8}$$

The optimal level of input use x_i^{t} is chosen such that the value of its marginal product ($Pf'h_i$) is equated to its per unit post-tax price, $v_i = w + \theta\gamma_i$ where $\theta\gamma_i$ is the tax burden per unit of applied input, that is:

$$Pf'h_i - w - \theta\gamma_i = 0, \quad \forall\alpha \quad \text{and} \quad i = 1, 2. \tag{9}$$

The pollution tax is equivalent to a firm-specific input tax, $\theta\gamma_i(\alpha)$ (as shown by Griffin and Bromley, 1982). As the pollution tax θ increases, the post-tax price of the applied input increases and this tends to reduce input use with a given technology.[5]

Proposition 1. *A pollution tax has a negative intensive margin effect on input-use and it raises the marginal land quality, a_i^{m}, that is needed for profitable operation with either technology. It has switching effect towards the conservation technology if this technology is input-saving.*

The proof is in the Appendix A. The pollution tax raises the price of the input and creates incentives to reduce input-use with either technology, as shown by (A.1) in the Appendix A. Since $\gamma_2 < \gamma_1$, and $\gamma'(\alpha) < 0$, the increase in post-tax input price and the negative intensive margin effect is smaller for microunits using the conservation technology and those having a higher land quality. If the share of tax payments in total revenue is small and if 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 (A.2) in the Appendix A shows that the tax also tends to raise the land quality at which production is no longer profitable and reduces the land acres on which production occurs. The larger the share of tax payments in total revenue, the more inelastic production is to effective input use and the smaller the impact of changes in land quality on effectiveness of input use, the larger is the exit effect of the tax. Condition (A.3) shows that an increase in the tax will induce some microunits to switch from the traditional to the conservation technology if the latter is input-saving, which also implies that the technology is pollution reducing given the assumptions made above. If $\Delta x < 0$ then the pollution-reducing effect of adoption is larger than its input-saving effect since $\gamma_1 > \gamma_2$. If the input-saving effect of adoption is small or the tax rate is low while Ω (see Appendix A) is large, the switching effect will be small and the adoption rate in the unregulated case could be close to that under a pollution tax policy. The effect of adoption on pollution per acre is: $\Delta z = \gamma_2\Delta x - x_1(\gamma_1 - \gamma_2)$ where $\Delta z = z_2 - z_1$ and $\Delta x = x_2 - x_1$. The effect of adoption on pollution per acre depends on its effect on input use and on the magnitude of the difference in pollution-intensities of the two technologies $(\gamma_2 - \gamma_1)$.

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[4] The analysis here excludes the deadweight loss due to the costs of raising government revenue to finance the subsidy. To this extent it underestimates the costs of abatement associated with a green payment policy relative to a pollution tax policy.

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

3.3. Micro-level decision-making with a green payment policy

Green payments could be provided either to induce greater adoption of the conservation technology by sharing the fixed costs of adoption or by subsidizing a reduction in input use or a combination of both approaches. A general model is presented below that considers a combined green payment policy under which a uniform subsidy per unit of input reduction below the privately optimal level x^{o} is provided and a cost-share subsidy is provided to lower the proportion of the fixed cost of adoption of a conservation technology borne by the microunit. This is also used to analyze cases where only one of the two types of green payments, a cost-share subsidy or an input reduction subsidy, is provided. Let $\Pi_i^{\mathrm{g}}(\alpha)$ denote the quasi-rent per acre that can be earned by using technology i under this combined green subsidy policy:

$$\Pi_i^{\mathrm{g}}(\alpha) = \max_{x_i}[Pf(h_i(\alpha)x_i) - wx_i - (1-c_i)k_i + r(x^{\mathrm{o}} - x_i)], \tag{10}$$

where r is the input reduction subsidy, $c_1 = 0$ and $c_2 = c$ is the cost-share subsidy for the conservation technology. Input use, marginal and switching quality are determined such that:

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

$$Py_2(\alpha^{\mathrm{sg}}) - wx_2(\alpha^{\mathrm{sg}}) - (1-c)k_2 + r(x^{\mathrm{o}} - x_2(\alpha^{\mathrm{sg}})) = Py_1(\alpha^{\mathrm{sg}}) - wx_1(\alpha^{\mathrm{sg}}) - k_1 + r(x^{\mathrm{o}} - x_1(\alpha^{\mathrm{sg}})), \tag{12}$$

$$Py_2(\alpha_2^{\mathrm{mg}}) - wx_2(\alpha_2^{\mathrm{mg}}) - (1-c)k_2 + r(x^{\mathrm{o}} - x_2(\alpha_i^{\mathrm{mg}})) = 0, \tag{13}$$

where the superscript g indicates the green payment policy.

A microunit chooses its quasi-rent maximizing levels of input use (with the combined green payment policy), x_i^{g}, by equating the value of marginal product to the input price w and the input reduction subsidy r, which raises the costs of input use and creates incentives to reduce input use with both technologies. If r were equal to zero, a cost-share policy by itself would not change the marginal condition that determines the level of input use. The intensive margin effect of a cost-share subsidy is therefore zero.

Proposition 2. *The intensive margin effect of an input-reduction subsidy is negative. Both an input-reduction subsidy and a cost-share subsidy create incentives for adoption of the conservation technology and for lowering the marginal land quality under production.*

The proof is shown in the Appendix A. Since the input reduction subsidy rate does not vary with technology choice or land quality, unlike a firm-specific input tax (or pollution tax), the negative intensive margin effect of the input reduction subsidy differs from that of a pollution tax (condition (A.4)). Comparing this effect of an input reduction subsidy with that of a pollution tax in (A.1) we see that since r is uniform across microunits while $\theta\gamma_i(\alpha)$ is relatively smaller for microunits with high α and those using the conservation technology, 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 efficiently targeted towards the polluters as a pollution tax.

Condition (A.5) in the Appendix A shows that with $c > 0$ and $r > 0$, both types of subsidies supplement each other in creating incentives for microunits previously using the traditional technology to switch to the conservation technology. The switching effect of the cost-share subsidy is larger than that of the input reduction subsidy if the input-saving effect of adoption is small while ck_2 is large. The impact of the cost-share subsidy and the input reduction subsidy on the marginal land quality is negative, as shown by condition (A.6), indicating that both subsidies create incentives for microunits that do not otherwise find it profitable to operate. The extensive margin effect of an input reduction subsidy by itself is likely to be smaller than that of a technology cost-share subsidy if the subsidy payments under the latter are larger, that is if, ck_2 is greater than $r(x^{\mathrm{o}} - x_2^{\mathrm{g}})$. The larger the share of subsidy payments in total revenue and the smaller the elasticities, the larger is the extensive-margin effect.

3.4. Policy comparisons

Comparing the technology switching effect of the pollution tax and a combined green payment policy in (A.3) and (A.5), we see that while the former depends on the magnitude of the pollution reducing effect of adoption, the latter depends on the input-saving effect of adoption and the savings in fixed costs due to a cost-share subsidy. If $c = 0$ and the conservation technology has a small pollution-reducing effect and a relatively larger input-saving effect, the tax will lead to a smaller percentage change in the switching land quality as compared to an input reduction subsidy. If $c > 0$ and the fixed costs of adoption are high then the technology adoption effect due to a green payment policy is even higher than that under a tax.

While the tax induces microunits to exit the industry, an input reduction subsidy and/or the cost-share subsidy induce entry. This tends to increase the pollution generated (relative to a restricted input reduction subsidy and/or the cost-share subsidy) and necessitates larger subsidy rates than the restricted versions of these policies to achieve the targeted level of abatement. Since a cost-share subsidy has no intensive margin effect and achieves pollution control only through technology switching it 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. However, this could be a very costly strategy for abatement if the conservation technology has high capital costs and input use is responsive to a tax, making input use reduction a preferable method of pollution control.

Instead of providing the subsidy to all farmers, it 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. The relative abatement costs of a green payment policy depend on the magnitude of its intensive, extensive and switching effects relative to a pollution tax. If the intensive and extensive margin effects of a pollution tax are small because tax payments are a small share of total revenue, the inefficiency of a restricted cost-share policy may not be too large. If the extent of heterogeneity among microunits is small, then a uniform input reduction subsidy could achieve intensive and switching effects that are very close to those of a pollution tax.

Although green payment policies are likely to be second best to a pollution tax, an important question is the extent to which alternative green payment policies differ in the costs of abatement they impose and the extent to which these costs are greater than those under a pollution tax. A comparison of the cost savings that could be realized by implementing more efficient policies with the administrative costs of implementing them can enable policy makers to choose among these various policies. This paper focuses on comparing the costs of abatement of alternative policies only. This is done next using a simulation model with production and pollution functions calibrated to irrigated cotton production under heterogeneous soil conditions in the San Joaquin Valley in California. Non-linear programming is used to solve both for the levels of the policy variables θ, r, and c that maximize gross social welfare while constraining aggregate pollution to a given level, and for the optimal input use and adoption decisions at the micro-level.

4. Numerical simulation

This simulation analyses the implications of alternative policies for reducing polluted drainage from cotton production on about 400,000 irrigated acres in the western portion of the San Joaquin Valley in California. 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. (1990). Its parameters are based on typical values of water-use and yields with furrow irrigation (Hanemann et al., 1987) which suggest that a maximum yield of 1300 pounds/acre can be obtained with an effective annual water application of 2.5 acre feet and that a yield of 1040 pounds/acre would result if 1.75 acre-feet of effective water is used. These parameters lead to the following function: $y_i = f(h_i x_i) = \max[-1589 + 2311 h_i x_i - 462(h_i x_i)^2, 0]$. This function implies that a minimum amount of effective water per acre ($h_i x_i \geq 0.823$) is required to obtain positive yields.

We use efficiency with furrow technology as a measure of land quality ($h_1(\alpha) = \alpha$). In the study area, land quality ranges from 0.2 (steep sandy soils) to 0.8 (level fields with heavy soils) (State Water Control

Board Report, 1987) 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 parameters (3, 3), which imply a mean efficiency of 0.5 and variance 0.013. Hanemann et al. (1987) 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 $\gamma_i = (1-h_i)^{k_i}$. As water-use efficiency increases, the pollution coefficient decreases. This function is calibrated using the information that the drainage coefficient with furrow, γ_1, is 0.175 when $h_1 = \alpha = 0.6$, and the drainage coefficient with drip, γ_2, is 0.04 when $h_2 = 0.95$ (Hanemann et al., 1987). We obtain $\kappa_1 = 1.902$ and $\kappa_2 = 1.074$. The fixed cost of adoption of furrow irrigation is US$ 500 per acre, while the fixed cost of adoption of drip is US$ 633 per acre. The water price is assumed to be US$ 55 per acre-foot and the price of cotton is assumed to be US$ 0.6 per pound.

4.1. *Implications of alternative policies*

With these prices, in the absence of any regulation, we find that land with quality <0.412, which is 24% of the land area, will be idle. Adoption of drip occurs on land with low quality, $0.412 \leq \alpha \leq 0.475$, while furrow irrigation occurs on land with high quality. Total quasi-rents in the region are US$ 11.2 million, total water use is 1.13 million acre-feet and cotton production is 390 million pounds. The level of drainage generated in the absence of any regulation is 204.76 thousand acre-feet. Table 1 shows the implications of alternative policies for the input use, adoption and land under production associated with achieving a 40% reduction in drainage relative to the unregulated level.

A pollution tax of US$ 22.8 per acre-foot of drainage is required to achieve the 40% abatement target. It leads to an increase in idle land from 24 to 54% and an increase in the marginal land quality level from 0.412 to 0.513. There is a switch from furrow to drip on 15% of the land area and the switching land quality increases from 0.475 to 0.52. The combination of the exit and adoption effects together with the higher post tax price of the input results in a 38% reduction in water-use from 1.13 million acre feet to 0.7 million acre feet.

In contrast, an unrestricted cost-share policy has a large entry effect and no intensive margin effect. It induces all available land to enter production and this necessitates a cost-share rate of 6.1% to induce sufficient adoption of the conservation technology to achieve the desired abatement target. The corresponding rate under the restricted cost-share subsidy policy is 4.7%. The large extensive margin effect and lack of any intensive margin effect under the cost-share policy results in water use that is 0.06 million acre-feet higher than in the base case and 0.49 million acre-feet higher than under a pollution tax policy. The unrestricted cost-share subsidy 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. Hence, while creating incentives to adopt a conservation technology and reducing pollution, an unrestricted cost-share subsidy can increase water use and land use.

An unrestricted input reduction subsidy, on the other hand, has very similar effects to a restricted input reduction subsidy policy because it does not have a large extensive-margin effect. The marginal land quality falls from 0.412 to 0.405 only. As a result there is not much difference in the subsidy rate required under the restricted and the unrestricted version of the input reduction subsidy. In the former case the subsidy rate is US$ 16.25 per acre-foot of reduction in water use while in the latter case it is US$ 16.6 per acre-foot of reduction. Input reduction subsidies also do not appear to have a large intensive-margin effect and achieve abatement primarily through the technology-switching effect. As a result, not only are the switching land quality levels under the restricted and the unrestricted input reduction subsidies very close to each other (0.536 and 0.54, respectively), they are also very close to that under the restricted cost-share subsidy (0.537). The restricted input reduction subsidy achieves only a slightly greater level of reduction in water use to 0.96 million acre feet as compared to the level of 0.98 million acre-feet under the unrestricted input reduction subsidy and the restricted cost-share subsidy.

Table 1
The technology switching, intensive and extensive-margin effects of alternative policies with 40% abatement

	Base case	Pollution tax US$ per acre-foot of drainage	Restricted cost-share and input reduction subsidy % of fixed costs US$ per acre-foot of water	Unrestricted cost-share and input reduction subsidy % of fixed costs US$ per acre-foot of water	Restricted cost-share policy % of fixed costs	Restricted input reduction subsidy US$ per acre-foot of water	Unrestricted input reduction subsidy US$ per acre-foot of water	Unrestricted cost-share policy % of fixed costs
Tax/subsidy rate	–	22.8	0.5% and US$ 14.6 per acre-foot	0.1% and US$ 17.5 per acre-foot	4.7%	US$ 16.25 per acre-foot	US$ 16.6 per acre-foot	6.1%
Idle land area (%)	24	54	24	17.9	24	24	22	0
Switch in land area away from furrow (%)	–	15	18.9	20.4	20	19	19	27
Marginal land quality	0.412	0.513	0.412	0.387	0.412	0.412	0.405	0.20
Switching land quality	0.475	0.52	0.534	0.539	0.537	0.536	0.540	0.56
Water use (million acre-feet)	1.13	0.70	0.97	1.02	0.98	0.96	0.98	1.19
Drainage (thousand acre-feet)	204.76	122.86	122.86	122.86	122.86	122.86	122.86	122.86

A combined policy with restricted cost-share and input reduction subsidy achieves the targeted reduction with only a 0.5% cost-share and a subsidy of US$ 14.6 per acre-foot of water reduction. By combining an intensive margin effect and technology adoption effect without any entry effect, this policy achieves abatement by having a switching land quality level of 0.534 which is the closest to that under the pollution tax. The extent of additional adoption needed under the restricted combined policy is 18.9% as compared to 15% under a pollution tax. This rate is lower than under the other subsidy policies analyzed here. This combined policy is the closest in replicating the incentives provided by a pollution tax policy. The cost-share subsidy targeted towards the adopters offsets a part of the uniformity of incentives provided by an input reduction subsidy rate that does not vary with technology choice or land quality.

4.2. Implications of alternative policies for costs of abatement and production levels

A pollution tax policy achieves the 40% abatement target at the lowest cost of abatement of US$ 0.86 million (Table 2). This represents 7.7% of the base level of gross social welfare. The combined restricted green payment policy that offers a cost-share and an input reduction subsidy achieves the targeted abatement with a cost of abatement of US$ 1 million. This represents 8.9% of the base level of social welfare. Hence, the difference between the least-cost policy and a restricted combined green payment policy is only 1.2% of the base level of social welfare. The unrestricted version of this combined policy costs 10% of the base level of social welfare. Among the other subsidy policies, a restricted cost-share policy has the lowest costs of abatement (10.7% of base level of social welfare) but is closely followed by the restricted and unrestricted input reduction subsidies (11.2 and 11.6% of the base level of social welfare). These policies are a maximum of 4% of the base level of social welfare (or US$ 0.44 million) more expensive than a pollution tax. Overall, these results indicate that green payment policies, although second best to pollution tax, do not lead to large losses relative to a pollution tax policy. These results are consistent with those obtained by Helfand and House (1995) on the relative costs of abatement with second-best input taxes which show that even the most inefficient input taxes/standards result in only a 2% welfare loss relative to the base level. This is possibly because these instruments lead to only small deviations from optimality that, as shown by the envelope theorem, result in only second-order effects (Akerlof and Yellen, 1985).

In contrast to this we find that the unrestricted cost-share subsidy policy leads to abatement costs that account for 21% of the base social welfare and that this policy is significantly more expensive (13.3% of base surplus) than a pollution tax policy. This is due to the large entry effect induced by the cost-share subsidy, with all 24% of available idle land now finding it profitable to enter production. Additionally, as the level of abatement increases, the difference between the costs of abatement of green payment policies and a pollution tax increases substantially, particularly for the unrestricted cost-share policy (Fig. 2). As compared to a pollution tax policy, at the 60% abatement level, costs of abatement as a percentage of base social welfare are 6% higher under a restricted combined policy and 50% higher under an unrestricted cost-share policy.

These policies differ considerably in their impact on aggregate output depending on whether they induce entry or exit of land or restrict the subsidy to land currently under production (Table 2 and Fig. 3). The pollution tax leads to a 39.1% reduction in production relative to the base level while achieving 40% abatement. The three restricted subsidy policies have no entry effects and therefore have negligible impacts on aggregate output. Although they induce technology adoption, which is yield-increasing because it increases the effective use of water, this effect is not very large and in the case of the restricted cost-share subsidy it results in an increase of only 1 million pounds of cotton, which is negligible compared to the base level. The unrestricted subsidy policies, particularly the cost-share subsidy (and at high levels of abatement even the unrestricted input reduction subsidy), lead to substantially higher levels of aggregate production. In the case of the unrestricted cost-share policy, even the subsidy needed for 10% abatement is sufficient to induce all available land into production and increase production by 32%. This increased level remains almost constant as the abatement target increases since further abatement is achieved through the technology adoption effect which does not affect aggregate output much.

Table 2
Implications of alternative policies for costs of 40% abatement and production levels

	Base case	Pollution tax	Restricted cost-share and input reduction subsidy	Unrestricted cost-share and input reduction subsidy	Restricted cost-share policy	Restricted input reduction subsidy	Unrestricted input reduction subsidy	Unrestricted cost-share policy
Output (million lbs.)	390.80	237.88	390.11	423.33	391.78	389.90	401.02	517.04
Tax revenue/subsidy payments (million US$)	–	2.78	2.64	2.91	4.40	2.72	2.83	10.43
Farm income (million US$) (including subsidy/net of tax)	11.19	7.55	12.84	12.98	14.4	12.66	12.72	19.27
Gross social welfare (million US$)	11.19	10.33	10.19	10.07	9.99	9.94	9.89	8.84
Cost of abatement (million US$)	–	0.86	1.00	1.12	1.2	1.25	1.3	2.35

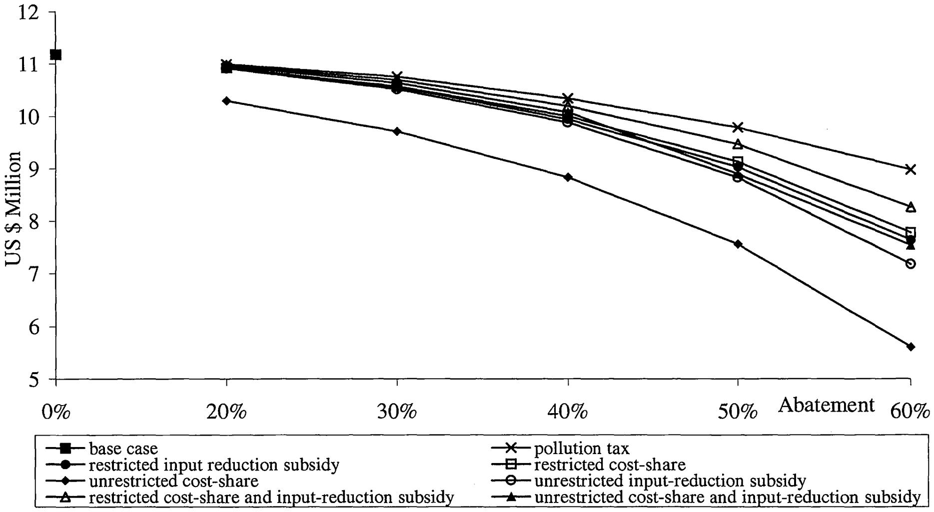

Fig. 2. Gross social welfare with alternative policies.

Among the policies considered here, farm income (inclusive of the subsidy but net of taxes) is highest under the unrestricted cost-share subsidy and lowest under the pollution tax policy. A pollution tax reduces farm income by 33% relative to the base case while the unrestricted cost-share subsidy 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. The two combined policies and the two input reduction subsidy policies lead to farm income levels that are very close to each other and not much higher than the base level. This indicates that programs that have small entry effects and achieve abatement primarily by subsidizing a reduction in input use have much smaller effects on aggregate farm income levels. The large entry effects under the unrestricted cost-share subsidy impose costs on the government (in the form of subsidy payments) that are almost four times higher than those under the two combined policies or the two input reduction subsidies at the 40% abatement level.

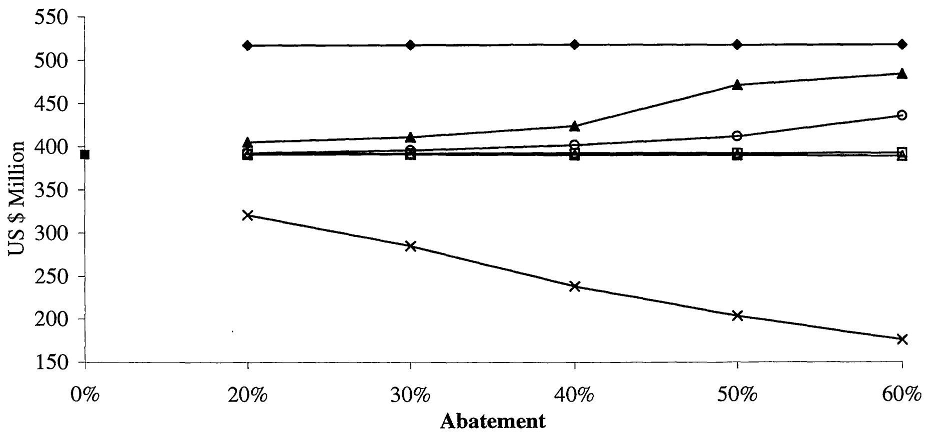

Fig. 3. Effect of alternative policies on aggregate output. The legend for Fig. 3 is the same as for Fig. 2.

5. 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 decisions of heterogeneous microunits, namely technology choice and input use. 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. Subsidy policies also differ from a tax in that they have positive extensive-margin effects unless specifically restricted to prevent entry of marginal land. The conceptual analysis shows how the parameters of the production and pollution functions together with the different intensive-margin, extensive-margin and switching-effects of alternative policies cause these policies to vary in the trade-offs they offer.

The numerical analysis shows that the restricted combined green payment policy, although second best to a pollution tax, does not impose significantly higher costs of abatement than a pollution tax policy. The restricted cost-share and the restricted input reduction subsidy are also similar in their costs of abatement and these costs are close to those with a pollution tax even at fairly high levels of abatement. However, an unrestricted cost-share subsidy leads to substantially higher costs of abatement as compared to the other policies considered here. Alternative green payment policies differ in the trade-offs they offer between social efficiency and farm income support. While the unrestricted cost-share policy leads to the lowest level of gross social welfare it leads to the highest level of farm income. On the other hand, input reduction subsidies and the combined policy lead to small efficiency losses but also small increases in farm income compared to the unrestricted cost-share subsidy. The budgetary implications of alternative policies also vary, with the cost of an unrestricted cost-share policy being almost four times as large as that of an input reduction subsidy.

If the primary purpose of agro-environmental policy is cost-effective environmental protection through voluntary participation and at low budgetary cost, then restricted combined subsidies or input-reduction subsidies are preferable to an unrestricted cost-share. In the event that a restricted green payment policy is politically difficult to implement, then an unrestricted input reduction subsidy is preferable to a cost-share subsidy alone, since it has relatively lower costs of abatement and requires smaller subsidy payments from the government. It also leads to water conservation and is less land expanding. However, if the purpose is farm income support then an unrestricted cost-share policy is likely to be preferred to provide both environmental benefits and increased farm income though at considerable costs to society and taxpayers.

These comparisons of the relative cost-effectiveness of alternative green payment policies do not take into account the costs of implementing these policies. While these costs are likely to be lower than those of implementing a pollution tax policy, they could be substantial if there is asymmetric information about the production choices made by farmers (Khanna et al., 1999). The costs of information gathering and implementation are likely to differ across policies depending on the information required about the choices made by polluters and the ease of collecting that information. Difficulties in obtaining information on input-use by farmers could make policies that offer greater flexibility to polluters in the methods of pollution control and lower social costs of abatement, such as a restricted combined input-reduction and cost-share subsidy or even input-reduction subsidies by themselves, costly to implement. Thus, policy choice needs to be based on a comparison of the gains in efficiency of pollution control through improved information acquisition with the costs of gathering information. Key findings of this paper are that the differences in the costs of abatement of alternative green payment policies (with the exception of an unrestricted cost-share subsidy) relative to each other and relative to a pollution tax are not substantial. Thus, it may not be socially optimal to choose the more information-intensive policies if costs of implementation are significant. As the technology for gathering information improves and the costs of gathering information fall, policy makers will be able to design more efficient incentive-based policies. Remote-sensing technologies and geographic information systems, which provide information about land quality from which the privately optimal technology and input-use levels can be inferred using models such as the one presented above, are increasingly available (National Research Council, 1997). Additionally, there is growing reliance on crop consultants, certified input applicators and professional dealers for input applications on farms. This will facilitate improved maintenance of records of technology and input choices made by farmers enabling implementation and targeting of green payments.

The analysis here also shows that alternative types of green payment policies vary considerably in their implications for aggregate output. Unrestricted cost-share subsidy policies to induce adoption of input-saving and pollution-reducing but output-increasing technologies, such as those considered here, can have substantial effects on aggregate output that can influence the pattern of trade between countries. Thus unrestricted cost-share subsidies may not only be socially costly, but also ineligible for green box exemption under the Uruguay Round Agreement.

The analysis in this paper is limited, but could be easily extended to analyze the effects of technology adoption and alternative policies on output price. We have assumed a perfectly elastic demand curve. If demand is relatively inelastic, then a pollution tax can be expected to increase output price, while green payment policies will reduce output price. These market price changes will create secondary influences on the intensive-margin, extensive-margin and technology-switching effects of an environmental policy. The framework developed here can also be extended to analyze the effects of green payment policies to induce adoption of other conservation technologies with appropriate modifications to the specifications of the relationship between effective and applied input use and of the production and pollution functions under alternative technologies. This analysis shows the value of data on the distribution of land quality and other heterogeneous physical variables in a region 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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Appendix A

Total differentiation of (9) is used to obtain the percentage change in input use with each technology due to the pollution tax, evaluated at x_i, the privately optimal level of input use:

$$\frac{\partial x_i^{\mathrm{t}}\theta}{\partial\theta x_i} = -\frac{\theta\gamma_i x_i}{Py_i\phi_i\varepsilon_i} < 0, \tag{A.1}$$

where $\phi_i = f'h_i x_i/f > 0$ and denotes the elasticity of output with respect to effective input use $h_i x_i$.

The marginal land quality α_2^{mt} under the tax is determined such that $Pf(h_2(\alpha_2^{\mathrm{mt}})x_2^{\mathrm{t}}) - wx_2^{\mathrm{t}} - k_2 - \theta\gamma_2(\alpha_2^{\mathrm{mt}})x_2^{\mathrm{t}} = 0$. Totally differentiating this with respect to θ we obtain: $[Pf'h_2'x_2 - \theta\gamma_2'x_2]\mathrm{d}\alpha_2^{\mathrm{m}} = \gamma_2 x_2\,\mathrm{d}\theta$, where primes denote partial derivatives. We evaluate it at the privately optimal level α_2^{m} (with $\theta = 0$) and use the definitions of ϕ_2 and η_2 to obtain the following expression for the percentage change in α_2^{m} due to the tax:

$$\frac{\partial\alpha_2^{\mathrm{m}}\theta}{\partial\theta\alpha_2^{\mathrm{m}}} = \frac{\theta z_2}{Py_2\phi_2\eta_2} > 0. \tag{A.2}$$

The switching land quality level under the pollution tax, α^{st} is determined such that $\Pi_1(\alpha^{\mathrm{st}},\theta) = \Pi_2(\alpha^{\mathrm{st}},\theta)$. To examine the impact of the tax on α^{st} we totally differentiate this condition with respect to θ and evaluate it at $\theta = 0$ to obtain:

$$\frac{\partial\alpha^{\mathrm{s}}\theta}{\partial\theta\alpha^{\mathrm{s}}} = \frac{(z_2(\alpha^{\mathrm{s}}) - z_1(\alpha^{\mathrm{s}}))\theta}{\Omega(\alpha^{\mathrm{s}})} > 0, \quad \text{if} \quad z_2(\alpha^{\mathrm{s}}) < z_1(\alpha^{\mathrm{s}}), \tag{A.3}$$

where $\Omega = 1/\alpha[w\eta_2(x_2 - x_1) + (\eta_2 - 1)wx_1]$. The first term on the right hand side is negative if the technology is input saving. The second term is always non-positive since $\eta_2 \leq 1$. Hence, Ω is negative for an input-saving conservation technology.

Total differentiation of (11) shows that the percentage change in input use due to the provision of r is:

$$\frac{\partial x_i^{\mathrm{g}}r}{\partial r x_i} = -\frac{r x_i}{Py_i\phi_i\varepsilon_i} < 0. \tag{A.4}$$

To analyze the effect of the combined green payment policy on the switching land quality level, we differentiate the switching land quality level in (12) with respect to c and r as follows and evaluate the differentials at the privately profit-maximizing level of α^{s} with $\mathrm{d}c = c$ and $\mathrm{d}r = r$:

$$\frac{1}{\alpha^{\mathrm{s}}}\left[\mathrm{d}\alpha^{\mathrm{sg}} = \frac{\partial\alpha^{\mathrm{sg}}}{\partial c}\,\mathrm{d}c + \frac{\partial\alpha^{\mathrm{sg}}}{\partial r}\,\mathrm{d}r\right] = -\frac{1}{\Omega(\alpha^{\mathrm{s}})}[ck_2 + (x_1^{\mathrm{g}} - x_2^{\mathrm{g}})r] > 0. \qquad (\mathrm{A.5})$$

We obtain the percentage change in the switching land quality level relative to the unregulated level as the sum of the percentage change due to the cost-share subsidy and the percentage change due to the input reduction subsidy. The term outside the bracket on the right hand side is negative for an input-saving technology. The term inside the bracket is positive for an input-saving technology. To analyze the effect of the combined green payment policy on the extensive margin, we totally differentiate the marginal land quality (with $i = 2$) in Eq. (13) with respect to c and with respect to r. We then evaluate the expression at the privately optimal marginal efficiency level, α_2^{m}, with $\mathrm{d}c = c$ and $\mathrm{d}r = r$, to obtain the percentage change in the marginal land quality:

$$\frac{1}{\alpha_2^{\mathrm{m}}}\left[\mathrm{d}\alpha_2^{\mathrm{mg}} = \frac{\partial\alpha_2^{\mathrm{mg}}}{\partial c}\mathrm{d}c + \frac{\partial\alpha_2^{\mathrm{mg}}}{\partial r}\mathrm{d}r\right] = -\frac{1}{Py_2\phi_2\eta_2}[ck_2 + (x^{\mathrm{o}} - x_2^{\mathrm{g}})r] < 0. \qquad (\mathrm{A.6})$$

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