2003

Suggested Subsidies are Sub-optimal Unless Combined with an Output Tax

Don Fullerton, *University of Texas at Austin*
Robert D. Mohr, *University of New Hampshire*

Contributions to Economic Analysis & Policy

Volume 2, *Issue* 1 | 2003 | *Article* 1

Suggested Subsidies are Sub-optimal Unless Combined with an Output Tax

Don Fullerton* Robert D. Mohr†

*University of Texas at Austin, dfullert@eco.utexas.edu
†University of New Hampshire, robert.mohr@unh.edu

Suggested Subsidies are Sub-optimal Unless Combined with an Output Tax

Don Fullerton and Robert D. Mohr

Abstract

Because of difficulties measuring pollution, many prior papers suggest a subsidy to some observable method of reducing pollution. We take three such papers as examples, and we extend each of them to show how welfare under the suggested subsidy can be increased by the addition of an output tax. While the suggested subsidy reduces damage per unit of output, it also decreases the firm's cost of production and the equilibrium break-even price. It might therefore increase output – unless combined with an output tax. While this general point has appeared in prior literature, it has been overlooked in specific applications. We illustrate the applicability of a tax-subsidy combination in three very different models of different environmental problems. Using one example, we show that a properly-constructed subsidy-tax combination is equivalent to a Pigovian tax. Another example is a computational model, extended here to show that the policy combination can yield a welfare gain that is more than three times the gain from using the subsidy alone. The third example is a theoretical model, used to show that the subsidy alone increases production and thus could increase total pollution. An additional output tax offsets this increase in production.

KEYWORDS: pollution abatement subsidy, emissions tax, two part instrument

Many existing papers point out that a direct tax on a socially-damaging activity (Pigou, 1920) may be costly or impossible to monitor and enforce. Many proceed to suggest and analyze a policy that would instead subsidize an alternative to the damaging activity. Three examples provide very different models of different environmental problems. First, Deacon (1995) develops a general equilibrium model of deforestation and points out that "the use of Pigovian taxes or marketable permits can be expected to encounter the same monitoring and enforcement problems that keep the market from providing forest services efficiently" (p.17). He analyzes a subsidy to non-forest inputs. Second, Sullivan (1987) develops a partial equilibrium model of toxic waste disposal and points out that "attempts to impose marginal-cost pricing on illegal disposers would generate substantial monitoring costs" (p.58). He analyzes a subsidy for legal disposal, which decreases illegal disposal but "also causes the underpricing of toxic disposal, generating efficiency cost in the form of an excessive volume of toxic waste" (p.59). Third, Stranlund (1997) develops an enforcement model of air pollution and notes that "when monitoring is difficult because the sources of pollution are widely dispersed or because emissions are not measured easily as in non-point pollution problems, regulators should be motivated to consider substituting technological aid for direct enforcement" (p.229). In other words, a subsidy for control technology can substitute for other policy tools in overall efforts to reduce pollution.

All of these papers provide correct, useful analyses of these subsidies. Deacon demonstrates effects of the subsidy on deforestation; Sullivan computes the potential benefit from a subsidy to proper waste disposal; and Stranlund shows that a subsidy might serve as a substitute for costly monitoring. Each paper achieves its objective. Here, we simply extend each of those models to show how welfare under each of those suggested subsidies can be further increased by the addition of an output tax.

This general point has appeared in prior literature. Both Eskeland and Devarajan (1996) and Palmer and Walls (1997) discuss combinations of instruments to deal with environmental externalities. Fullerton (1997) shows that the effects of a tax on a dirty input can be matched by the combination of a subsidy to clean inputs and a tax on output (a combination he calls a "two-part instrument"). Fullerton and Wolverton (1999) and Walls and Palmer (2001) provide closed-form solutions for the first-best two-part instrument. The general presumption in these papers is that a tax can readily be imposed upon any market transaction such as the sale of a final good or service, because the invoice can be verified by the other party to the transaction. Similarly, eligibility for a subsidy can be verified for clean market inputs such as labor, capital, legal disposal, or the purchase of forest-conserving technologies or abatement technologies. Problems can arise with Pigovian taxes because the producer makes no market transaction for deforestation, dumping, or emissions.[1] Trees can be cut without

[1] We do not mean to imply that Pigovian taxes are *always* difficult to implement. The carbon content of fossil fuels can be calculated before combustion, while sulfur dioxide of large utilities can be measured by continuous emissions monitoring equipment. Thus, the Pigovian tax may be preferable for large utilities, while the two-part instrument might be better for small emitters or other pollutants. The choice may change along with monitoring technology, such as electronic pricing for traffic congestion.

any record that they ever existed. Illegal waste can be dumped at midnight. Emissions are self-reported. Without expensive audits, they are often easy to hide.

The intuition behind the two-part instrument can be simply stated. In each case, the unavailable Pigovian tax would raise the relative price of the damaging input and induce firms to substitute into the other input, reducing damage per unit of output (the "substitution effect"). It would also raise the price of output and thus reduce the equilibrium number of units (the "output effect"). The suggested subsidy in each case would make a similar change to relative input prices and can thus reduce damage per unit of output, but it *decreases* the firm's cost of production and therefore decreases the equilibrium break-even price. Thus the subsidy alone might *increase* output and could *increase* total pollution (see, e. g. Baumol and Oates, 1988, Chapter 14). The two-part instrument uses the same subsidy to achieve the desired substitution effect, and it uses the output tax to fix the output effect.

While this intuition is straightforward, actual policies and academic analyses often focus on a subsidy alone.[2] Others focus on the substitution effect alone. For example, the corporate average fuel economy (CAFE) standards in the US reduce fuel use per mile with no direct effect on the number of miles.[3] Our point is that these policies as well as prior papers unnecessarily limit the menu of policy options. Here, we demonstrate the usefulness of the two-part instrument by applying it to three specific contexts. Because these examples are so diverse, we hope to demonstrate how the concept could be applied in many other contexts as well. We demonstrate the two-part instrument within each of the three pre-existing models, using the same equations and notation as in each prior paper. In each case we analyze the same suggested subsidy, and we add a tax on output. In two cases, this step requires that we extend the prior model to consider the output market. In each of these three diverse examples, we show how this policy combination raises welfare by more than the subsidy alone.[4]

We also show that the effect on welfare may be quite large. Using Sullivan's computational model, we show that the addition of the output tax provides a gain that is three times the gain from the subsidy alone. This magnitude cannot be assumed to generalize to other circumstances, but it illustrates the potential gain. In a different

[2] For example, the US Department of Agriculture (USDA) sponsors a Cooperative Forestry Program that provides "technical and financial assistance to help rural and urban citizens, including private landowners, care for forests" (USDA, 2000). Municipal trash and recycling collection programs subsidize the proper disposal of waste. The Environmental Protection Agency (EPA) subsidizes new abatement technologies: to reduce air pollution, the EPA's 33/50 Program provides information and offers technological assistance to firms (US EPA, 1992), and the Green Lights Program subsidizes energy efficient lighting (US EPA, 1993). The Department of Energy (DOE) promotes the use of alternative energy sources and conducts basic research on how to abate and reduce pollution (US DOE, 1999).

[3] Indeed, CAFE standards reduce gas costs per mile and thus may *increase* miles driven. This "rebound effect" is analogous to the output effect mentioned above. We thank a referee for this point.

[4] Note, however, that we focus on this one point using prior models that were designed to cover a rich set of policy problems. Deacon's subsidy is to labor, while Sullivan and Stranlund's subsidies are meant to aid environmental enforcement. Furthermore, rather than a simple monetary payment as in the other cases, Stranlund envisioned his "subsidy" to encompass an array of options that regulators have used to promote the adoption of more advanced emissions control technologies.

example, Fullerton and West (2000) calculate the effect on vehicle pollution from a subsidy to clean-car purchases, and they find that the addition of a gas tax provides a welfare gain that is 3.5 times as large. Perhaps these relative gains are large because the subsidy in each case provides a gain that is small, but the point remains that any subsidy policy might be dramatically improved by the addition of an output tax.

The remainder of this paper consists of four sections: one for each of the prior models and one to conclude. We start with Deacon's (1995) model of deforestation because we can use it to provide a simple introduction of the theory. We then discuss important caveats – the extent to which simplifications in the model may also limit the applicability of the two-part instrument. The following section uses Sullivan's (1987) computational model of toxic waste, and the third section uses Stranlund's (1997) model of technological adoption.

1. A Model of Deforestation

Deacon (1995) develops a general equilibrium model of deforestation and derives a Pigovian tax. Government has access to lump-sum revenue, so any tax in this model is used only to affect relative prices. Thus, the Pigovian tax is first best, and his second-best analysis concerns imperfect instruments such as a subsidy alone, not the complications of other distorting taxes. We maintain this assumption throughout this paper. Deacon then considers the possibility that the Pigovian tax is unenforceable, and he studies the effects of several alternative instruments (one at a time). Here, we briefly outline the key features of Deacon's model, and we then show that the two-part instrument can replicate the effects of the first-best Pigovian tax.

Deacon's model depicts a small open economy populated by identical individuals. The representative agent gets utility from three sources:

$$W = W(x^c, y^c, Q) \tag{1.1}$$

where x^c denotes the consumption of a forest-using good, y^c denotes the consumption of a numeraire that does not require any forest inputs to produce, and Q is the service flow from undestroyed forest.

The amount of land is normalized to one unit per individual. Land can be left as forest or it can be used in production of X. The proportion used in production is denoted by P, so:

$$Q + P = 1 \tag{1.2}$$

The production functions for X, Y, and P are:

$$X = X(L^X, P) \tag{1.3}$$
$$Y = \alpha L^Y \tag{1.4}$$
$$P = (\alpha/\beta)L^P \tag{1.5}$$

where X is produced using labor (L^X) and cleared land (P), Y is produced using only labor (L^Y) times a constant (α), and the clearing of land (P) uses labor (L^P) times another constant (α/β).[5] Each agent's endowment of labor is normalized to one:

(1.6) $$1 = L^P + L^X + L^Y$$

The economy trades internationally, and the value of exports must equal that of imports:

(1.7) $$\nu x^e = y^m$$

where x^e denotes exports of good X, y^m denotes the imports of good Y, and ν is the relative world price of X. All production must be consumed or traded, so:

(1.8) $$y^m \equiv y^c - Y$$
(1.9) $$x^e \equiv X - x^c$$

To represent the social planner's problem, Deacon inserts the information contained in the preceding eight equations (1.2) – (1.9) into the utility function (1.1) and maximizes. Rearranging the optimal first-order conditions yields:

(1.10a) $$\frac{X_L}{X_P} = \frac{\alpha}{(W_Q/W_y) + \beta}$$

(1.10b) $$\frac{W_x}{W_y} = \nu$$

(1.10c) $$\nu X_P = \frac{W_Q}{W_y} + \beta$$

where subscripts denote partial derivatives (e.g. $X_L = \partial X/\partial L^X$ and $W_x = \partial W/\partial x^c$). Equation (1.10a) shows that inputs into X are selected so that the ratio of marginal products equals the ratio of their marginal social costs, where the latter includes the marginal value of forgone forest services (W_Q/W_y). Equation (1.10b) shows that consumers match the ratio of marginal utilities to the ratio of prices $(\nu/1)$. Finally, (1.10c) shows that deforestation optimally stops at the point where the value of the marginal product of deforestation equals the marginal social cost. Combined, these three conditions fully describe the efficient equilibrium.

To see how this social planner's solution compares to a market equilibrium, Deacon lets each agent regard the flow of forest services (Q) as fixed. Furthermore, he allows government three policy instruments. In his model, τ is a tax on exports (x^e),

[5] This formulation implies that α and β are the effective prices of the two inputs in the production of X (labor and cleared land, respectively).

λ is a tax on labor (L^X), and π is a Pigovian tax on deforestation (P). He shows that the Pigovian tax achieves all the optimal conditions (1.10a – 1.10c), but neither τ nor λ can do the job. The export tax τ may reduce the production of X, but it provides no incentive to substitute away from P. A labor subsidy ($\lambda < 0$) can induce substitution away from P, but might encourage production.

Thus, Deacon accomplishes his goal of showing economic effects of each instrument. He does not try to find second-best rates (which do not have closed-form solutions anyway), but he does show that an increase in λ (from $\lambda = 0$) might raise or lower welfare. Thus, we infer that the second-best employment tax λ might be positive (to discourage producing the forest-using good X) or negative (to encourage substitution in production towards L^X and away from P). In this extension, we change the model in only one respect: instead of saying that τ applies only to exports, we let the tax apply to all production of X. With this single change, we provide closed-form solutions for λ and τ that have unambiguous signs, a combination that induces agents to act as if they faced a Pigovian tax – even when π is unavailable.

The first-order conditions for the market equilibrium are derived from the separate maximization problems of the consumer and the producer.[6] We place all three possible tax rates into the producer's problem. Thus, every unit of X generates revenue of $(\nu - \tau)$ for the producer, while every unit of x^c costs the consumer ν. The individual consumer (who regards Q as fixed) chooses consumption goods to maximize $W(x^c, y^c, Q)$ subject to the budget constraint. Therefore:

$$\frac{W_x}{W_y} = \nu \tag{1.11}$$

This market condition matches the second social planner's condition (1.10b).

To maximize profits under a fixed set of world prices, producers allocate labor among its three possible uses. These producers also ignore the damage imposed by deforestation, but they do account for the cost of taxes (π, τ, λ). The production problem is to maximize:

$$\mathcal{L} = (\nu - \tau)X(L^X, (\alpha/\beta)L^P) + \alpha L^Y - \pi[(\alpha/\beta)L^P] - \lambda L^X + \mu[1 - L^X - L^Y - L^P] \tag{1.12}$$

with respect to the choices, L^X, L^Y, and L^P. The first-order conditions are:

$$(\nu - \tau)X_L = \lambda + \mu \tag{1.13a}$$

$$(\nu - \tau)\left(\frac{\alpha}{\beta}\right)X_P = \pi\left(\frac{\alpha}{\beta}\right) + \mu \tag{1.13b}$$

$$\alpha = \mu \tag{1.13c}$$

[6] The approach used here differs slightly from Deacon's. He first derives the cost function for X and then plugs that cost function into the consumer's budget constraint. The two approaches are equivalent.

Combining these conditions produces:

$$\frac{X_L}{X_P} = \frac{(\alpha + \lambda)}{(\beta + \pi)} \tag{1.14}$$

If all taxes are zero ($\lambda = \pi = \tau = 0$), then producers set $X_L/X_P = \alpha/\beta$, which violates (1.10a). Thus, the unregulated equilibrium is inefficient. As Deacon shows, if government adds a tax on deforestation at the rate $\pi = W_Q/W_y$ (keeping $\lambda = \tau = 0$), then (1.14) matches (1.10a). Also, substitution of (1.13c) into (1.13b) shows that (1.13b) matches (1.10c). Thus, the use of a single Pigovian tax ensures that all three of the social planner's conditions are met.

As Deacon points out, a tax on deforestation might be difficult to implement and enforce. Farmers use their own labor and cut their own trees, so neither L^P nor P is used in conjunction with a market transaction. Neither has an invoice that can be used to enforce a tax. If the sale of output *is* a market transaction, however, then X is observed and the output tax (τ) may be more easily enforced.

If $\pi = 0$, our point is that government can set:

$$\lambda = \frac{-\alpha(W_Q/W_y)}{\beta + (W_Q/W_y)} < 0 \qquad \text{and} \qquad \tau = \frac{(W_Q/W_y)}{X_P} > 0 \tag{1.15}$$

These provide closed-form solutions for first-best tax rates with unambiguous signs: the government must subsidize the non-forest input, L^X, and tax output X. The choice of λ in (1.15) can be inserted into the firm's condition (1.14) to match the social planner's condition (1.10a). With this subsidy to labor by itself, however, total deforestation by producers would exceed the intent of the social planner in (1.10c). The tax on output in (1.15) ensures that this additional condition is met. By subsidizing labor and taxing output, government induces agents to act *as if* they faced a Pigovian tax.

A few important caveats are in order. Usually, one can think of relevant caveats by listing simplifications in the model: many identical firms using only two inputs to produce one output in competitive markets with perfect information and no other distortions. In this case, however, many assumptions affect both solutions similarly. Non-competitive pricing would complicate the two-part instrument, for example, but it also complicates the calculation of optimal emission taxes. Similarly, other tax distortions require modifications to both solutions. The problem of measuring marginal damage is similar for both solutions. Monitoring pollution is a worse problem for the Pigovian tax, of course, but other problems are specific to the two-part instrument.

First, in some cases, the output tax itself might be difficult to enforce. Subsistence farmers in developing nations may eat their own output or trade informally. Perhaps only exports can be taxed, as Deacon points out. He does not employ the export tax together with the labor subsidy, and we know that this combination is not first best, but we also know that the use of these two instruments together must perform better than the use of each one alone. Second, if production uses several non-polluting inputs, then each must be subsidized. The solution may then involve more than the "two-part instrument" in equation (1.15). Third, heterogeneity matters. If parameters α or β in production functions (1.4) and (1.5) differ among firms, then the optimal subsidy rate in (1.15) may differ. Perfect implementation could be complicated and the first-best outcome very difficult to attain. A direct tax on deforestation, if it were available, would not suffer from this problem because marginal damage does not depend on the firm ($\pi = W_Q/W_y$). Without such a tax, however, even a uniform subsidy and output tax must perform better than the uniform subsidy alone. Fourth, the two-part instrument may not always replicate the effect of the emissions tax (such as without constant returns to scale or a profits tax). Still, the tax-subsidy combination always dominates the subsidy alone.

Finally, not all environmental subsidies reduce costs and encourage output in ways that require an output tax. A different kind of subsidy might be paid directly for reductions in pollution, which *raises* the opportunity cost of pollution and production. It may provide rents to those paid for reductions, but it raises the price of output and has allocation effects that match the Pigovian tax (Baumol and Oates, 1988). The crucial feature of subsidies considered in this paper is that they reduce costs by applying to inputs other than the damaging activity (i.e. labor, legal disposal, technology). See Parry (1998) for a discussion of subsidy types and examples of each.

Despite these caveats, this use of Deacon's model offers additional insight for policymaking. Because the single policy instrument (λ) has ambiguous effects on deforestation, public policy is difficult to construct and evaluate. Here, in contrast, the combination of two instruments produces unambiguous effects and clear directives to policymakers: environmental policy can indeed subsidize the non-polluting input to production, if it is combined with a tax on output.

2. A Model of Toxic Waste Disposal

Sullivan (1987) builds a computational model and uses it to show how a subsidy to legal disposal can significantly reduce social costs associated with illegal dumping of toxic waste. Even proper disposal of waste imposes costs on society, however, and this subsidy increases the amount of such waste. To show how a tax-subsidy combination could improve welfare within Sullivan's framework, we review his model, replicate his computational results, and then add an output tax. In order to model the effects of an output tax, we must modify Sullivan's framework. Most notably, we add consumers and their final output demand. We show that these modifications yield a factor demand curve and a measure of welfare that are perfectly consistent with Sullivan's assumptions. We replicate the welfare gain from Sullivan's subsidy to legal disposal, and we show that adding an output tax provides a welfare gain three times as large.

Sullivan's model consists of a set of nearly-identical firms that differ only with respect to how effectively they avoid detection when dumping waste illegally. Firms that can avoid detection most effectively choose to dispose of all their waste illegally, while other firms use legal disposal. The marginal firm is indifferent between legal and illegal disposal.

Each firm makes two decisions: how to dispose of waste (legally or illegally) and how much waste to produce. Each uses the disposal method that generates the smallest expected cost. The relative costs of illegal and legal disposal depend on the size of the subsidy to legal disposal, the government's resources devoted to detecting illegal disposal, and the heterogeneous trait of the firm. The firm decides how much waste to produce based on a downward-sloping factor demand curve for waste. The factor price is the firm's expected disposal cost. Thus, a subsidy changes all firms' relative factor prices and shifts some firms at the margin from illegal to legal disposal. But because the subsidy reduces the cost of disposal for all firms using legal disposal, it increases the chosen waste generated.

Sullivan's m firms are ordered according to the likelihood of detection when dumping waste illegally. The first firm $(j = 1)$ is the least likely to be observed, and the last firm $(j = m)$ is the most likely to be observed. Using Sullivan's notation, the probability of detection is a linear function $(\Phi + \tau j)$, where Φ and τ are constants (for any given level of enforcement).[7]

Thus, firm j faces an expected cost or "price" per barrel of illegal dumping:

$$P_I(j) = f\cdot(\Phi + \tau j) = 765\cdot(.014 + .000018j) \tag{2.1}$$

where f is the fine for illegal dumping, and where the right hand side shows Sullivan's parameter values. All firms face the same market price per barrel of legal disposal (C_L) and the same rate of subsidy (s). Thus, all firms face a net price for legal disposal given by:[8]

$$P_L = C_L\cdot(1 - s) = 30\cdot(1 - s) \tag{2.2}$$

Each firm chooses to dispose of waste in the least-cost manner, and so each faces a price of waste disposal given by $P_w(j) = \min\,[P_L\,,\,P_I(j)]$. To see how many firms dispose of waste illegally, note that the indifferent firm, j', faces the same cost for legal or illegal disposal. Set (2.1) equal to (2.2) and solve for j :

$$j' = \frac{C_L(1-s) - \Phi f}{\tau f} \tag{2.3}$$

[7] Sullivan models Φ as a function of resources (R) devoted to detection, and he calculates the effects on waste and welfare in his model from changes in the government's monitoring effort. Since we are concerned only with other policies (subsidies and taxes), we fix R and thus Φ.

[8] To choose parameter values, Sullivan uses direct evidence and other prior empirical literature. For example, parameters in the firm's cost of illegal dumping in (2.1) above are based on prior results from Ehrlich (1974). The market for legal disposal is meant to internalize all social costs (e.g. through regulation). The initial market price of legal disposal (C_L=\$30) is based on direct evidence of transport, disposal, and social costs per ton of legal waste at two specific California disposal facilities.

The first j' firms dispose of waste illegally, while the remainder use legal disposal. Every firm j has a downward-sloping demand for waste:

$$w(j) = \frac{k}{P_w(j)} = \frac{30}{P_w(j)} \tag{2.4}$$

where k is a constant.[9]

Before turning to measurement of the costs and benefits of a policy, it is worth noting that equations (2.3) and (2.4) will drive our results. Equation (2.3) shows that a subsidy has the desirable effect of inducing more firms to dispose of waste legally: higher s means lower j'. The subsidy also has the undesirable effect of decreasing the price of waste, $P_w(j)$, and therefore, increasing the quantity of waste demanded (in 2.4). We can offset the second effect, however, by adding a tax on output.

Sullivan models the social marginal cost of illegal disposal, C_I, to be constant. Using his notation and parameter values, the total social cost of illegal disposal is:

$$TC_I = I \cdot C_I = I \cdot \psi \cdot C_L = I(8.5)(30) \tag{2.5}$$

where I is the volume of illegal waste, and ψ is a constant greater than one (so that $C_I > C_L$). In contrast, the social marginal cost of legal disposal, $mc(L)$, increases linearly with legal waste, L, so $mc(L) = .003(L)$.[10] Therefore, the total cost of legal waste is triangular:

$$TC_L = .5L \cdot mc(L) = .5L(.003L) \tag{2.6}$$

The benefit to firm j of generating waste $w(j)$ is the area below its factor demand curve (inverting equation 2.4):[11]

$$b(j) = \int_0^{w(j)} \frac{k}{\omega} d\omega \tag{2.7}$$

The total benefit is the sum across $m = 10{,}000$ firms of all individual benefits:

[9] When we extend the model to account for the output market, we will specify k as a function of income and of parameters from a utility function and a production function.

[10] Sullivan's calculation involves 10,000 firms that each produce one barrel of legal waste in the optimum allocation, so $mc(L) = .003(10{,}000) = 30 = C_L$ (the gross price per legal barrel in 2.2 above). This rising social marginal cost of legal disposal could eventually exceed the constant social marginal cost of illegal disposal, but only at L=85,000 (far larger than any reasonable scenario in this model).

[11] Since the integral is not defined at the lower limit of integration, we follow Sullivan by using a lower limit of 0.001 in computations.

(2.8) $$TB(W) = \int_1^m b(j)dj$$

Taking the benefit of pollution (equation 2.8) and subtracting the costs (equations 2.5 and 2.6) yields the value of the waste market.

Net welfare is this value of waste minus the social cost of administering a policy. For Sullivan, this social cost includes a direct cost of enforcement (R) and the excess burden of raising money for enforcement and for subsidies. Our own programs can replicate his results using his formulas, but in this paper we assume that lump-sum taxes are available and thus omit his excess burden calculations.[12]

We now modify Sullivan's model to allow for an output tax. We model consumer demand (and therefore output) in the simplest way that's consistent with Sullivan's model. We assume that each firm behaves competitively, earns zero profits, and receives a market price P_x for its output x (with index j suppressed). For each output x, a representative price-taking consumer has a Cobb-Douglas demand function based on exogenous income, y, while facing *ad valorem* tax, t. Therefore:[13]

(2.9) $$x = \frac{\gamma y}{P_x(1+t)}$$

where γ is a preference parameter. We assume that x is produced using toxic waste and some other input via Cobb-Douglas production, so the firm's expenditure on waste is a constant share of sales revenue:

(2.10) $$P_w w = \alpha P_x x$$

To obtain the factor demand for waste, substitute (2.9) into (2.10) and solve for w:

(2.11) $$w = \frac{\alpha\gamma y/(1+t)}{P_w} = \frac{k/(1+t)}{P_w}$$

12 In addition, results in Bovenberg and de Mooij (1994) raise doubts about the kind of excess burden calculation in Sullivan (1987). It is true that subsidies might have to be financed by raising some other distorting tax, like a wage tax, which would reduce the real net wage and reduce labor supply. However, the subsidy for waste disposal would reduce the equilibrium cost of goods sold and thus *raise* the real net wage. This effect partly offsets the change to excess burden. Parry (1998) discusses the fiscal implications of environmental subsidies.

13 Because firms have different disposal costs, zero profits imply different output prices. Thus, we cannot assume that they all operate competitively in the same output market. Instead, we must assume that their output markets are segmented. The firms may produce different outputs, or they may produce the same output in geographically separated markets. We only require that each expenditure $[x_j P_{xj}(1+t)]$ is the same constant (γy), while firms behave competitively, face the same disposal prices, and differ only in terms of illegal waste detection probability.

This equation modifies (2.4) by the addition of an output tax. Since Sullivan used k = 30, we set $\alpha\gamma y = 30$ to be consistent with Sullivan when the output tax is zero.[14]

Table 1 shows the results of our calculations. The first two columns show results when the output tax is zero, as in Sullivan (1987). The subsidy rate is zero in the first column, to replicate Sullivan's "Laissez-Faire" case, and it is .349 in the second column to replicate his "Optimum Subsidy" case. These results emphasize Sullivan's central point: when illegal disposal is hard to observe, a subsidy to legal disposal can be an effective policy tool. It reduces illegal waste by 42% (from 2,241 to 1,307 barrels), and it increases the welfare benefit of this market by 11% (from 1,388 to 1,543 in $ thousands). In doing so, however, this policy raises the total amount of waste by 45% (from 10,841 to 15,685 barrels).

Table 1: Computational Results for Toxic Waste Policy

	Laissez-faire	**Suggested Subsidy**	**Suggested Subsidy with Output Tax**	**Optimal Subsidy-Tax Combination**
Policy variables				
Subsidy rate	0	0.349	0.349	0.643
Subsidy budget (thousand $)	0	150.5	71.7	193.0
Output tax rate	0	0	1.10	1.80
Output tax revenue (thousand $)	0	0	523.8	642.9
Volume of disposal (barrels)				
Legal	8,600	14,378	6,847	10,004
Illegal	2,241	1,307	623	0
Total	10,841	15,685	7,470	10,004
Number of unlawful firms	1,400	640	640	0
Benefits and costs				
Benefit of waste (thousand $)	2,091	2,206	1,984	2,072
TC_I (thousand $)	572	333	159	0
TC_L (thousand $)	111	310	70	150
Net value of waste (thousand $)	1,408	1,563	1,755	1,922
Enforcement cost (thousands $)	20	20	20	20
Net welfare (thousand $)	1,388	1,543	1,735	1,902
Gain relative to laissez-faire	0	155	347	514

The next two columns show how a tax-subsidy combination can improve upon the suggested subsidy policy. The third column calculates the benefit-maximizing

[14] We have no need to specify separate values for α, γ, and y. Each is an exogenous constant, and we need only their product.

output tax when the subsidy is still .349, as in the previous column. If $t = 1.10$, then the welfare gain relative to the laissez-faire equilibrium improves to $347 thousand – more than twice the gain from the subsidy alone. The additional gain comes from reducing both legal and illegal waste.

The availability of an output tax means, however, that .349 is no longer the optimal subsidy rate. The fourth column of Table 1 shows the results of our search for the optimal values of both rates simultaneously. In this case, the optimal policy provides a subsidy of .643, large enough to induce all firms to dispose of waste legally, and it imposes a relatively large tax on output ($t = 1.80$). The net welfare benefit from this market is now 37% larger than with no policy, a gain of $514 thousand – more than three times the gain from Sullivan's subsidy alone. The intuition behind this impressive gain is straightforward. In Sullivan's framework, the subsidy to legal disposal causes total waste to rise by 45%. Even legal waste imposes social cost. Therefore, the subsidy must be used in moderation. When the subsidy is combined with a sufficiently large output tax, however, the demands for both types of wastes fall. Government can then use the subsidy more aggressively to switch waste from illegal to legal disposal.

We next calculate that the welfare-maximizing illegal waste tax, if it were available, would be $19.29 per barrel of illegal waste. The outcome of this calculation exactly matches the last column of Table 1. Thus, in this model as well as the previous one, the optimal two-part instrument replicates the effects of the unavailable waste tax – even though each part applies to an observable market transaction: a subsidy to legal disposal and a tax on sale of output.

3. A Model of Technological Adoption

Stranlund (1997) analyzes three policy tools of a government that wants firms to abate pollution: an abatement standard (s), the probability of an audit (p), and publicly-provided technological assistance (q) for pollution abatement technology. In order to achieve any abatement, government must use strictly positive amounts of the first two tools. If audits are expensive, Stranlund shows that a cost-minimizing government may also use positive amounts of technological assistance. By providing such assistance, the government can achieve a given level of abatement while doing fewer audits.

Stranlund's framework considers a risk-neutral firm that minimizes expected compliance cost while facing a standard for total emissions (equivalently, abatement). We extend his model to analyze the trade-off between monitoring and technological aid when firms face a *per-unit* emissions or abatement standard. Thus we broaden the applicability of his analysis, as per-unit standards are common policy tools. For example, policies to control mobile-source pollution focus on emissions per mile, rather than hard-to-monitor total emissions. Also, whereas Stranlund leaves implicit the firm's choice of output, we add explicit consideration of how the per-unit abatement standard affects output. We can then add a tax on output.

Whereas Stranlund allows output implicitly to change, and uses a to represent total abatement, we use a to represent abatement *per unit*. Similarly, the abatement standard (s) represents the required abatement per unit of output. When all of Stranlund's variables are re-defined to represent amounts per unit of output, we then simply note that all his derivations still hold and all his results can be re-interpreted to involve abatement or emissions per unit. We then *add* explicit changes in output and analyze what happens to total output and total emissions.

Extending the model in this way produces an interesting result. Because technological aid reduces costs to firms, equilibrium output rises. Therefore, while this aid increases abatement per unit, it also increases the number of units of output. Consequently, the effect of technological aid on total emissions is ambiguous. In many industries, the cost of pollution control equipment is negligible when compared to the industry's other costs. In these cases, the impact of a technology subsidy on output is likely to be negligible, and our extension does not significantly modify Stranlund's results. In other industries, however, pollution control is a significant fraction of overall costs.[15] In these cases, we show that a cost-minimizing government may still wish to conduct environmental policy by using technological aid. However, the use of technological aid is sub-optimal unless accompanied by a tax on output.

As Stranlund models them, the compliance costs for reducing emissions consist of three parts. First, the firm pays the direct cost of abatement, $v(a, z)$, which depends on abatement and on the level of pollution control technology (z). We re-define a as abatement per unit and v as the cost per unit, but all derivations follow Stranlund: the cost per unit rises with abatement ($\partial v/\partial a \equiv v_a > 0$) and falls with better technology ($\partial v/\partial z \equiv v_z < 0$). Second, the firm faces the cost of maintaining and using the technology, $w(z, q)$. This (per unit) cost increases as the level of technology increases ($w_z>0$), but may be offset by a government subsidy or technological aid, q (where $w_q<0$).[16] Third, the firm may pay a fine if it does not fully comply with the "required" abatement standard (s). The fine (per unit) is a function f of the degree to which a firm "cheats", $(s - a)$, and the expected fine depends on the probability of an audit (p). Overall compliance costs (per unit of output) are thus defined by:

$$C(a, z) = v(a, z) + w(z, q) + pf(s - a) \qquad (3.1)$$

Here, we retain Stranlund's consideration of heterogeneity (even though we suppress his firm-specific index for notational simplicity). In principle, these costs can vary among firms both because firms have different ability to abate and because a regulator can set different abatement standards, probability of audit, degree of technological aid,

---

[15] U.S. Commerce Department (1994) compares firms' expenditures on pollution abatement to the value of output. The data show significant variation by industry. For example, firms producing petroleum and coal products (SIC 29) spend about 2¢ per dollar of output, while firms producing stone, clay and glass products (SIC 32) spend about one-tenth of that amount.

[16] In Stranlund's formulation, government assistance comes in the form of a publicly-provided good that all firms may access. We do not consider the degree to which this aid is rival or excludable, so we use the terms "subsidy" and "technological aid" interchangeably.

and fine for non-compliance (even though Stranlund assumes that technological aid and fines are uniform).

To study Stranlund's policy options in a model where output varies, we add notation x to denote output, and we say that the firm's "potential pollution" is proportional to output. In fact, we can define a unit of "potential pollution" as the amount associated with one unit of output. With no abatement per unit $(a = 0)$, emissions are x. Then actual total emissions are:

$$e = x(1-a) \tag{3.2}$$

We also add a production function in terms of a single input, labor (ℓ), so that:

$$x = g(\ell) \tag{3.3}$$

where $g_\ell > 0$ and $g_{\ell\ell} < 0$. Each price-taking firm faces the market price P for its output, and it must pay an output tax t. Thus, the firm chooses z, a, and ℓ to maximize profits (Π):

$$\Pi(z, a, \ell) = g(\ell)[P - t - C(a, z)] - \ell \tag{3.4}$$

where ℓ is the numeraire. After using equation (3.2) and simplifying, the problem produces the following first-order conditions:

$$v_z(a,z) + w_z(z,q) = 0 \tag{3.5a}$$

$$v_a(a,z) - pf'(s-a) \leq 0 \quad [\text{if} < 0, \text{then } a = s] \tag{3.5b}$$

$$g_\ell \cdot [P - t - C(a, z)] - 1 = 0 \tag{3.5c}$$

where the subscripts denote partial derivatives. The first two conditions are identical to those of Stranlund's model (his equations 2.2 and 2.3, p. 232). Thus, his comparative static results hold here as well: when firms do not fully comply $(a < s)$, they increase abatement in response to increased aid $(a_q > 0)$, an increased standard $(a_s > 0)$, or increased audits $(a_p > 0)$. We merely re-interpret his results to show the effects of these policies on abatement per unit. Thus, we proceed directly to show effects on total pollution. Differentiating the first order conditions shows the output response to a technological subsidy:

$$x_q \equiv g_\ell \cdot \ell_q = \frac{(g_\ell)^2 \cdot w_q}{g_{\ell\ell} \cdot [P - t - C(a,z)]} > 0 \tag{3.6}$$

The sign of $x_q > 0$ follows because w_q and $g_{\ell\ell}$ are both negative while the net price $[P - t - C(a, z)]$ is positive.[17] Therefore, equation (3.6) verifies that the subsidy q reduces the firm's marginal cost and therefore raises its optimal level of output. Further comparative static analysis shows that x_p, x_s, and x_t are all negative. In addition, a_t and z_t are both zero: if a firm is already minimizing its cost per unit, then a tax on output does not affect abatement per unit or technology per unit. Since $e = x(1 - a)$, these results define how each instrument affects total emissions:

(3.7a) $$e_p = x_p(1-a) - xa_p < 0$$

(3.7b) $$e_s = x_s(1-a) - xa_s < 0$$

(3.7c) $$e_t = x_t(1-a) < 0$$

(3.7d) $$e_q = x_q(1-a) - xa_q \gtrless 0$$

where subscripts again denote partial derivatives. Stranlund shows that $a_q > 0$, $a_s > 0$, and $a_p > 0$. Thus, we show here that *total* emissions (e) are reduced by increased audits (p), an increased standard (s), or by an output tax (t).

Equation (3.7d) looks at the effects of technological aid on emissions. Since both a_q and x_q are positive, the sign of e_q depends on relative magnitudes. If abatement costs are only a small fraction of the firm's total costs, then x_q may be quite small. If x_q were zero, then the firm does not change output, and our extension reduces to Stranlund's original model. On the other hand, a technological subsidy might well affect output of the firm. From equation (3.7d), the condition for e_q to be positive is $\frac{x_q}{x} > \frac{a_q}{(1-a)}$. Since $(1 - a)$ is emissions and $-a_q$ is the change in emissions (both per unit of output), the firm's total emissions rise if the percentage change in output exceeds the percentage change in per-unit emissions. This condition may hold for any number of (heterogeneous) firms within an industry, and so it may hold for the aggregate as well. If so, then the subsidy to abatement may increase aggregate pollution.

The possibility that technological aid may increase emissions fundamentally changes Stranlund's result. With a fixed total abatement standard, he shows that regulators who want firms to cut total emissions can view monitoring and technological aid as substitutes. Using the same methodology as Stranlund, we next show that if the abatement standard is fixed per unit, then monitoring and technological aid may no longer be substitutes. All else equal, increased aid may require more monitoring.

As in Stranlund, at this point, the abatement standard (s) and the fine (f) are fixed. The regulator optimally trades off the probability of an audit (p) and the subsidy (q) to induce the cost-minimizing choice of technology and abatement per unit. Since

[17] Because the firm has no fixed costs and decreasing returns to scale $(g_{\ell\ell} < 0)$, any firm producing positive output must be making positive profits $[P - t - C(a, z)]$.

we add consideration of an output tax, our regulator must find the cost-minimizing combination (q, t, and p) to achieve the target for total pollution ($e \leq \bar{e}$).

In order to derive the relationship between aid (q) and monitoring (p), let $p^*(q, t, \bar{e})$ be the minimum monitoring effort needed to achieve the compliance goal, $\bar{e}$, given any level of aid and tax. Stranlund uses first-order conditions (3.5a and 3.5b) to define the firm's choice of a as a function of policy variables, $a(q, s, p)$. Since s is fixed, this can be written as $a(q, p)$. Similarly, we use (3.5c) to define output x as a function of all policy variables, $x(q, t, p)$. Therefore, the function p^* is defined implicitly by:

$$\bar{e} = x(q, t, p^*(q, t, \bar{e}))\cdot[1 - a(q, p^*(q, t, \bar{e}))] \tag{3.8}$$

Differentiate (3.8) with respect to q, rearrange, and use (3.7a) and (3.7d) to get:

$$p_q^* = \frac{-e_q}{e_p} \gtrless 0 \tag{3.9}$$

Because Stranlund is concerned with a total emission standard, the comparable expression in this model is $p_q^* = -a_q/a_p < 0$ (his equation 2.10, p. 233). The implication is that monitoring and aid are substitutes. When firms face a per-unit standard, however, we just showed that the sign of $p_q^* = -e_q/e_p$ is ambiguous (because the sign of e_q is ambiguous). Regulators can view monitoring and technological aid as substitutes *only* if increased aid leads to lower pollution ($e_q < 0$).

Nonetheless, we next show that if regulators have three tools (q, p, and t), they can again view the first two as substitutes. That is, regulators may well substitute technological aid for monitoring, in this more general setting, *if* they can combine the technology subsidy with a tax on output. The intuition behind this conclusion is simple. A regulator can reduce pollution through various combinations of reduced output and increased abatement per unit, and the overall pollution goal can be accomplished in a two-stage process. The first stage we assume to be exactly the same as in his paper (redefining variables per unit): the regulator chooses the levels of aid and monitoring to achieve the desired abatement per unit. With respect to this abatement, as Stranlund shows, monitoring and aid *do* act as substitutes. Thus, the regulator may want to use a positive amount of aid. Our extension focuses on the second part of the regulator's problem. Having achieved the desired abatement per unit, the regulator sets an output goal. Taking into account the optimal choices of monitoring and aid, the regulator sets the output tax to meet this second goal. Since abatement is not a function of the output tax, this choice does not alter abatement.

To model this two-stage problem, we adhere to Stranlund's model and allow the regulator to minimize the total social costs associated with regulation. In our extension, these costs can be split into two categories: the costs associated with a certain level of abatement per unit, plus the loss of consumer surplus associated with diminished output.

Stranlund identifies the costs associated with per-unit abatement as the sum of costs borne by the firm, $v(a, z) + w(z, q)$, and costs borne by government. The latter include the cost per audit, r, and the cost of aid (where the unit price of aid is normalized to one). Note that the expected fine, $pf(s\text{-}a)$, is a transfer, so it does not enter social costs. Maintaining the assumption that the standard is fixed, the expected social cost associated with the firm's abatement is $[v(a, z) + w(z, q) + rp + q]$. Like Stranlund, we assume that this function is convex and that the regulator chooses p and q to minimize this cost of achieving a particular goal for a.[18] Given those choices (p^* and q^*), and the firm's optimal responses (including z^*), this cost can be defined as a function of the goal for a:

(3.10) $$\Phi(a) = v(a, z^*) + w(z^*, q^*) + rp^* + q^*$$

In addition, these policies reduce output and thus diminish consumer surplus. Let $\bar{x}$ be the firm's output when government applies none of its policy tools. We then define $\Omega(\bar{x} - x)$ as the lost surplus when decreasing output from $\bar{x}$ to x. To minimize the overall costs of achieving any particular reduction of pollution, the regulator therefore chooses x and a to minimize:

(3.11) $$\mathcal{L} = \Phi(a) + \Omega(\bar{x} - x) + \lambda(\bar{e} - x(1 - a))$$

This problem's first-order conditions describe the optimal mix of per-unit abatement (a) and output reduction ($\bar{x} - x$). The regulator chooses p and q (in 3.10) to achieve the optimal a. Then, output is controlled by choosing t conditional upon those choices (p^* and q^*). In other words, if the regulator chooses to limit per-firm output to some level, x^*, then the optimal t satisfies $x^* = x(p^*, q^*, t)$. Inverting this expression, we have the optimal tax rate:[19]

(3.12) $$t^* = t(p^*, q^*, x^*)$$

Stranlund finds that a regulator can view monitoring and aid as substitutes, but we find this result does not hold with a per-unit emission standard. Nonetheless, Stranlund's basic intuition comes through unscathed. Our extension allows the regulator to solve the problem sequentially. Stranlund's model describes the first part of that sequence – how the regulator uses technological aid to minimize the costs of abatement per unit. Our contribution shows that different monitoring-subsidy

---

[18] The goal for a may be less than the standard, s, because firms may cheat when minimizing their own expected costs in equation (3.1).

[19] Each parameter may differ among firms, and so the optimal value of this tax rate would differ among firms. Clearly, such a policy would be difficult to implement. Even a uniform output tax can improve upon the welfare gain from using only the abatement subsidy, however, and a computational version of this model could be used to show how much the gain exceeds that from a subsidy alone (or falls short of that from firm-specific taxes).

combinations have different effects on output, which in turn affects pollution. However, the regulator can control output by using an output tax. Thus, Stranlund's results still hold, even if aid tends to increase pollution, but only if the regulator combines the optimal monitoring-aid package with an optimal output tax.

4. Conclusion

Deacon, Sullivan and Stranlund study an important and topical subject, since regulators currently use a variety of environmental subsidies as policy tools. These three papers show that such subsidies have positive effects. Subsidies are especially appealing when a Pigovian tax is not available. However, these policies and analyses may miss the opportunity for further welfare gains made possible by combining the environmental subsidy with a tax on output.

Using Deacon's model, we show a simple case where a two-part instrument can be equivalent to an emissions tax. We also list a number of caveats. Because of the substantial welfare gain possible from adding an output tax to a subsidy policy, this combination is worth additional research. In particular, further research can investigate each of the caveats: how is this choice of policy influenced by imperfect competition, information asymmetries, or other market failures? One important topic for future research, as suggested by a referee, is to compare the incentives for R&D. While the emissions tax can provide incentives for the invention of cleaner technologies over time, in addition to controlling pollution each year, a subsidy cannot be provided for technologies not yet invented. The tax-subsidy combination might provide comparable incentives only if firms assume that new technologies *will* receive subsidies at appropriate rates. While this point and others may favor the emissions tax over the two-part instrument, however, none of them pertain to the main point of this paper: in cases where the emissions tax is not feasible or where policy already employs a subsidy, welfare can be improved by the addition of an output tax.

Sometimes, that improvement can be substantial. In Sullivan's computational model, a subsidy by itself increases social benefits by 11% (compared to the laissez-faire equilibrium). A subsidy-tax combination increases that gain to 37% of laissez-faire market benefits – more than three times the gain from using the subsidy alone.

Our final example provides insight into this improvement. Using Stranlund's model with a per-unit standard, we show that a subsidy increases output. Therefore a subsidy, used alone, has ambiguous effects on pollution and may require increased monitoring. To prevent output from rising, however, regulators can use an output tax. Thus, indeed, a subsidy *can* help achieve optimal results. To do so, however, the regulator must combine it with a tax on output.

Colophon

Don Fullerton is at the Department of Economics, University of Texas, Austin, TX 78712 (dfullert@eco.utexas.edu), and Robert Mohr is at the Department of Economics,

University of New Hampshire, Durham, NH 03824 (rmohr@cisunix.unh.edu). For funding this research, we thank the University of Texas and the National Science Foundation (grant #SBR9811324). Helpful suggestions were provided by Bob Deacon, Aaron Edlin, Art O'Sullivan (formerly Sullivan), John Stranlund, Sarah West, Rob Williams, and three referees. This paper is part of the NBER's research program in Public Economics. Any opinions expressed in this paper are those of the authors and not those of the NSF or the NBER.

References

Baumol, W. J. and W. E. Oates, *The Theory of Environmental Policy*, Second Edition, New York: Cambridge University Press (1988).

Bovenberg, A. L. and R. A. de Mooij, "Environmental levies and distortionary taxation," *American Economic Review* **84**, 1085-1089 (1994).

Deacon, R., "Assessing the relationship between government policy and deforestation," *Journal of Environmental Economics and Management* **28**, 1-18 (1995).

Ehrlich, I., "Participation in illegitimate activities: An economic analysis," in G. S. Becker and W. M. Landers, eds., *Essays in Economics of Crime and Punishment*, New York: National Bureau of Economic Research (1974).

Eskeland, G. and S. Devarajan, *Taxing Bads by Taxing Goods: Pollution Control with Presumptive Charges*, Washington, DC: The World Bank (1996).

Fullerton, D., "Environmental levies and distortionary taxation: Comment," *American Economic Review* **87**, 245-251 (1997).

Fullerton, D. and S. West, "Tax and Subsidy Combinations for the Control of Car Pollution," NBER Working Paper No. 7774, Cambridge, MA (July 2000).

Fullerton, D. and A. Wolverton, "The case for a two-part instrument," in A. Panagariya, P. R. Portney and R. M. Schwab, eds., *Environmental and Public Economics: Essays in Honor of Wallace E. Oates*, Cheltenham, UK: Edward Elgar (1999).

Palmer, K. and M. Walls, "Optimal policies for solid waste disposal: Taxes, subsidies, and standards," *Journal of Public Economics* **65**, 193-205 (1997).

Parry, I. W. H., "A second-best analysis of environmental subsidies," *International Tax and Public Finance* **5**, 153-170 (1998).

Pigou, A., *The Economics of Welfare*. London: MacMillan (1920).

Stranlund, J., "Public technological aid to support compliance to environmental standards," *Journal of Environmental Economics and Management* **34**, 228-239 (1997).

Sullivan, A. M., "Policy options for toxic disposal: Laissez-faire, subsidization, and enforcement," *Journal of Environmental Economics and Management* **14**, 58-71 (1987).

U.S. Department of Agriculture, "USDA Forest Service, State & Private Forestry, Cooperative Forestry," web page, http://www.fs.fed.us/spf/coop/, Washington DC: USDA (July 13, 2000 version).

U.S. Department of Commerce (Bureau of the Census), "Pollution Abatement Costs and Expenditures: 1994," Current Industrial Reports, MA299(94)-1, Washington, DC: U.S. Government Printing Office (1994).

U.S. Department of Energy, "Strategic Plan of the Office of Science," Washington DC: U.S. DOE (1999).

U.S. Environmental Protection Agency, "EPA's 33/50 Program Second Progress Report: Reducing Risk through Voluntary Action," Washington DC: U.S. EPA (1992).

U.S. Environmental Protection Agency, "Green Lights: An Enlightened Approach to Energy Efficiency and Pollution," Washington DC: U.S. EPA (1993).

Walls M. and K. Palmer, "Upstream pollution, downstream waste disposal, and the design of comprehensive environmental policies," *Journal of Environmental Economics and Management* **41**, 94-108 (2001).